19

Decompression Theory: Swiss Practice

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In 1959 a young Swiss, Hannes Keller, confronted the world with the problems of deep diving. At that time little progress was being made in developing deep diving techniques by the leading maritime countries such as England, France and the USA. There was no Swiss Decompression Theory and no tradition to restrict the approach. Such lack of experience favours the development of a simple working hypothesis.

DEVELOPMENT OF THE METHOD OF 'MIXED GAS DECOMPRESSION'

The newcomer to this field of research had five facts to work from:

1. Reasonably safe decompression tables existed for air diving to depths as far as 200 ft (7 ATA).
2. Inert gases were known to have cerebral effects, which varied between individuals. An accepted figure for P_{N_2} tolerance was 5 to 6 ATS.
3. The greater gas density at depth increased the breathing resistance, particularly where turbulent flow existed in valves and air passages.
4. The possibility of shortening decompression time by breathing a high P_{O_2} was limited by the toxic effects of hyperoxia.
5. The observation that longer decompression was necessary to avoid troubles after oxyhelium dives with short bottom time than with equivalent air dives.

These facts suggested that the saturation of some tissues occurred faster with helium than with nitrogen. The assumption of different saturation speeds implied a possibility of shortening decompression time by combining advantageously a sequence of inert gases such as helium, nitrogen, hydrogen, neon and argon with a high partial pressure of oxygen. In theory it seemed clear that a change of inert gas from helium to nitrogen during decompression, would hasten the elimination of helium because the helium pressure gradient between blood and tissue is increased, while at the same time the intake of nitrogen would occur more slowly.

The special features of the pilot experiments in deep diving were:

Slow compression, breathing 100% oxygen, from 1·0 to 2·5 ATA.

Fast compression at a rate of 2 to 3 ATS/min to total pressure.

Change from helium to nitrogen during decompression.

Continuous decompression to maintain a high pressure gradient of inert gas between tissues and blood.

Premixed gases breathed through a mouthpiece from either open circuit or semi-closed apparatus.

Assumptions made in calculating saturation and desaturation with different inert gases

Saturation and desaturation follow an exponential curve. A spectrum of various half-times can be used to calculate the equalization of the partial

TABLE 19.1

Molecular weights and solubility coefficients of various gases at 37° to 38°C (FASEB 1971)

	H_2	He	Ne	N_2	Ar	O_2
Molecular weight	2·016	4·003	20·183	28·016	39·948	32·00
Solubility, ml/ml at 760 mm Hg, 37°C						
Water	0·0166	0·0086	0·0096	0·0123	0·028	0·0239
Whole blood	0·0149	0·0088	0·0093	0·0130	0·026	0·0223
Olive oil	0·0484	0·0159	0·0199	0·0670	0·148	0·1120

TABLE 19.2

Relationship of solubility coefficients

	N_2/H_2	N_2/He	N_2/Ne	N_2/Ar	H_2/He
Whole blood and watery tissues	0·872	1·477	1·398	0·500	1·693
Pure fat as oil	1·384	4·214	3·367	0·453	3·044

pressures of inspired inert gas and of inert gas dissolved in the tissues. In 1959 the conventional air tables were based on a maximum half-time for nitrogen of about 4 hours.

For a study of inert gas exchange it was important to determine the different saturation speeds for individual gases. It was easy to explain the different half-times for the same gas by differences in the perfusion rates for the tissues. For a constant perfusion rate, the saturation speed depends mainly on the physicochemical properties of the inert gases. A difference in the saturation speed could be the result of different solubility coefficients in fatty and watery tissues; or different speeds of pressure equalization, related to the molecular weight of the inert gases.

Tables 19.1 and 19.2 give the molecular weights, the solubility factors in whole blood, water and olive oil, and the relationship between the solubility coefficients.

The different solubilities imply considerable variation in the masses of the dissolved gases for full saturation of all tissues. This is of significance for their toxic effects as well as for decompression.

In decompression sickness, the available mass of gas controls both volume and surface area of bubbles formed; this in turn determines the degree of tissue deformation. The size of the bubbles also depends on the gas volume due to the diffusion of oxygen, carbon dioxide and other inert gases. In this connection helium is preferable to hydrogen as a light gas, while as a heavy gas nitrogen is preferable to argon. Neon would be just as suitable as helium. The great variation in the solubility ratios of these gases in oil and water (Table 19.3) influences the speed of saturation during compression, bottom time and decompression. The partition coefficient is practically identical for nitrogen and argon. For hydrogen the coefficient is smaller than either of these two gases but larger than the values for helium and neon.

Because of these ratios, the rate of saturation of helium in purely fat tissue is approximately three times faster than nitrogen. This would apply to subcutaneous fat. The equalization of pressure for hydrogen in a fatty tissue is, however, only 1·8 times faster than nitrogen. There are no significant differences between helium and neon, or between nitrogen and argon. For very fatty tissues, hydrogen with a slightly slower saturation speed would have certain advantages over helium.

As far as the speed of equalization of pressures

TABLE 19.3

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

	H_2	He	Ne	N_2	Ar	O_2
	2·921	1·849	2·073	5·460	5·286	4·694
Relationship	N_2/H_2	N_2/He	N_2/Ne	N_2/Ar	H_2/He	
	1·869	2·953	2·634	1·033	1·580	

TABLE 19.4

Square roots of molecular weights

	H_2	He	Ne	N_2	Ar	O_2
	1·420	2·001	4·492	5·293	6·320	5·657
Relationship	N_2/H_2	N_2/He	N_2/Ne	N_2/Ar	H_2/He	
	3·728	2·646	1·178	0·837	0·710	

in watery tissues is concerned, the different solubility coefficients of these inert gases in oil and water are not important. 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 relatively long diffusion routes. Under these conditions the rate of pressure equalization depends on diffusion, which is governed by the molecular weight of the gases. The saturation speeds of two gases are in inverse proportion to the square root of their molecular weights (Table 19.4). Thus, for watery tissues, saturation and desaturation will occur approximately 3·7 times faster with hydrogen than with nitrogen. Helium will be about 2·6 times faster than nitrogen and no significant differences may be expected between neon, nitrogen and argon. It may be concluded that a practical advantage in the use of different inert gases could be obtained by using helium and nitrogen but that no such advantage could be expected from the use of neon or argon. *The gases suitable for multiple inert gas decompression are, therefore, reduced to helium and nitrogen.* In reviewing these theoretical assumptions it can now be said that the conclusions have been substantiated. The tests with argon, neon and hydrogen, which were carried out in the early part of the programme, did not suggest any advantage in using them for decompression after deep diving.

The hypothesis for calculation of decompression in 1960 was reduced to this simple model:

> For the same inert gas, different half-times were related to the perfusion rates of the tissues.
>
> For a tissue with a given perfusion rate, the ratio of half-times for different inert gases is equal to the square root of their molecular weights.
>
> The same supersaturation factors for different inert gases are based only on the ratio between the inert gas pressure in the tissue and the total ambient pressure.

The partial pressures of the different inert gases in the same tissue must be added together. It would be wrong to attempt a decompression where the supersaturation factor was not exceeded for each gas individually.

Using this working hypothesis some deep diving experiments were devised and performed in the wet chamber facilities of the French Navy in Toulon (GERS) and of the US Navy in Washington (EDU) during 1960/61 (Table 19.5).

The financial support of the US Navy enabled the development and improvement of the method of 'mixed gas decompression' and it was shown

TABLE 19.5

Pilot experiments with H. Keller

Date	*ATA*	*Bottom time*	*Decompression (min)*	*Location*
4.11.60	26·0	c. 10 sec	47	GERS
25.4.61	31·0	c. 10 sec	31	GERS
26.4.61	22·5	10 min*	140	GERS
10.5.61	22·5	10 min*	135	EDU

* With physical work.

that this method is also valid for longer bottom times and for different divers.

EXPERIMENTS IN 1962 SPONSORED BY THE US NAVY

All the decompressions to be described, with the exception of the 26·0 and 31·0 ATA experiments (see Table 19.6), were carried out successfully by at least four different divers without serious symptoms of oxygen poisoning or decompression sickness. Like the pilot experiments mentioned earlier, these tests were carried out with pre-mixed gases and an open circuit or semi-closed breathing system. The inert gas change takes place immediately using this technique. Further, the short decompression time after short exposures permits the change from helium to nitrogen to be combined with a high oxygen concentration. If 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 air. Decompression took place continuously in all these experiments.

TABLE 19.6

Mixed gas decompression after helium dives

ATA	*Bottom time (min)*	*Decompression (min)*	*Decompressions (number)*	*Different subjects*
5·0	120	20	7	7
10·0–11·0	60*	105–125	9	9
16·0	30	220	6	6
21·0	20*	230	5	5
26·0	10	270	2	2
31·0	5*	270	4	2

* Carried out in the pressure chamber, and also with swimming excursions in the sea (Keller & Bühlmann 1965).

In Fig. 19.1 is illustrated the possibility of shortening decompression time by changing the inert gas from helium to nitrogen on the bottom. The exposure is 120 mins at 130 ft (5 ATA). The P_{O_2} amounts to 2 ATS during the exposure and the decompression. The change of inert gas from helium to nitrogen takes place during the dive at 130 ft (5 ATA). Nitrogen can be breathed without trouble at this depth and the change permits the elimination of helium. The P_{N_2} of 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; it then increases during the nitrogen phase to 1·65 ATS. The P_{He} 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 P_{inert} total of only 2 ATS. By breathing oxygen for 15 min, the P_{He} and P_{N_2} are decreased till the critical value for surfacing is reached (total $P_{inert} = 1·6$ ATS).

If the experiment were to be performed with 60% nitrogen as the sole inert gas, a P_{N_2} of approximately 2·6 ATS would occur in the same tissue after 120 min. This pressure would only decrease to the critical value after breathing pure oxygen for 40 min. Thus the change of inert gas on the bottom results in a saving of 25 min in decompression time.

If, however, the diver breathes 60% helium during the whole exposure, the 20-min tissue is almost saturated after 120 min; this, together with the remaining N_2, would result in a P_{inert} total of some 3·2 ATS in the tissue. In this case breathing oxygen for 25 min from 50 ft to the surface would be sufficient to decrease the P_{inert} total to 1·6 ATS.

If a mixture of 40% oxygen, 44% helium and 16% nitrogen were to be breathed during the first phase (thus maintaining the P_{N_2} constant at 0·8 ATS) the decompression using 100% oxygen between 50 ft (2·5 ATA) and the surface would take 20 min. The total decompression time would then be nearly as short as the experiment illustrated.

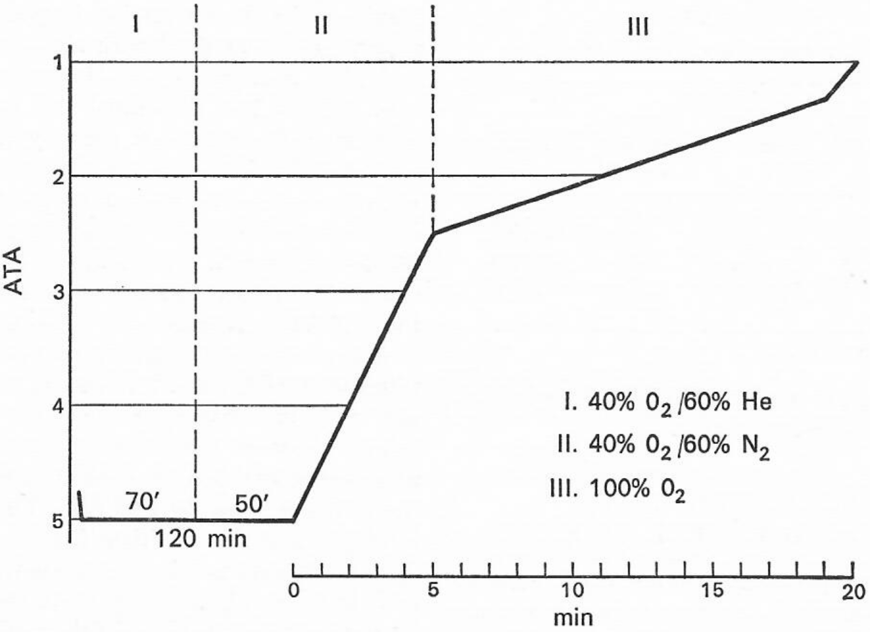

FIG. 19.1. Bottom time 120 min at 130 ft (5 ATA) with 40% oxygen, 60% helium ($P_{He} = 3$ ATS). Inert gas change from helium to nitrogen after 70 min. Decompression time 20 min with inhalation of 100% oxygen from 50 ft to surface (2·5 to 1·0 ATA)

The differences in decompression time described above show that the change of inert gas from helium to nitrogen, after exposures at shallow depth, is only an advantage in shortening decompression time for bottom times up to about 120 min. For longer exposures and at greater depths, the inert gas change can take place only during the decompression and is moved more and more towards the final phase as these features of the dive increase.

Fig. 19.2 shows two possible ways of decompressing after an exposure of 60 min at 330 ft (11 ATA). The Po_2 amounts to 1·65 ATS during the period at depth and also increases to more than 2 ATS for a short time during decompression. In version (a) the diver breathes air between 200 and 115 ft (7 and 4·5 ATA), 50% oxygen and 50% nitrogen between 115 and 50 ft (4·5 and 2·5 ATA) and thereafter 100% oxygen. In version (b) there is no phase of breathing pure oxygen and the total decompression time is 385 min, whereas it was only 105 min in version (a).

Fig. 19.3 gives an example of a short decompression for a 30-min exposure at 500 ft (16 ATA). The Po_2 is 2·4 to 2·5 ATS and the nitrogen concentration of the breathing mixture is increased in the early decompression phases.

Decompressions using the same gas mixtures but with lower oxygen concentration at full pressure, have been performed after bottom times of 20 min at 660 ft (21 ATA), 10 min at 825 ft (26 ATA) and 5 min at 1000 ft (31 ATA). For further details see Figs 19.4 and 19.5.

By the end of these tests, which finished in December 1962 off San Diego, USA, the following conclusions could be drawn:

> It is possible to undertake deep diving in the ocean and permit work on the Continental Shelf.
>
> The bottom times necessary for work require many hours of decompression. It is difficult for divers to use breathing apparatus for these periods so an underwater pressure chamber becomes essential for deep diving.
>
> Long bottom and decompression times cause the slow tissues, such as bones and joints, to

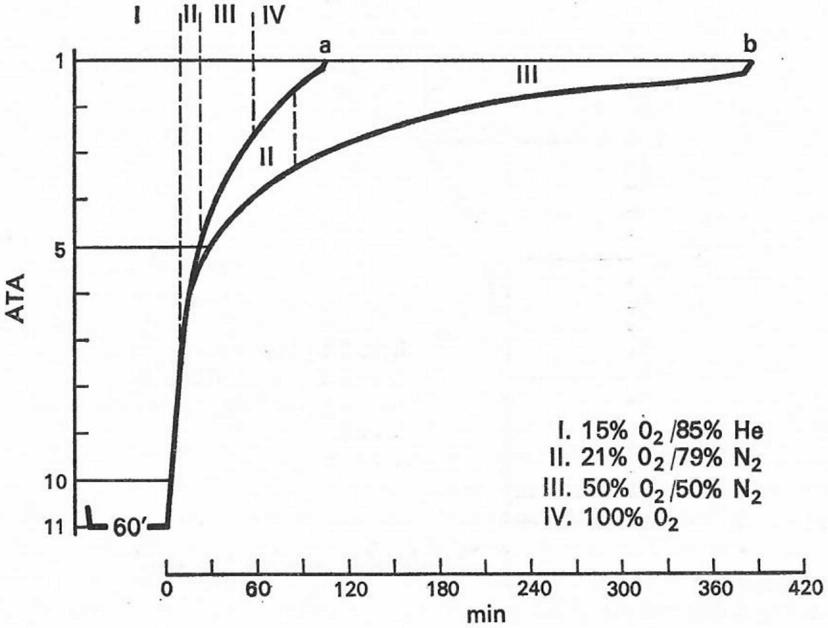

FIG. 19.2. Bottom time 60 min at 330 ft (11 ATA) with 15% oxygen, 85% helium ($P_{He} = 9{\cdot}35$ ATS). Version (a)—inert gas change from helium to nitrogen with different oxygen partial pressures and 100% oxygen at pressures less than 50 ft (2·5 ATA). Total decompression time 105 min. Version (b)—air breathing from 120 to 35 ft (6 to 2·5 ATA) following 50% oxygen/50% nitrogen. Total decompression time 385 min

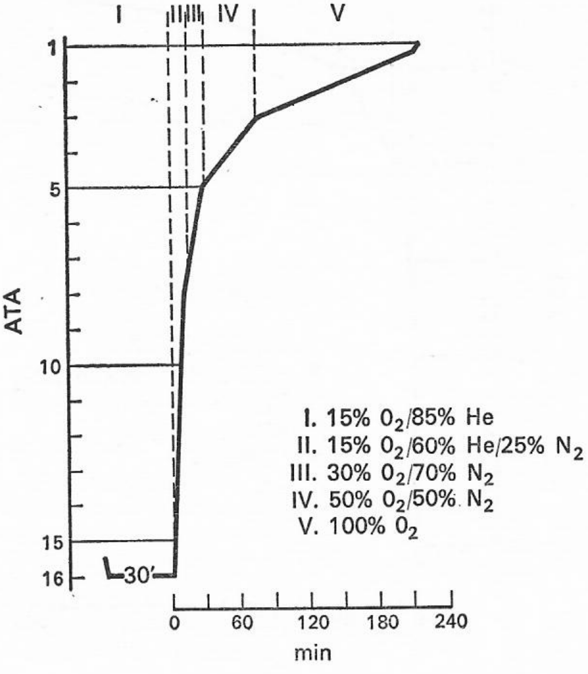

FIG. 19.3. Bottom time 30 min at 500 ft (16 ATA) with 15% oxygen, 85% helium ($P_{He} = 13{\cdot}6$ ATS). Adding stepwise oxygen and nitrogen. 100% oxygen below 2·5 ATA. Total decompression time 220 min

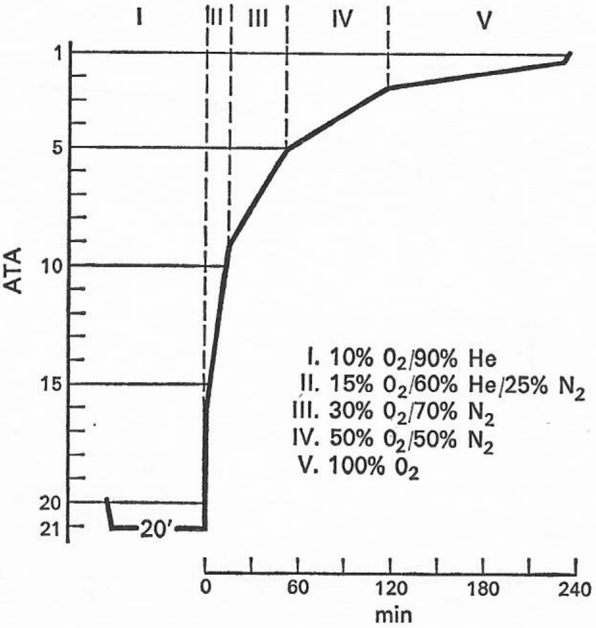

FIG. 19.4. Bottom time 20 min at 660 ft (21 ATA) with 10% oxygen, 90% helium (P_{He}=18·9 ATS). Stepwise increase of oxygen to 100%. From 500 to 260 ft (16 to 9 ATA) helium as well as nitrogen in the gas mixture, thereafter nitrogen only. Total decompression time 230 min

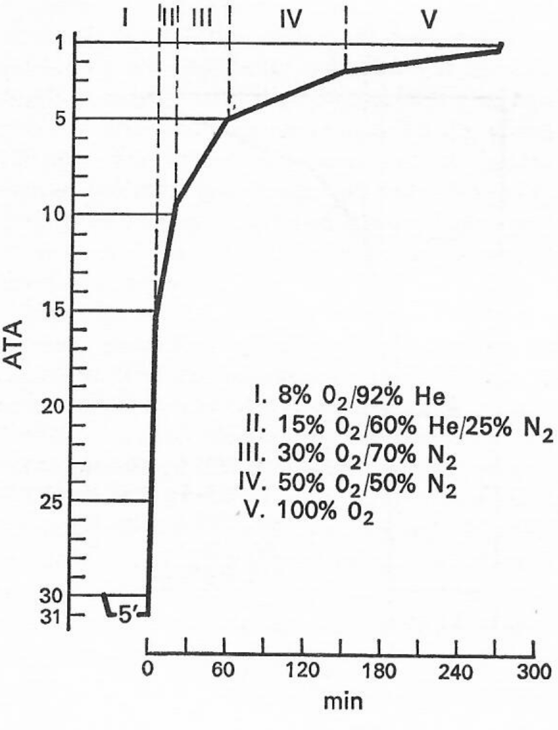

FIG. 19.5. Bottom time 5 min at 1000 ft (31 ATA) with 8% oxygen, 92% helium (P_{He}=28·5 ATS). Carried out in the pressure chamber and in water. Identical procedure as in Fig. 19.4. Total decompression time 270 min

become saturated. These are the tissues that control the rate of decompression.

It would be impossible to develop decompression tables, which would be reasonably safe for professional divers, without a study of saturation dives.

FUNDAMENTAL RESEARCH AND PROLONGED EXPERIMENTS AS A BASIS FOR DETERMINING DECOMPRESSION TABLES 1964 TO 1972

The general features of the trials were as follows:

Compression rate 1·0 to 1·5 ATS/min.

Chamber initially filled with air and pressurized with helium and pure oxygen, thus maintaining a constant P_{N_2} of 0·8 ATS. Change from helium to nitrogen as the inert gas by flushing the chamber with air.

Independent analysis of oxygen, helium, nitrogen and carbon dioxide.

Due allowance for the contamination of oxy-helium atmosphere by nitrogen in calculating decompression.

Limiting the use of breathing apparatus, with prepared gas mixtures, to excursions in the water.

Measured physical work during bottom time.

Continuous decompression to first stop and thereafter decompression in steps.

These conditions could only be achieved with a fully equipped system of high pressure chambers as was available in Zürich after 1964.

Half-time spectrum for helium and nitrogen

In order to calculate the decompression for long exposures and to determine the optimum time for changing inert gases, it is essential to know the half-time of the slowest tissues. Assuming that the same half-times are valid for saturation and desaturation, the longest half-times were determined by finding the minimum decompression time, breathing pure oxygen, after prolonged periods at 100 ft (4 ATA) during which either 20% oxygen, 80% helium or 20% oxygen, 80% nitrogen was used (Bühlmann, Frey & Keller 1967). No bends occur after an exposure to a P_{He} of 3·2 ATS (Fig. 19.6), provided that decompression is based on the longest half-time of 160 to 180 min. In

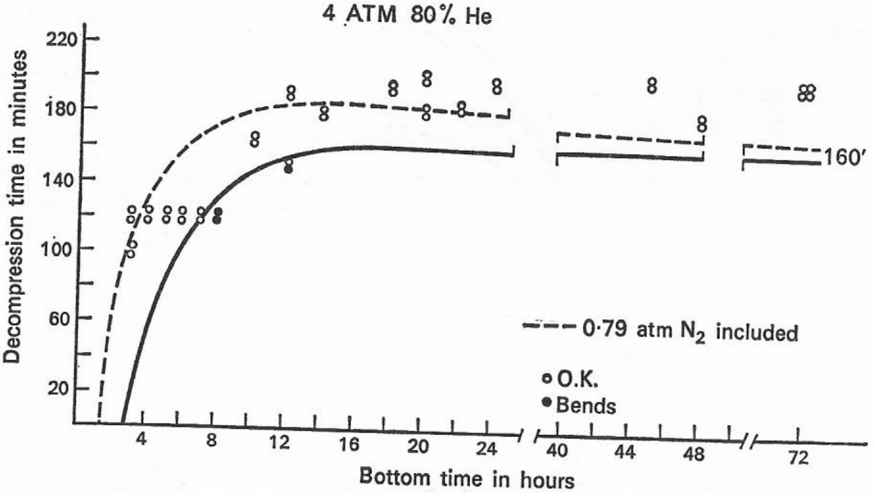

FIG. 19.6. The results of 40 experiments are presented. Bottom times with 80% helium, 20% oxygen at 100 ft (4 ATA) varied from 3 to 72 hours (abscissa). Decompression times breathing 100% oxygen are given in minutes on the ordinate. The line in dashes represents the minimum decompression times for a half-time of 160 min starting with a normal P_{N_2} of 0·8 ATS in the tissues. This P_{N_2} in the tissues 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

these experiments the initial P_{N_2} of 0·8 ATS was allowed for, and a ratio between the total partial pressure of inert gases and the ambient pressure on the surface of 1·55 to 1·60 was used in calculation. After an exposure of 24 hours 99% saturation is reached; beyond this, as can be seen in Fig. 19.6, no longer time for decompression is required whatever the bottom time.

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

As the tissues in ligaments, joint capsules and menisci are mainly water, the predilection of the bends for knee and ankle joints with either helium or nitrogen suggests that a 'diffusion-limited' system is involved.

Because of the results of the saturation experiments at 100 ft (4 ATA) (see Fig. 19.7) and successful decompressions after short exposures at high pressure, we assume *that saturation and de-*

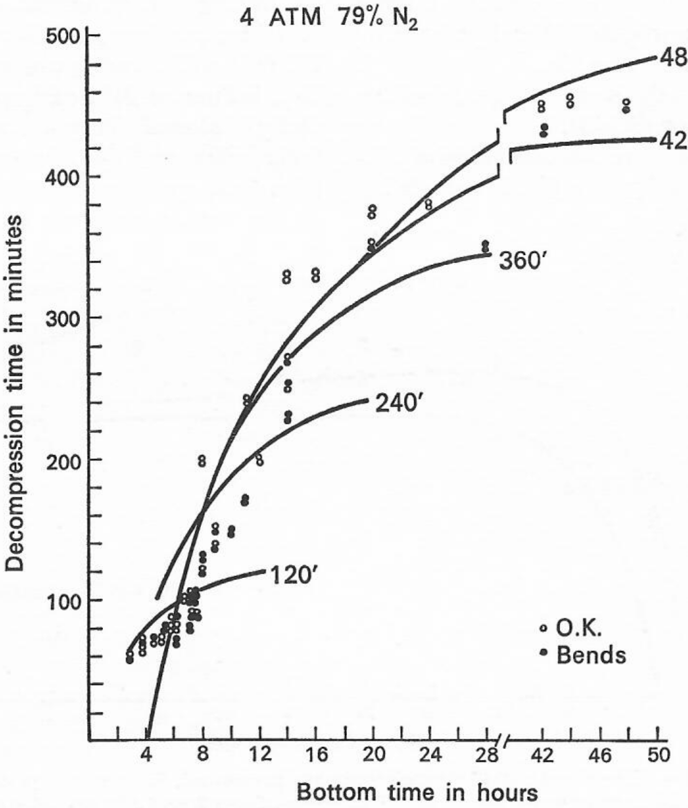

FIG. 19.7. The results of 80 experiments are presented. Bottom times with compressed air at 100 ft (4 ATA) varied from 3 to 48 hours (abscissa). Decompression times breathing 100% oxygen are given in minutes on the ordinate. The lines represent the minimum decompression times for half-times of 120 to 480 min calculated with a surfacing ratio of 1·6 to 1·0

saturation in all tissues is 2·6 times faster with helium than with nitrogen.

If we suppose the half-time to be determined mainly by the perfusion of the different tissues, it can be expected that any change of half-time will depend on physical work, particularly for the slow tissues. It is probable that during sleep, with a reduction of cardiac output, the longest half-times will increase. When saturation with helium, on the basis of a longest half-time of 180 min, involves decompression lasting many hours or even days we allow maximum half-times of 240 min for helium and 635 min for nitrogen in calculating the actual decompression. This method of allowing for the effect of physical work applies only to saturation dives. More specific account must be taken of physical work in determining the decompression for intervention dives with bottom times between 30 and 60 min.

The influence of physical work on decompression

The effect of physical work on decompression was examined by determining the minimum decompression time for simulated oxy-helium dives by 82 different subjects (Schibli & Bühlmann 1972). Details of the experimental conditions are summarized in Table 19.7.

The descent times of 7 min for the 4·5 ATA tests and 12 min for the 10 ATA tests, were not included in the bottom times.

The P_{N_2} remained constant at 0·8 ATS during descent and time on bottom. The subjects performed work on a bicycle ergometer with a load of 80W (490 m-kg/min) before the experiments and during time on the bottom. Each subject worked 15 min/hour on the bottom. The average pulse rate increased from 60 to 100. During decompression the same form of bicycling was done, starting below 2·5 ATA breathing pure oxygen.

A simple oxygen decompression was used for the 4·5 ATA experiments. Mixed gas decompression was used for the 10 ATA experiments; air was breathed between 6·0 and 4·0 ATA, 50% oxygen, 50% nitrogen between 4·0 and 2·0 ATA and 100% oxygen between 2·0 and 1·0 ATA.

Minimum decompression times were established, first without work on the bottom and secondly with work on the bottom. If bends occurred in muscles or joints during or after decompression, then the decompression was recalculated and increased for the next experimental run.

After 180 min at 4·5 ATA the minimum decompression time without work was 150 min and with work it was 180 min (Fig. 19.8).

The minimum decompression time without work after 60 min at 10 ATA was 250 min. If work was performed this minimum decompression without symptoms increased to 360 min (Fig. 19.9). This decompression time after work is approximately equal to the decompression computed for a 90-min bottom time at 10 ATA without work.

For the longer period of 120 min bottom time at 10 ATA the minimum decompression time was 475 min without work and 565 min with work on the bottom (Fig. 19.10).

These results demonstrate clearly that the minimum decompression time must be longer after a dive with work than after a similar dive without work. These differences in decompression decrease with longer bottom time. The results can be interpreted as an increased perfusion with work in the muscles, joints and skin, whereas the perfusion of

TABLE 19.7
Experimental conditions

ATA	*Bottom time (min)*	*Breathing gas on bottom (%)*			*Tests without work*	*Tests with work*	*Tests with work on bottom and decompressing*	*Total*
		O_2	He	N_2				
4·5	180	11	71	18	12	25	18	76
10·0	60	10	82	8	15	39	22	42
10·0	120	10	82	8	15	27	—	55
					42	91	40	173

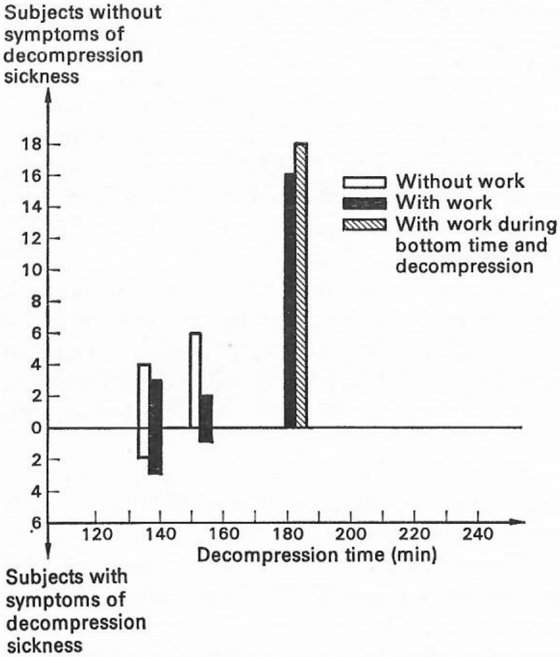

FIG. 19.8. The results of 55 decompressions are presented. 180-min bottom time at 115 ft (4·5 ATA) breathing 11% oxygen, 71% helium, 18% nitrogen. Number of subjects without and with symptoms of insufficient decompression shown as function of decompression time, for cases without work (white), with work at bottom (black), and with work at bottom as well as during decompression (hatched)

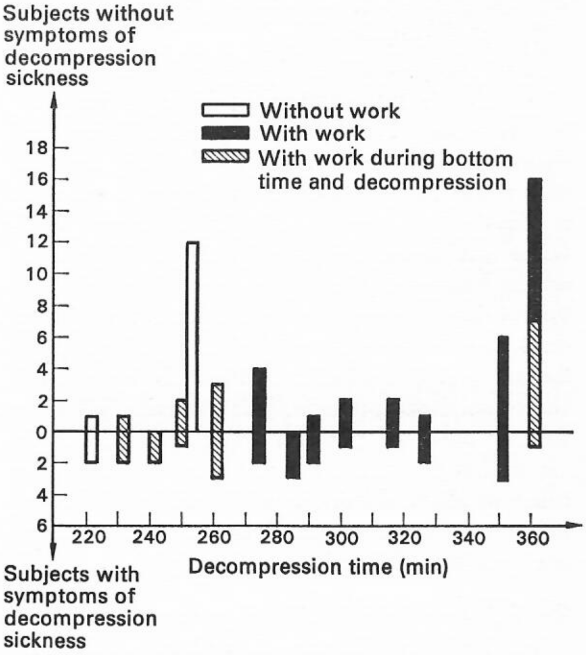

FIG. 19.9. The results of 76 decompressions are presented. 60-min bottom time at 300 ft (10 ATA) breathing 10% oxygen, 82% helium, 8% nitrogen. (For explanations see Fig. 19.8)

TABLE 19.8

Adaptation of half-times for dives with physical work

He *half-time (min)*	*Virtual bottom time as a percentage of real bottom time*
105	120
120	120
150	135
180	135
210	145
240	145

the central nervous system is practically constant. Accordingly, the first phase of decompression, which is limited by the fast tissues, is equal whether or not work is performed. The second phase, however, must be prolonged when work takes place on the bottom, since the slow tissues, which are more fully saturated than without work, now control the rate of ascent. To take account of these considerations decompression after work is computed using *virtual bottom times* for tissues with helium half-times of 105 to 240 min (Table 19.8).

Theoretically it might be assumed that work during decompression will shorten the decompression time as a result of the increased blood flow in the slow tissues of the extremities. This question cannot be resolved from these experiments but it is unlikely, since the decompression time is too long for continuous work. However, no symptoms of insufficient decompression were provoked by bicycling during decompression. There may be some benefit in intermittent work during decompression as it counteracts the reduced circulation caused by high oxygen partial pressure.

Summarizing, it may be said that the effect of physical work in increasing the saturation of the inert gas has to be taken into account for calculating the decompression after short-duration dives.

The use of *virtual bottom times* in doing this has the advantage that the spectrum of half-times and

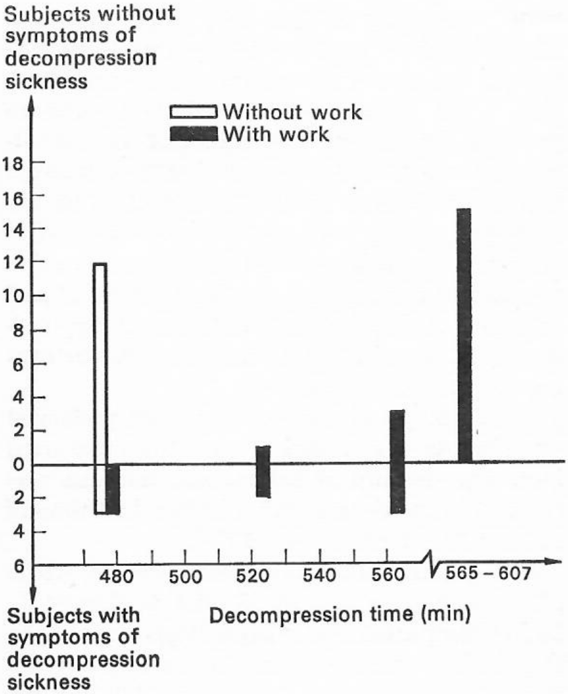

FIG. 19.10. The results of 42 decompressions are presented. 120-min bottom time at 300 ft (10 ATA) breathing 10% oxygen, 82% helium, 8% nitrogen. (For explanations see Fig. 19.8)

the supersaturation factors are constant for all dives.

Tolerable supersaturation factors

It has been learned by experience that Haldane's supersaturation factor of 1·6 is tolerated by the slow tissues during the surfacing phase. Fast tissues can take a higher factor, near 2·0, without provoking symptoms. Deep diving experience demonstrates that the supersaturation factors have to be drastically reduced for all tissues. There is no theoretical concept to account for this phenomenon. In practice, the factors for different half-times are reduced in relation to the total partial pressure of inert gas. Present experience concerning tolerable supersaturation factors is given in Fig. 19.11. The factors for the slow tissues are well confirmed by saturation experiments up to 31 ATA. The curve for helium half-times of 45 to 90 min is the result of the analysis of so-called vertigo bends during decompression after experiments between 5·0 and 31·0 ATA (Bühlmann & Gehring 1975). No troubles of this kind occurred using supersaturation factors in accordance with this curve. The factors for tissues with helium half-times of 5 to 10 min are estimated and not confirmed by decompression incidents.

Prolonged exposures and saturation experiments

The saturation experiments were conducted on the same basis as those at 100 ft (4 ATA). Details of the experiments are summarized in Table 19.9.

Some of these dives formed part of the 1966 'Capshell' trials in the Mediterranean, which were organized by Cdr J. R. Carr, RN (retd).

Decompression after deep dives lasting for some hours and for full saturation was simplified by putting oxygen, helium and air directly into the pressure chambers. The Po_2 averaged less than 1·0 ATS, with a short and transient increase above

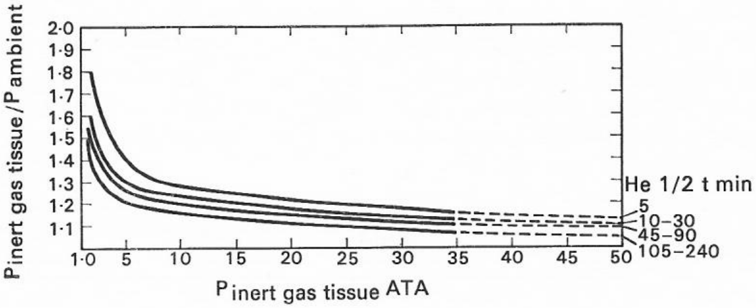

FIG. 19.11. Tolerated supersaturation (ordinate) for tissues with different helium half-times depending on the total inert gas pressure in the respective tissues (abscissa). A helium half-time of 240 min corresponds to a nitrogen half-time of 635 min

TABLE 19.9

Mixed gas decompression after long and saturation dives at 4 to 31 ATA with oxy-helium

ATA	*Bottom time (hours)*	*Decom-pression (hours)*	*Decom-pressions (number)*	*Different subjects*
4	72*	6	4	4
11	6	22	6	5
16	6	40	6	5
23	6*	52	22	12
23	2 × 6†	60	6	5
23	68 & 78	62, 64, 68	7	5
31	2	50	2	2
31	3	58	2	2
31	4	64	2	2
31	81	88	3	3
(51	80	156		)

* Carried out in the pressure chamber, and also with swimming excursions in the sea.

† Carried out as a repetitive dive for 6 and 4 to 6 hours within 48 hours, partly in the water.

2·0 ATS when using a 50% oxygen, 50% nitrogen mixture. In all these experiments there was a comfortable temperature, practically no CO_2 and a relative humidity of 70 to 90% in the chambers. The contamination of oxy-nitrogen mixtures with helium was measured and taken into consideration when calculating the effective pressure gradient for helium. The effects of venous admixture was estimated by reducing the calculated helium elimination by 10% during the first decompression stop and again for one stop after changing from helium to nitrogen. Decompression was carried out in steps, varying between 15 and 120 min. A supersaturation factor of approximately 1·5 was used for the final step when returning to atmospheric pressure.

The decompression procedures in our prolonged experiments were identical once the same total inert gas pressure of helium and nitrogen was reached in the tissues with a helium half-time of 180 to 240 min (Bühlmann 1971).

In Fig. 19.12 is shown the decompression profile of the saturation dive at 31 ATA performed 3–10 February 1969 in the Deep Trials Unit of the Royal Navy at Alverstoke. On the first day the three divers made an excursion to 36·0 ATA for 1 hour. During the second and third days they

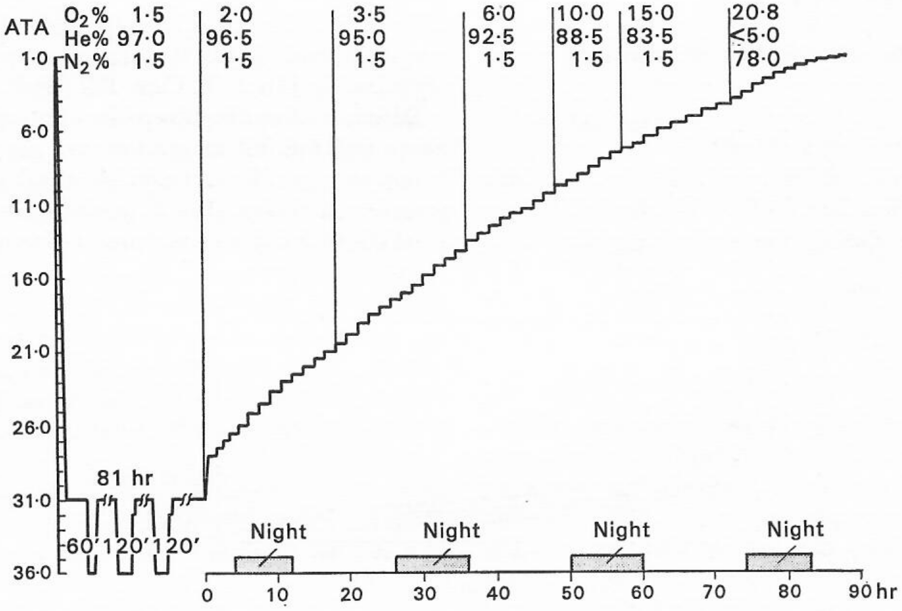

FIG. 19.12. Decompression after saturation at 1000 ft (31 ATA) with 97% helium. During the first, second, and third days, excursions were made to 1150 ft (36 ATA) utilizing the same breathing mixture. Stepwise increase of oxygen to 15%. Change to air breathing at 100 ft (4 ATA). Total decompression time 88 hours

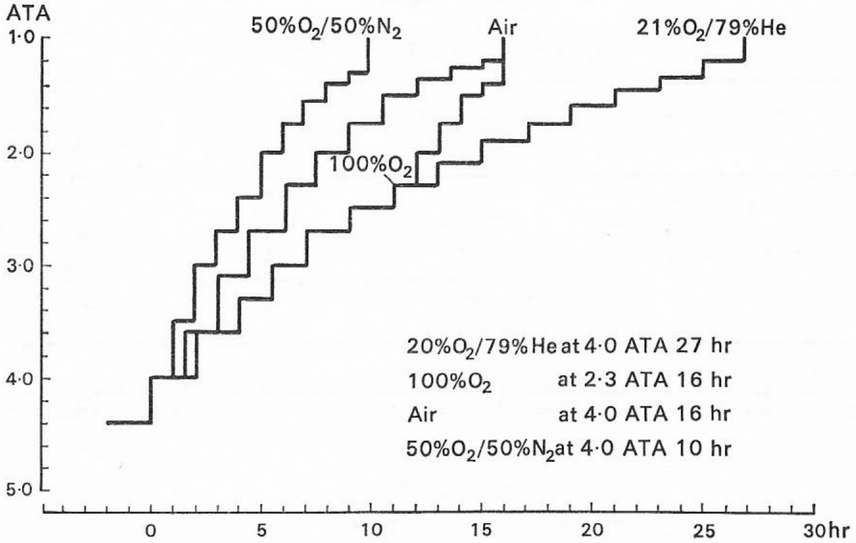

FIG. 19.13. Final decompression below 100 ft (4 ATA) after saturation and long-duration diving with oxygen–helium mixtures using the same principles of calculation: 10 hours with 50% oxygen, 50% nitrogen below 75 to 100 ft (3·3 to 4·0 ATA); 16 hours with air below 100 ft (4 ATA); 27 hours with 21% oxygen, 79% helium (not performed); and 16 hours with 100% oxygen below 45 ft (2·4 ATA) (not performed)

made excursions of 2 hours to 36·0 ATA, with swimming and physical work in the wet compartment.

Decompression from 36·0 to 31·0 ATA in 20 and 30 min respectively occurred without incident. The total decompression time, scheduled for 88 hours, was trouble free except for one diver who had knee pains in the final stages and had to be separated from the others for short treatment. Unlike the other two, who were in diving practice, this subject had made his previous dive 12 months before the saturation experiment.

The three saturation dives at 23·0 ATA, which were performed by 5 different subjects (2 made two dives each), passed off without any symptoms of insufficient decompression.

It is interesting to compare different theoretical versions of the final states of decompression below 4·0 ATA (Fig. 19.13).

Final decompression would take 27 hours breathing 21% oxygen, 79% helium, against 16 hours using air, and 10 hours using 50% oxygen, 50% nitrogen, if the same factors are used in the calculations. While the gain in changing inert gas in the final stage (below 4·0 ATA) is not so very large, it is sufficient to be of value in practice. Experience with the two versions of the final decompression is given in Table 19.10.

The frequency of minor bends, some of which disappear without treatment, is not high but it shows that the decompression is near the limit. If these results are compared with the much longer procedures of American, British and French methods, this technique of calculating decompression is no less safe and is certainly more economical in time.

The saturation dives at 23·0 ATA and 31·0 ATA confirmed the assumption of a longest helium half-time of 240 min and a longest nitrogen half-time of 635 min in calculating decompressions which last for days.

Deep diving with mixed inert gases

Contrary to the expectation of some authors, mainly in America, the technique of saturation diving has had limited practical application. However, only 7 years after the pilot experiments, short-duration diving using oxy-helium has become

TABLE 19.10

Final decompression stage after prolonged deep dives

Breathing gas	*Decompressions (number)*	*Minor bends (number)*	*Subjects (number)*
A. 50% O_2/50% N_2 below 3·3 to 4·0 ATA	16	1	8
B. Air below 4·0 ATA	6	1	4
	22	2	12*

* 8 different subjects.

Dives—Repetitive dive within 24 hours with total bottom time of 8 to 12 hours at 23·0 ATA; saturation at 23·0 ATA; bottom times of 2 to 4 hours at 31·0 ATA; saturation at 31·0 ATA.

TABLE 19.11

30 min bottom time at 500 ft (16·0 ATA)

	Breathing mixture 6·0 to 16·0 ATA			*Breathing mixture during decompression*	*Decompression time (min)*
	O_2	He	N_2		
Version a	6	89	5	20% O_2 below 6 ATA 100% O_2 below 2 ATA	1010
Version b	6	89	5	air below 6 ATA 100% O_2 below 2 ATA	645
Version c^1	6	70	24	air below 6 ATA 100% O_2 below 2 ATA	580
Version c^2	6	70	24	air below 6 ATA and up to surface	850

Version a: descent time 15 min, compression with oxygen–helium. Version b: compression with air to 6·0 ATA.

Version c^1 and version c^2 mixture is 3 parts air, 7 parts helium. Allowance is made in the calculations for a contamination of 2 to 4% helium when air is breathed.

routine work for a large number of professional divers in water depths between 300 and 600 ft (10 and 19 ATA) with bottom times chiefly between 15 and 45 min.

This leads to the questions whether the consumption of helium, which is very expensive in Europe, can be reduced and whether decompression times can be shortened, by using oxygen–helium–nitrogen breathing mixtures.

From the practical point of view it is desirable that the mixtures should be prepared by using air and pure helium.

Tables 19.11 and 19.12 show that a small shortening of decompression time is possible, using identical values for descent time, oxygen concentration on bottom, supersaturation factors and corrections for physical work.

TABLE 19.12

P_{inert} in the slowest tissues at the end of decompression

	He	N_2
Version a	1·19	0·32
Version b	0·61	0·90
Version c^1	0·50	0·01
Version c^2	0·25	1·26

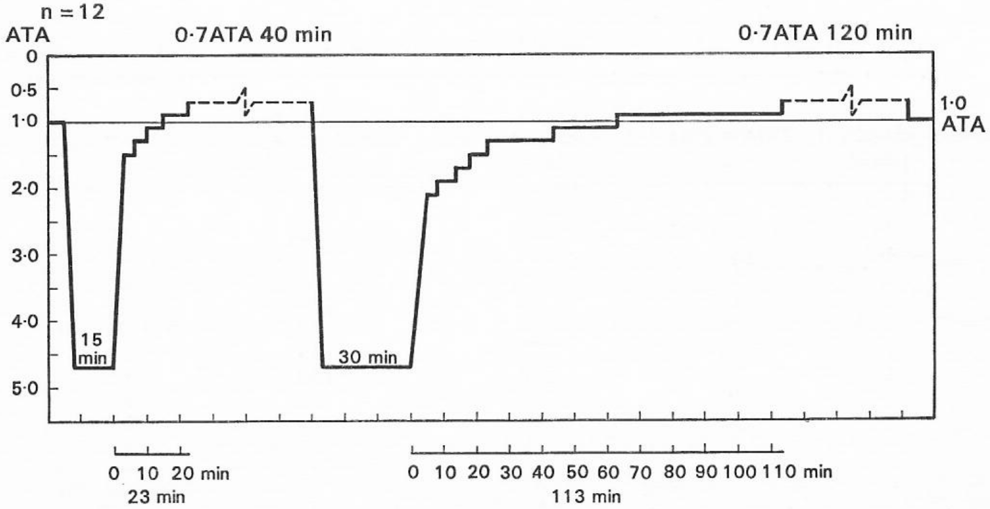

FIG. 19.14. Decompression after air diving in altitude. Simulated repetitive dive at 0·7 ATA altitude (10 000 ft; 3000 m). 15-min bottom time at 133 ft (4·7 ATA). Decompression time 23 min breathing air. 40-min interval at 0·7 ATA. Second dive with 30-min bottom time. Decompression time 113 min. Last step but one at 1·1 ATA, last step at 0·9 ATA. 120-min interval at 0·7 ATA

AIR DIVING AT HIGH ALTITUDES

Although at high altitude the P_{N_2} in the body is lower at a given depth than it would be at this depth at sea level, the ratio between P_{N_2} at depth and P ambient at surface is greater. If the same supersaturation factors are used for diving at high altitude, it is necessary to modify decompression tables that are valid for sea level. Hitherto there have been no tested decompression tables for diving at high altitude. In Switzerland, diving in mountain lakes is important both for sports divers and for the Swiss Army. We have calculated decompression tables for use at heights of 2500 ft (750 m) up to 10 000 ft (3000 m), which are based on the supersaturation factors quoted in Fig. 19.11, the effective P_{N_2} and the ambient pressure. These were tested by simulated dives at 0·7 ATA (10 000 ft; 3000 m) and by real dives at 4000 ft (1250 m; 0·85 ATA).

In order to allow greater safety it was supposed that the diver reached the mountain lake by helicopter within a few minutes, before his body could become adapted to the lower pressure. Thus the calculations were made for an initial P_{N_2} of 0·8 ATS in all tissues. Furthermore the supersaturation factor on surfacing was chosen to allow for a further reduction of pressure, which might be brought about by travelling by plane or car to a higher place after the dive. Repetitive diving is needed by sport and military divers and so a high proportion of simulated and real dives were undertaken as repetitive dives with a surface interval of 10 to 15 min (Fig. 19.14). At this point additional tissues with nitrogen half-times up to 200 min were considered. After the simulated dives the subjects remained at 0·7 ATA for 120 to 180 min after surfacing so that any delayed symptoms of decompression sickness would not be suppressed by returning to normal atmospheric pressure. Physical work on the bicycle ergometer was undertaken during the tests. The same final steps, at 13 ft (4 m) and 7 ft (2 m), are used in decompression after all high altitude dives.

These experiments, which were free of symptoms due to insufficient decompression, have shown that calculations, based on our simple working hypothesis for deep diving, also give satisfactory results for diving at high altitudes (Bühlmann, Schibli & Gehring 1973).

SUMMARY

No theory has been developed to describe uptake and elimination of inert gases and their

TABLE 19.13

106 simulated dives at 0·7 ATA

Depth (ATA)	*Bottom time (min)*	*Decompression (min)*	*Interval at 0·7 ATA after dive (min)*	*Number of subjects*
5·2	30	105	180	12
4·2	60	158	120	12
4·2	120	376	120	12
4·7	25	60	45	11
3·7*	17	42	180	3
3·7*	22	52	120	8
4·7	15	23	40	12
4·7*	30	113	120	12
4·7	20	25	45	12
4·7*	25	113	120	12
				106 (50 different subjects)

* Repetitive dives.

TABLE 19.14

222 real dives at 4000 ft altitude (0·85 ATA), water temperature 10 to 16°C

Depth (ATA)	*Bottom time (min)*	*Decompression (min)*	*Interval at 0·85 ATA after dive*	*Number of subjects*
3·85	15	17	20 to 24 hours	14
3·85	15	12	20 to 24 hours	28
2·35	15	3	45 min	20
2·65*	15	15	20 to 24 hours	20
2·85	10	3	10 min	70
2·35*	15	13	20 to 24 hours	70
				222 (112 different subjects)

* Repetitive dives.

behaviour in the human body during pressure changes. The 'Swiss Decompression Theory' is only a method of calculating saturation and desaturation in a way which permits safe decompression. The use of different inert gases, such as helium and nitrogen, to shorten decompression is a characteristic of this method.

The calculation is based on the following principles:

> Saturation and desaturation are treated as an equalization of pressure throughout the body.

Different half-times for the same inert gas are interpreted as the result of different perfusion rates in the tissues, which vary with the haemodynamic condition.

The ratio of half-times between nitrogen and helium is 2·646 for a given perfusion rate (diffusion-limited system).

A spectrum of half-times of 2 to 240 min is employed for helium with a corresponding one of 5·3 to 635 min for nitrogen.

Supersaturation factors ($P_{\text{inert total}}/P_{\text{ambient}}$)

decrease with increasing P_{inert} total and also with longer half-times. They have to be determined experimentally.

The faster saturation of slow tissues, which are sensitive to bends, during muscular work is allowed for by introducing '*virtual bottom time*'.

This method of calculation applies, without any special adaptation, to:

Simulated and real dives.

Air diving at sea level and at high altitudes, where the ambient pressure is reduced.

Saturation diving in conventional depths using air or oxy-helium.

Deep diving to 31 ATA for all exposures, from short periods up to full saturation.

Exposures using mixtures of different inert gases at the same time.

Change of inert gas during decompression.

Use of pure oxygen as breathing gas to shorten the final stages of decompression.

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