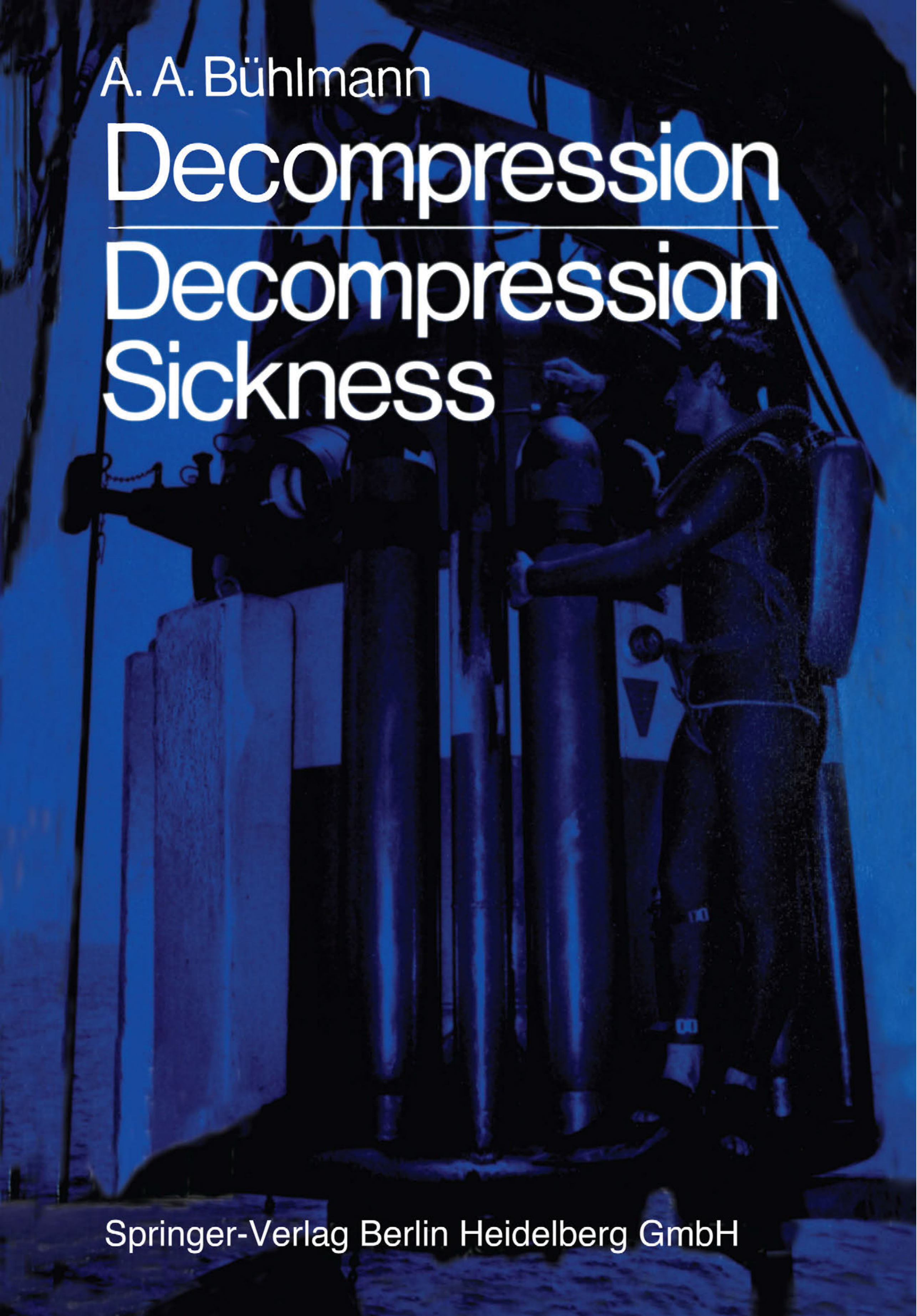
A. A. Bühlmann

Decompression

Decompression Sickness



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ALLE ZEIT WACH
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Decompression – Decompression Sickness

With 20 Figures and 24 Tables

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Preface

The Laboratory of Hyperbaric Physiology of the Medical Clinic of the University of Zurich came into existence in 1960 thanks to private initiative and a readiness to undertake risks; the successful start was made possible with help from the French Navy and the United States Navy. A prerequisite for the development of the laboratory was also the benevolence of the authorities of the University of Zurich toward a research project from which scarcely any practical use could be expected for the land-locked country of Switzerland. The development of the laboratory and the systematic research were supported generously from 1964 by Shell Internationale Petroleum Maatschappij of The Hague.

The basic theme of the research was always the well-being and functional ability of the human being in an atmosphere of abnormal pressure and or abnormal composition.

Many connections became obvious with respiratory physiology, circulatory physiology, and physiology at great heigts, and close contact with other special laboratories of the Medical Clinic proved very valuable. With a relatively small number of steady collaborators it was possible to master an extensive experimental program. Special thanks are due to Mr. Benno Schenk, who as technical head was responsible for the exact performance of all the hyperbaric experiments.

Without the enthusiasm and willingness for enterprise of the many voluntary collaborators the program of experiments could not have been realized. Mr. Rino Gamba, who participated from 1964 until 1968 in all of the important experiments at depths of 30, 220, and 300 m, is mentioned here as representative of all the voluntary collaborators.

Decompression was the principal problem encountered during preparation for the first deep diving trials. The persistent reexamination and expansion of the original concept finally yielded a method of decompression that is theoretically sound and has been tested widely for nitrogen and helium. In research there are no terminal solutions, but the Swiss practice of decompression has reached a state that justifies a summary description. So much detail has been amassed in the special literature that it is scarcely possible to read it all, but what has been lacking is the description of a method by which a low-risk decompression can be calculated for every imaginable exposure upon the basis of pressure, time, and gas breathed.

In Zurich, diving medicine and research on decompression are applied research related to internal medicine. This monograph is intended not only for the specialists in hyperbaric medicine and hyperbaric technic, but also for physiologists, internists, neurologists, specialists in intensive care, occupational physicians, and practitioners of medicine connected with insurance.

By avoiding the description of complicated biophysical models and mathematical derivations, for which he is not competent anyway, the author hopes to have improved the readability of the monograph and therefore also the understanding of that which he believes useful.

Zurich, May 1984 A. A. Bühlmann

Hannes Keller climbing into the water tank of the pressure chamber of the French Navy in Toulon on 25 April 1961. The first simulated dive corresponding to a depth of 300 m

Contents

1 Introduction

In 1961 Hannes Keller demonstrated within 14 days in Toulon and Washington two dives to a depth of 215 m and one to 300 m. These exposures to high pressures with their lack of effect on mental and physical competence indicated a break through for deep diving with helium, with which difficulties had arisen during decompression in earlier trials. The specialists were impressed less by the depths reached than by the rapid decompression without unpleasant sequelae for the diver.

Before the demonstrations, tests had been made in Zurich in a small pressure chamber. The purpose was to combine the advantages of helium, which is light, with those of nitrogen, which is heavy. With helium "depth drunkeness," nitrogen narcosis, is avoided, while the introduction of as much nitrogen as possible enabled the use of the decompression tables of the United States Navy and the Groupe d'Etudes et de Recherches Sous-marines de la Marine Nationale Francaise (GERS) of the French Navy for calculating of decompression.

Free of every diving tradition and free of the inhibition of specialized knowledge, a simple concept was developed to calculate the equalization of pressure between breathing gases and tissues for the simultaneous and successive use of nitrogen and helium in the gas breathed. The successful pilot experiments were the occasion for the United States Navy to support a series of experiments of dives of somewhat longer duration at depths of 150–300 m. For these experiments it was necessary to test the tolerance with different subjects, which marked the beginning of the experimental research on decompression in the Laboratory of Hyperbaric Physiology in Zurich.

On 3 December 1962 Keller and the journalist Peter Small reached a depth of 300 m (1000 ft) in the open sea near San Diego. Keller left the pressure capsule, swam a few meters, and in compliance with the schedule returned to the capsule after a few minutes. During the decompression in the pressure chamber difficulties arose with the transport of gas to the breathing equipment; these difficulties cost the life of Small. The first real deep dive in the open sea to a depth of 300 m was as much a success as a tragedy. For all the participants it was an unforgotten lesson concerning safety in diving. The development of new ideas and devices is not sufficient: the divers must be trained systematically so that they react correctly when difficulties arise.

To secure what had already been achieved required broad experimental research. Further progress was to be expected only from a gradual procedure; such a development has been made possible in Zurich since 1964 by Shell Internationale Petroleum Maatschappij B.V. In 1966 prolonged exposures to helium-oxygen mixtures at depths of 30 and 220 m were executed in the Mediterranean; thanks to the circumspect direction of Commander John Carr, these "Capshell trials" passed without serious incident. They were completed by exposures to saturation at 220 and 300 m in Zurich and at the Royal Navy base in Alverstoke, UK. At that time the first publications appeared concerning the "high pressure nervous syndrome" (HPNS), which presented a new barrier to the practical use of very deep diving. However, as early as 1969 gradual compression to avoid serious HPNS was demonstrated; the three test divers reached a depth of 350 m in 325 min and suffered no adverse effects. The usefulness of the concept of gradual compression was confirmed in 1981 for 450–575 m.

After the oil crisis of 1973, professional diving acquired practical importance in the search for and extraction of petroleum in the ocean. Since then in the USA, England, France, Norway, and Zurich simulated depths of 400–650 m have been repeatedly reached in hyperbaric chambers, depths at which it may be necessary to work in the very near future.

Deep diving promoted the development of methods of decompression for exposures to helium, while improvement of decompression techniques after lengthy hyperbaric exposures when breathing air was neglected. Lasting arthropathies and aseptic osteonecroses are as frequent now as ever among professional divers and caisson workers who work at only slightly increased pressures but are exposed to them daily and for hours at a time [1].

With the concept developed in Zurich the simultaneous breathing of nitrogen and helium and the change from helium to nitrogen were fundamental; it was therefore always necessary in this research to consider both inert gases. In Switzerland there is additionally, interest in dives in mountain lakes; for this reason the tolerance to nitrogen in a decreased ambient pressure was also investigated. The result was the discovery of relationships to aviation medicine and to experiments that had been executed in the USA by Behnke as early as 1941 [2].

The goal of experimental research on decompression is to develop a method of decompression that involves little danger, based on pressure, time, and the composition of the respiratory gases. A method of that kind can be adequate only if it has general validity, i. e., is applicable for both brief and long exposures to air as well as exposures to different inert gases for several days or weeks and for every ambient pressure that is possible for the human being. The pursuit of this goal presupposed a continuity in the planning of the experiments over a long period of time; this continuity was provided by the laboratory in Zurich. Experiments that were meant primarily for other themes, for example the HPNS, or the development of new systems of masks, were arranged so that they also yielded results for decompression research.

Tolerances may be determined empirically only with controlled exposures; the reproducibility is tested by exceeding the liminal values. This inevitably produces multiple experiences with the symptomatology of inadequate decompression and therapy for the different forms of decompression sickness. In contrast to the methods of decompression, no great differences in the treatment of decompression sickness exist between the various centers. Nevertheless, in the past 10 years some improvements for professional and amateur divers have been achieved, which is the reason for this short presentation of current Swiss practice.

As long as the human being strives to leave the atmosphere to which he is accustomed inadequate decompression will occur. However, with the development of better methods of decompression the frequency of decompression sickness may be reduced. Any physician is likely to be confronted with decompression sickness; if he is able to make the diagnosis and initiate a timely and correct treatment, he may make a decisive contribution toward averting enduring and disabling damage to the nervous system and of the joints.

2 Physical and Biological Bases

2.1 Pressure, Force, Work

Force, weight, and pressure are derived from the force of gravity at the surface of the Earth. Normal gravitational acceleration at sea-level and at 45° latitude is

$$g_n = 9.80665 \text{ m s}^{-2}.$$

The Newton (N) is defined as the force that imparts to a mass of 1 kg an acceleration of 1 m s^{-2}; the Pascal (Pa), the unit of pressure, is equal by definition to a force of 1 N acting upon an area of 1 m^2, thus

$$1 \text{ Pa} \equiv 1 \text{ N m}^{-2} = 10^{-5} \text{ bar}.$$

In meteorology the bar and millibar have been used as units of pressure since 1955:

$$1 \text{ bar} \equiv 100 \text{ kPa and}$$
$$1 \text{ mbar} \equiv 100 \text{ Pa}.$$

Mercury and water columns are very sensitive and demonstrative instruments for the measurement of pressure:

	bar	Torr (mm Hg)	kp cm^{-2}
Standard International Unit	*1*	750.062	1.01972
Normal atmospheric pressure (atm)	1.01325	*760*	1.03323
Technical atmosphere (at)	0.980665	735.559	*1*

A column of fresh water 10 m in height at a temperature of 4 °C exerts a pressure of just about 0.98 bar; if the water contains 30 g sodium chloride per liter, the pressure is about 1 bar. The bar or sometimes the pascal will be used as the unit of pressure; the rough conversion 10 feet of seawater ~0.3 bar may be used.

The product force times distance through which the force acts is work; work per unit of time is power. The unit of work is the joule (J); the unit of power, the watt (W):

$1\,J \equiv 1\,Nm \equiv 1\,kg\,m^2\,s^{-2} = 0.2389\,cal_{15}$ and
$1\,J/s \equiv 1\,W = 0.102\,m\,kp\,s^{-1}$.

2.2 Composition of Atmospheric Air

The gaseous composition of the atmospheric air remains practically constant up to very great heights (about 100000 m) above sea level; see Table 1. In all combustion oxygen is consumed and carbon dioxide produced, so that the proportions of these gases that participate in an "exchange" may vary greatly according to the supply of fresh air. If unused, fresh air is breathed, the amount of nitrogen and argon together is 79%. The term "inert gases" for these two gases is not really correct, because they act narcotically above normal pressure. This is the reason for replacing nitrogen with helium in deep diving. The content of water vapor increases with increasing temperature; at 37 °C in the saturated inspired air in the respiratory passages the vapor pressure is 0.063 bar.

The thermal conductivity of helium is significantly larger than that of nitrogen (Table 1). The rate at which heat is transported with the respiratory gases increases with their increasing density. In deep diving with helium the respiratory gas must be warmed to avoid a dangerous loss of heat.

Table 1. Composition of dry atmospheric air, molecular weight of gases, thermal conductivity at normal pressure and a temperature of 25 °C

	Proportion (F)	Mol. wt.	Thermal conductivity (μW/cm)
Oxygen	0.20948	31.999	264
Carbon dioxide	0.00031	44.010	164
Nitrogen	0.78084	*28.013*	*259*
Argon	0.00934	39.948	177
Neon	0.00002	20.183	489
Helium	0.000005	*4.0026*	*1500*
Hydrogen	0.0000005	2.0159	1810
Other	0.0000045		
Air at normal pressure	1	28.964 Average	260

2.3 Absorption and Release of Gas in the Lungs

In the lungs the blood absorbs oxygen from the gas in the alveoli and releases carbon dioxide into the alveoli. In adults the area of the surface of exchange between the blood and the gases in the alveoli is about 100–200 m^2. Ventilation of the alveoli, which is regulated by the respiratory centers depending on the gaseous exchange, assures nearly constant values of the alveolar partial pressure of oxygen and carbon dioxide. The ventilated alveolar volume at the end of a normal expiration in adults is about 2–4 liters. The partial pressure of each gas breathed can be determined from the total pressure P, the vapor pressure of water at 37 °C, and the fraction F of the gas in the mixture, thus

$$PIO_2 = 0.21 \cdot (P - 0.063) \text{ and}$$
$$PIN_2 = 0.79 \cdot (P - 0.063).$$

Where PIO_2 and PIN_2 are the inspiratory partial pressures of oxygen and nitrogen. In correspondence with the exchange of gases in the alveoli, the partial pressure of oxygen (PO_2) decreases in the respiratory tract up to the exchange surface, while the partial pressure of carbon dioxide (PCO_2) increases. During rest and slight effort the volume of inspired oxygen is slightly larger than that of the expired carbon dioxide. So that the volume of the lungs and alveoli stays constant, a flow of fresh air causes the alveolar PO_2 to increase. This correction of pressure is dependent upon the ratio R of the quantity of expired CO_2 to that of absorbed O_2, i.e., the respiratory quotient. It stops when $R = 1$. Where PAO_2 is the alveolar partial pressure of O_2, FIO_2 and $FICO_2$ are respectively the fractions of O_2 and CO_2 in the inspiratory air,

$$PAO_2 = PIO_2 - \left[(PACO_2 - PICO_2) \cdot (FIO_2 + \frac{1 - FIO_2}{R})\right].$$

These relations and the nonuniform ventilation and circulation of different regions of the lungs also influence the alveolar and arterial PN_2, which at rest and at normal pressure is about 0.01–0.02 bar more than the inspiratory PN_2. At pressures above normal this difference may be ignored.

In a mixture of gases the component gases are distributed passively by various molecular and atomic motions so uniformly that each gas exerts a spatially uniform partial pressure. Diffusion of a gas through a membrane and the uniform distribution of a dissolved gas in a medium require a pressure gradient. The rate of diffusion, the speed of equalization of pressure, is a function of molecular weight; the rates of diffusion of gases are inversely proportional to the square roots of their respective molecular weights. Equalization of pressure with helium is 2.645 times as fast as with nitrogen. It is assumed that in normal condition there is a practically complete equalization of pressure between alveoli and capillaries of the lungs for O_2 and CO_2.

At a given pressure gradient the volume of the gas that diffuses is a function of the area, the solubility in the media to be traversed, and the distance. After equalization of pressure the dissolved volumes of the various gases are markedly different, corresponding to their very dissimilar coefficients of solubility (Table 2).

2.4 Transport of Gases in the Circulatory System

The normal volume of blood in an adult is about 70 ml/kg body weight, thus about 5 liters, of which 30%–35% is in the arterial part of the circulatory system, i.e., the pulmonary veins, the left heart, and the arteries of the systemic circulation. The

Table 2. Volumes of gases (STPD) in physical solution at a gas pressure of 1.0 bar at 37 °C, solubility factors, values in ml/liter

	Whole blood[a]	Olive oil
Oxygen	23.252	110.535
Carbon dioxide	483.565	about 870
Helium	*8.686*	*15.693*
Neon	9.178	19.640
Nitrogen	*12.831*	*66.129*
Hydrogen	14.705	47.767
Argon	25.660	146.065

[a] Whole blood with a hematocrit of 45%

Table 3. Respiratory and circulatory values at rest and during strenuous work on a bicycle ergometer

		At rest	80 W	175 W
O_2 uptake (STPD)	l/min	0.25	1.20	2.5
Pulmonary ventilation (BTPS)	l/min	6.8	31.0	62.5
Cardiac output	l/min	6.0	12.0	18.0
Pulse rate	per min	60	110	164
Arterial blood pressure	mm Hg	125/70	150/90	185/95

STPD, at standard temperature and pressure, dry, 0 °C, 760 mm Hg; BTPS, at body temperature and effective gas pressure, volume with saturation by water vapor at 37 °C.
Because inspiration and expiration are necessary for the pulmonary ventilation, twice the volume of gas must be transported per unit of time through the respiratory tract.

greater volume of blood is venous and flows in the veins to the right heart. With respiration of air at normal pressure and with a normal concentration of hemoglobin, about 200 ml O_2, 500 ml CO_2, and 9.6 ml N_2 are transported in 1 liter of blood.

The output of the right and the left heart in the adult at rest is about 3.0–3.5 l/min/m^2 of body surface or about 5–6 l/min; with heavy physical work it may become three-to-four times as much. The flow of blood through the different parts of the lungs varies somewhat with posture because of gravity. With an increase in the flow of blood through the heart and its supply to the lungs, the resistance to flow decreases in all parts of the lungs to a minimum and the distribution of the perfusion becomes very uniform.

The systemic circulation is divided into a large number of parallel circuits. The supply of blood to the different organs is very different compared with their divers weights and varies with their functional status. During physical work the supply of blood to the working muscle is increased greatly by vascular dilatation and simultaneously the perfusion of other organs is reduced by vascular constriction. The increased production of heat with physical work requires an increased dissipation of heat through the skin, which explains why the supply of blood to the skin and the subcutaneous fatty tissues increases. In water the dissipation of heat is much greater

Table 4. Distribution of cardiac output to the various organs and consumption of oxygen by these organs while at rest and during work

	Weight (kg)	Perfusion of blood (l/min/kg)		Consumption of oxygen (ml/min)	
		At rest	Work	At rest	Work
Brain and spinal cord	1.7	0.50	0.50	40	40
Kidneys	0.3	4.00	3.00	20	20
Stomach, intestine, liver 5.5 kg[a]	1.5	0.80	0.60	65	65
Heart	0.3	0.70	2.00	25	*165*
Skeletal musculature	30.0	0.04	0.40	60	*2000*
Joints and bones	14.0	0.03	0.06	15	25
Skin and fatty tissue	12.0	0.04	0.10	15	50
Remainder	10.0			10	135
	75.0			250	2500

[a] The perfusion of blood through the stomach and intestine and then through the liver is predominantly in series. The rate of 0.8 l/min/kg for a liver with a weight of 1.5 kg

than in air, so that when swimming without protective clothing the supply of blood to the skin is not increased, but decreased. The supply of blood to the brain and spinal cord is very nearly constant in normal circumstances and is scarcely influenced by muscular work. Tables 3 and 4 present the most important respiratory and circulatory values measured during rest and exercise.

2.5 Saturation with Nitrogen While Breathing Air at Normal Pressure

The absorption and release of the metabolically quasi-inert gases N_2, Ar, He, Ne, and H_2 occurs mainly through the lungs. At a given pressure gradient the absorption and release through the skin is much smaller, yet at a high pressure gradient not negligible [4].

The complete equalization of the pressure of nitrogen between alveoli, blood, and all tissues and organs of the human body requires several days: after 3 days it is 99% (Sect. 3.3.2). If nitrogen is breathed at a constant partial pressure for 3 days, the pressure gradient between alveoli, blood, and tissues practically vanishes. If normal air is breathed at a pressure of 1 bar, the partial pressure of nitrogen, including that of argon, is 0.75 bar in all organs and fluids of the body. In the whole organism, varying with the content of fat, there is 15–17 ml N_2/kg. Whether the ambient pressure is decreased or increased, the initial pressure of the inert gases must be considered when calculating the equalization of pressure.

3 Abnormal Atmosphere

3.1 Alteration of the Composition of Gases at Normal Pressure

3.1.1 Hyperoxia

A partial pressure of oxygen in the inspiratory air that is above normal can cause damage to the respiratory tract, the parenchyma of the lungs, the nervous system, and the eyes; the pressure and the duration of exposure to it are decisive. Bodily rest increases the tolerance, while physical effort reduces it. If pure oxygen is breathed at 1.0 bar, after 24 h there is an increase in the volume of interstitial fluid in the lungs together with a reduction of the compliance and impairment of the diffusion of gases. If the exposure is to last for days or weeks the inspiratory partial pressure of oxygen should not be more than 0.4–0.5 bar.

Inspiration of oxygen at a partial pressure of more than 6 bar causes abrupt loss of consciousness with tonic-clonic cramps. An inspiratory P_{O_2} of 2.0–2.5 bar, as is usual in therapy with hyperbaric oxygen, is tolerated well for 4–5 h when at rest, but during effort or work, e.g., swimming, may be followed by states of acute confusion, which in water would be mortally dangerous because of the possibility of drowning. Diving with pure oxygen is therefore limited to a depth of 6–7 m. If more than 21% oxygen is breathed at normal pressure, nitrogen is released with breathing. Organs that are well supplied with blood release the nitrogen more rapidly than the tissues less well supplied. If pure oxygen is breathed for 1 h, the initial P_{N_2} of 0.75 bar in the brain is reduced by something more than half. This reduction has, however, no practical importance for a subsequent exposure to above-normal pressure.

3.1.2 Replacement of Nitrogen by Helium or Other Inert Gases

When nitrogen in the respiratory gas is replaced by helium, it is absorbed in the lungs and simultaneously nitrogen is released. Between alveoli and blood and in the organs between blood and tissues a countercurrent diffusion of gases takes place. Helium may be breathed for months without damage arising; it is possible then in this way to "saturate" the body with helium and to "wash out" the nitrogen from the tissues completely. Neon is not much lighter than nitrogen but is only slightly more soluble than helium (Tables 1 and 2). If the smallest possible quantity of inert gas is to be accepted by the tissues, argon is unsuitable as a replacement for nitrogen because of its high solubility in aqueous solutions and fat.

In the presence of turbulent flow in the respiratory tract, respiration is eased by the replacement of nitrogen by helium, but aggravated by argon.

3.1.3 *The Pressure Cabin*

In a pressure-proof cabin with a supply of a normal composition of gas at normal pressure man can leave the surface of Earth without risk of hypoxia, hyperoxia, or abnormal saturation with nitrogen. The concept of the submarine vessel is old. During the First and Second World Wars submarine vessels were very important in naval warfare; now, propelled by nuclear power and armed with rockets they are an integral part of the navies of the super powers. The principle of the closed pressure-resistant space, which maintains for the crew a normal atmosphere independent of depth, remains the same.

In 1932 the physicist Auguste Piccard ascended in a free balloon from Dübendorf, Switzerland, and in a pressure-resistant sphere reached a height of 16940 m above sea level. He also built the bathyscaphe Trieste, with which, in 1960, his son Jacques and the American Don Walsh reached a depth of 10916 m in the Marianas Trench of the Pacific Ocean. After the Second World War the pressure cabin, or "pressurized cabin," was commonly used for commercial aircraft. The cosmonaut in his capsule, and in his suit during excursions into free space and onto the Moon, is in an atmosphere that is nearly normal in pressure and composition of gases.

If a large leak develops in the pressure cabin at heights exceeding 8000 m, the sudden decrease in pressure subjects the passengers to "explosive decompression" (see Sect. 3.4.1). Submarine vessels with conventional Diesel engines and electric motors dive to scarcely more than about 50–65 m. If ascent and emersion are no longer possible, the crew can be rescued from such depths. Rescue would necessitate a rapid compression with compressed air to a pressure equal to that of the water, opening the air lock, and ascent with a life jacket to the surface. This procedure must be practised to be successful in an emergency. The most frequent dangerous incident during training is a ruptured lung with gas embolus into the central nervous system, which demands fast recompression (see Sects. 4.1 and 4.3).

The diver in an armored suit is at normal pressure with in a pressure-proof and thus very heavy suit; the arms have a certain mobility and grasping tools actuated from within serve as hands. Yet all structures intended to combine the advantage of a normal atmosphere with the possibilities available to a diver who is exposed to above normal pressure have so far been unsuccessful; the diver in the armored suit is not mobile enough to execute the same work. Inspections under water where no works has to be done are executed better by small submarine boats.

3.2 Increased and Reduced Ambient Pressure

3.2.1 *Altitude and Hypoxia*

With increasing altitude and concomitantly decreasing air pressure, the inspiratory and hence alveolar partial pressure of oxygen decreases. With hyperventilation the alveolar P_{O_2} can be increased somewhat by decreasing the P_{CO_2}, but there is little possibility of using hyperventilation to compensate for the hypoxia caused by altitude, especially when work is performed. At heights as low as 2000–2500 m above sea level the human capacity for physical work for long periods is somewhat reduced as a consequence of the hypoxia, as shown by the 1968 Olympic Games in Mexico City at 2200 m above sea level. At 7500 m above sea level most nonadapted test subjects become unconscious within a few minutes. By breathing pure oxygen this limit can be increased to 14000–15000 m above sea level. Table 5 presents data concerning partial pressures of oxygen and nitrogen at abnormal ambient pressures.

Table 5. Abnormal atmosphere, inspiratory partial pressure of oxygen and nitrogen

		50 m under water	0–150 m above sea level	3500 m above sea level	7500 m above sea level	14500 m above sea level
Gas breathed		Air	Air	Air	Air	Pure oxygen
Ambient pressure	bar	6.0	1.0	0.68	0.38	0.13
PIO_2	mbar	1240	196	129	66	67
PIN_2	mbar	4690	740	487	250	0

1 mbar = 0.75 mm Hg = 0.1 kPa

The adaption to high altitudes mainly concerns the erythropoiesis with the development of polyglobulia, with which the circulatory system's capacity to transport oxygen is increased. The affinity of hemoglobin for oxygen decreases somewhat, which causes an increase in the P_{O_2} in tissues.

Acute mountain sickness with symptoms such as headache, nausea, dry cough, intrathoracic pain upon deep inspiration and the pulmonary edema caused by hypoxia does not occur immediately when the critical height is reached, but only 1–5 days later. When critical heights, 3000 m above sea level and higher, are reached within a few hours by automobile, railway, or aircraft, mountain sickness is more frequent than with an ascent that takes days. After an adaption period of 1–2 week mountain sickness is rare.

In 1978 Reinhold Messner together with Peter Habeler accomplished the first ascent of Mount Everest, 8848 m above sea level, without supplementing respiratory air with oxygen, and then repeated this accomplishment alone in 1980. With this a healthy human being's adaptability to severe hypoxia, hitherto scarcely thought possible, was proved. At these heights the arterial partial pressure of oxygen is about 4–5 kPa (30.0–37.5 mm Hg). Such low oxygen pressure is also evident during light effort in patients with a serious stenosis of the pulmonary artery combined with ventricular septal defect.

The water content of air decreases as the temperature drops: at −10 °C it is only about 10% that at 20–23 °C. Conversely the respiratory air is saturated with water vapor by the mucous membranes of the respiratory passages in correspondence with a body temperature of 37 °C. The consequence of this is a great increase in the loss of water by respiration; under the conditions in the Himalayas this loss amounts to 3–4 liters per day. If this loss is not replaced by a corresponding volume of water, the consequence is dangerous dehydration and hemoconcentration with the risk of thrombi forming in the veins and the central nervous system.

3.2.2 Equalization of Pressure in the Gas-Filled Spaces, Barotrauma

3.2.2.1 Paranasal Sinuses and Middle Ear

With changes in the ambient pressure the pressure in the gas-filled spaces of the body must,adapt to the external pressure. The equalization of pressure in the gastrointestinal tract generally causes no difficulties. However, in contrast to the stomach, intestine, and lungs, the volume of the paranasal sinuses, including the frontal, maxillary, sphenoid, and various ethmoid sinuses, can not be altered. These rigid cavities, which are connected with the rhinopharyngeal space, must accept gas during compression and release it during decompression. Swelling of the rhinopharyngeal mucosa can hinder the flow of gas into these spaces so that during compression an increasing pressure difference is produced in them. This negative pressure causes swelling, and possibly even bleeding, of the mucosa that lines the sinuses. Barotrauma of the paranasal sinuses, of which the maxillary sinus is affected most frequently, does not lead to permanent damage.

The middle ear is connected by rather long tubal canals with the oral cavity, and communicates with the mastoid cells, which do not contain gas in everyone. The equalization of pressure with the middle ear requires an active opening of the tubal canals by swallowing, creating an overpressure in the rhinopharyngeal space (Valsalva maneuver). If the equalization of pressure is hindered during an increase in the ambient pressure, the tympanic membrane curves inward into the cavum tympani, which is ordinarily very painful. It compression continues, at a difference of pressure of more than 0.5 bar the tympanic membrane will probably tear. If water enters the middle ear, "vestibular symptoms" with rotary vertigo may ensue and this could lead to drowning during free diving. A relative negative pressure in the middle ear leads, even without a tear in the tympanic membrane, to a swelling of the mucosa and efflux of fluid in the tubal canal, which hinders the equalization of pressure during decompression. With a relative overpressure in the middle ear the membranes of the round window and of the oval window bulge into the inner ear. A sudden overpressure in the cochlea and the semicircular canals leads to symptoms related to the inner ear, with loss of hearing, extraneous sounds in the ear (tinnitus), dizziness, nystagmus, and possibly, vomiting. These symptoms regress only slowly without recompression and may persist in part.

3.2.2.2 Lungs

In "breath-hold" diving, the thoracic skeleton and the lungs are compressed, as in the submergence of whales and dolphins, and then expand again during ascent. The quantity of gas in the lungs, the number of molecules, apart from those of oxygen and carbon dioxide, remains constant. The volume of the thorax and lungs can be reduced to the residual volume of the lungs, about 20%–25% of the total capacity.

After full inspiration it would therefore be possible without difficulty to dive with held breath to a depth of 30–40 m. Because apnea for more than a minute is an exception, such depths cannot be attained without special aids.

If there is respiration during alteration of the ambient pressure, the volume of the lungs remains practically constant. If the ambient pressure increases, the content of gas must increase too, whereas if the ambient pressure decreases, gas must flow out of the alveoli to the outside. The unhindered influx and efflux of gas presupposes open respiratory passages. At long as breathing is spontaneous or is accomplished artificially through an endotracheal tube, the influx of gas during compression is essentially assured. If bronchi are obstructed, the parts distal to the obstruction become compressed.

The unhindered efflux of gas during ascent is more critical. An obstruction of the bronchi as, for example, in chronic bronchitis causes a regional overinflation during decreasing ambient pressure, whereas an obstruction of the larynx or of the trachea leads to an overpressure in all alveoli. When straining and coughing, the normal pulmonary parenchyma can withstand an overpressure of about 0.10–0.12 bar, while at greater pressures or in the presence of damage to the parenchyma with increased fragility, a rupture of the lung may ensue. A rupture at the surface of the lung leads to pneumothorax. If the richly vascularized central parts of the lungs are injured, as a rule no pneumothorax ensues, but gas enters the mediastinum and a mediastinal and a cutaneous emphysema may develop. In case of a central rupture, gas bubbles invade the pulmonary capillaries, so that an arterial gas embolism might enter the central nervous system. Attacks of coughing over a period of days, as, for example, in allergic alveolitis, can lead to a rupture of the lung with a mediastinal emphysema and accumulation of gas in subcutaneous tissue, without symptoms of a gas embolism arising. This shows that larger volumes of gas can be resorbed asymptomatically at a constant ambient pressure.

If a central rupture of the lung occurs during ascent, the gas that is infused into the blood forms bubbles whose volumes increase and in the region of the embolism obstruct the capillaries. This obstruction hinders the perfusion and consequently the resorption of gas. In this way multiple ischemic foci form in the brain, in the spinal cord, and occasionally in the myocardium; the chance of spontaneous recovery is least for the spinal cord. The central rupture of the lung with arterial gas embolism occurs frequently in sport diving and in training emergency ascents from submarines.

When the respiratory passages are partially obstructed, even the slow ascent from shallow depths can lead to barotrauma of the lungs. The arterial embolism of gas into the central nervous system is an imperative indication for the fastest possible recompression (see also Sect. 4.3.2). Without recompression enduring damage must be expected.

3.3 Uptake and Release of Inert Gas by the Tissues

3.3.1 Half-Value Times, the Mathematical Bases

It is generally accepted that the inert gas pressure gradient is the driving force in the equalization of the inert gas pressure between the gas breathed, and that in the blood and tissues, and that the rate of this equalization of pressure for the uptake and release of the inert gas is exponential. If pressure-difference and exposure-time are known, the equalization can be calculated by means of half-value times:

The pressure of the inert gas in the tissue (Pi. g. t.) for a given half-value time after a given time of exposure (t_E) is calculated by

$$\mathrm{Pi.g.t.}(t_E) = \mathrm{Pi.g.t.}(t_O) + \left[\mathrm{PIi.g.} - \mathrm{Pi.g.t.}(t_O)\right] \cdot \left[1 - e^{-k \cdot t_E}\right] \text{ or } \cdot \left[1 - e^{-0.69315 \cdot t_E/½t}\right].$$

Pi.g.t. (t_E)	is the pressure of the inert gas in the tissue at the end of the exposure,
Pi.g.t. (t_O)	is the pressure of the inert gas in the tissue at the beginning of the exposure,
PI i.g.	is the pressure of the inert gas in inspiration,
e	is the base of natural logarithms, 2.71828 . . .;
k	is the natural logarithm of 2, 0.69315, divided by the half-value time.

The numerical value of the first expression in parentheses is the effective pressure gradient; the value of the second expression is the proportion of the gradient that must be added to the initial pressure of the inert gas in the tissue or, when inert gas is released, subtracted from the initial pressure. The value of this proportion is 0.5 when the time of exposure (t_E) and the half-value time are the same. To facilitate calculating the equalization of the inert gas pressure, Table 21 in Appendix A gives the value of the second expression for the values 0.01–9.0 for the ratio of exposure time to half-value time.

The equalization of the inert gas pressure between the gas in the alveoli and the blood that flows through the lungs takes place quickly, whereas that between the blood and those tissues that have a low blood supply is slow. The large differences in the blood supply of the various tissues and the variability resulting from physical activity require a large range of half-value times to be considered.

3.3.2 Longest Half-Value Time for Nitrogen and Helium in Man

For decades 240 min was considered to be the longest half-value time for nitrogen in man. In the middle of the 1960s exposures to air and to mixtures of oxygen and helium lasting some days were tried in various countries. These showed that with helium a practically complete equalization – a saturation – is reached in 1–1.5 days but with nitrogen not until after 3–4 days [13]. Longer exposures did not require any additional decompression. From these results it was possible to derive that the longest half-value time of helium must be reckoned to be 3-4 h, but that of nitrogen, at least 8-10 h [13].

In Zurich from 1960 to 1962 the first experiments in deep diving were carried out with the assumption that the equalization of pressure occurred as a function of atomic or molecular weight, i.e., that the equalization of pressure of helium was 2.65 times as fast as that of nitrogen [19]. In decompression only the correctly calculable inert gas pressure was considered, and for every compartment the partial pressure of helium was added to that of nitrogen, according to their corresponding half-value times. According to this concept it is logical that while breathing a mixture of oxygen and helium the inert gas pressure can be higher than that of the inspiratory partial pressure of helium, depending on the length of exposure up to the complete elimination of nitrogen. This apparent contradiction, but above all the neglect of the very different solubilities of helium and nitrogen in aqueous solutions and those containing fat, explains why this method of calculating cdecompression was considered by the specialists as to "simple." It was overlooked that the concept developed in Zurich offered a plausible explanation for the difficulties that had arisen during decompression when the first attempts were made to substitute helium for nitrogen long ago.

The practical use of the method was demonstrated subsequently with a large number of simulated and real dives. It was proved that the factor 2.65 and the summation of PHe and PN_2 were correct when helium and nitrogen are breathed together or in any sequence, whether either the initial PN_2 remains constant in all tissues at 0.75 bar or there is countercurrent diffusion of helium and nitrogen (see Sect. 3.4.4).

On the basis of these trials and experiments 16 compartments with half-value times for helium of 1-240 min, corresponding to half-value times for nitrogen of 2.65-635 min, are considered for calculating the equalization of the pressure of the inert gas (see also Sect. 3.5.2).

3.4 Decompression

3.4.1 "Explosive" Decompression

If a human being with a normal partial pressure of nitrogen of 0.75 bar in all tissues is brought within a few minutes to a height of 10000-11000 m above sea level, i.e., into an ambient pressure of 0.26 to 0.23 bar, and left there, nitrogen bubbles form in all organs that are not supplied well by blood, e.g., the skin and subcutaneous fatty tissue. A cutaneous emphysema develops. The passage of gas bubbles and fat out of the injured fatty tissue causes a serious gas and fat embolism in the lungs with serious impairment of the gas exchange. Some of the gas bubbles and fat particles pass the pulmonary vessels and enter the systemic circulation. This situation is known to aviation medicine and corresponds to an "explosive" decompression, which leads to serious decompression sickness with potentially lethal complications.

Something similar would affect a diver who breathed air for 120 min or longer at a depth of 30 m or more and then, without practising decompression, returned within a few minutes to normal pressure at the surface. Gas bubbles would also form in his brain and spinal cord, so that neural symptoms would dominate the ailment from the beginning.

If the diver breathed air for only 5–10 min at a depth of 40 m, the PN_2 will be 3.5–3.9 bar in the arterial blood, but only slightly increased in the skin and other tissues, corresponding to the half-value times. If the diver then returns to the surface within 1 min, gas bubbles will be released into the arterial blood, leading to disturbances of vision and possibly to unconsciousness. If the diver becomes unconscious in the water during such a rapid ascent, the risk of drowning is high. Without perfusion the nitrogen that is dissolved in the tissues cannot be dissipated. The PN_2 in the tissues corresponds to about the premortal value. A cutaneous emphysema will develop when the corpse reaches the surface only in the first example, regardless of the depth to which the drowned person sank. This emphysema shows that the PN_2 in the skin became so high during the dive that it could no longer be tolerated at a normal ambient pressure without formation of bubbles.

During the Second World War aircraft without pressure cabins that reached heights of 6000–8000 m above sea level were developed, but the ascent required several min and the pilots breathed oxygen. In 1941 Behnke showed that with a fast decrease in pressure from 1.0 to 0.38 bar, corresponding to the pressure at a height of 7500 m above sea level, pain arises in the joints if the low pressure is maintained for 1–2 h. The difference in pressure between a PN_2 of 0.75 bar in the joints and an ambient pressure of 0.38 bar was not tolerated by all the subjects without pain, although they showed no symptoms of gas embolism or of formation of gas bubbles in the central nervous system [2].

The example of explosive decompression and the experiences of aviation medicine demonstrate the causal importance of the formation of gas bubbles for the genesis of decompression sickness, but they also show the influence of the duration of decompression. With explosive decompression, individual differences of tolerance and physical condition have no effect on the incidence of serious decompression sickness. If the decompression time for an adequate dissipation of inert gas is not drastically too short, only some divers show symptoms of decompression sickness even when, for example, gas bubbles in the blood can be demonstrated sonographically.

It is understandable therefore that there is an ever recurring discussion of the factors that can elicit, independent of the pressure of the inert gas, a pathogenic formation of gas bubbles. They were attributed to, for example, physical agitation, physical work, and even cosmic rays. On the basis of systematic investigations it may be stated that physical work during decompression does not provoke any increase in the incidence of pain in the joints as long as the course and time of decompression suffice [24].

3.4.2 Tolerated Partial Pressure of Nitrogen at an Ambient Pressure of 1.0 Bar

As long as the gas breathed contains oxygen, during equalization of pressure with the breathing gas the pressure of the inert gas in the blood and tissue is always less than the ambient pressure. If at normal ambient pressure the PN_2 in the tissue is 0.75 bar, the ambient pressure of 1.0 bar could be decreased to 0.75 bar, equal to that at 2500 m above sea level, without producing an overpressure of nitrogen. If air is breathed at a pressure of 0.75 bar, the inspiratory PN_2 is 0.54 bar, so that nitrogen is released with breathing to correspond with the pressure gradient of 0.21 bar. Decompression by way of this "O_2 window" is sure but very slow.

Experience has shown that with a PN_2 of 0.75 bar in all the tissues the ambient pressure may be decreased to 0.48 bar (5900 m above sea level) without symptoms of inadequate decompression becoming apparent. In this situation the tissues tolerate an overpressure of nitrogen of 0.27 bar. If air is breathed at an ambient pressure of 0.48 bar, the inspiratory PN_2 is 0.33 bar and the pressure gradient for the release of nitrogen is 0.42 bar. Larger pressure gradients of inert gas between tissue, blood, and breathing gas result from the tolerance of the tissues to an overpressure of an inert gas; these gradients accelerate the elimination of the inert gases and thus the decompression.

Haldane observed that after exposure of several hours to an overpressure corresponding to a depth of water of 10 m, one could return immediately to the surface without difficulties occurring [15]. When breathing air at an ambient pressure of 2.0 bar, the inspiratory PN_2 is 1.53 bar. The tissues that have achieved an equalization of nitrogen pressure during the exposure with stand, according to this observation, an overpressure of nitrogen of 0.53 bar at an ambient pressure of 1.0 bar. The ratio of 1.53 : 1.0 has since played and important part in the research on decompression, yet the consideration given to this ratio must be put into its proper perspective. After breathing air at an ambient pressure of 2.0 bar for 5 h, the PN_2 in a tissue with a half-value time of 300 min for nitrogen is only 1.14 bar; conversely one can breathe air at an ambient pressure of 4.0 bar for 20 min and return to normal pressure in 2–3 min. With this "decompressionless" dive a tissue with a half-value time of 20 min for nitrogen has a PN_2 of 1.93 bar; at an ambient pressure of 1.0 bar this tissue tolerates an overpressure of 0.93 bar.

The tolerated overpressure of nitrogen is an empirical value and can not be calculated from physicochemical data. It is influenced by the half-value times, in that tissues with short half-value times tolerate a higher overpressure of inert gas than do tissues with long half-value times. Since these times are determined essentially by how the tissues are perfused with blood, tissues or organs that are perfused richly with blood can endure a higher pressure of inert gas asymptomatically than those tissues that are perfused less with blood.

The US Navy's standard decompression tables for air are firmly based on experience [26]. If the PN_2 tolerated at the end of decompression when a pressure of 1.0 bar is reached is calculated upon the basis of these tables, the result is close to the half-value time of nitrogen. This relation follows a curve and is shown in Fig. 1. The tables of the US Navy give 240 min as the longest half-value time for nitrogen, which is also true for the tables for exceptional exposures in regard to time and depth. The analysis of the tables shows that for the half-value time of 240 min a partial pressure of nitrogen of 1.45 bar is tolerated at an ambient pressure of 1.0 bar. For longer half-value times this value, depending on the length of exposure, is exceeded in part quite considerably. From 1970 to 1978 individual dives, e.g., 50 and 60 min at 57 m and 70 min at 48 and 51 m, were displaced from the normal table into the exceptional range; in other words, the normal range was reduced and the exceptional range extended. The decompression times in these exceptional ranges have

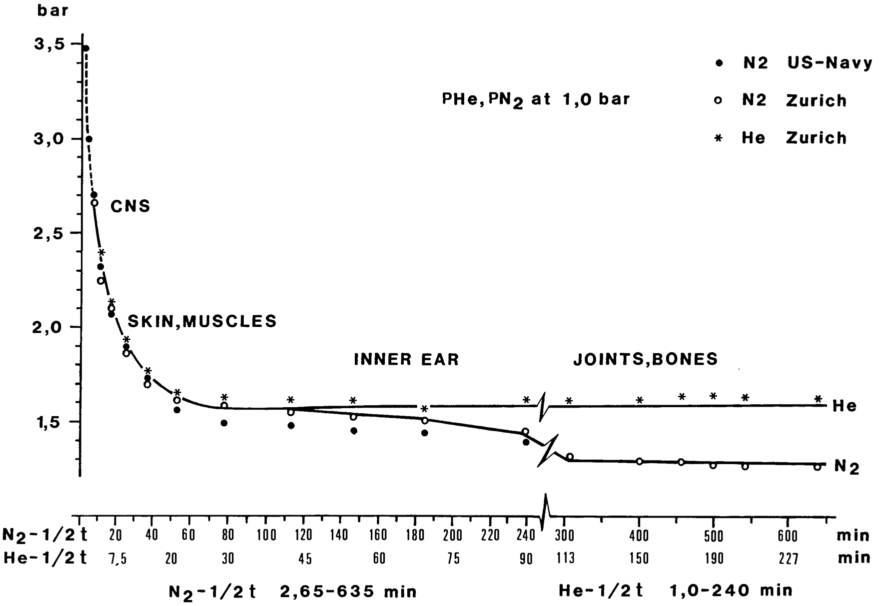


Fig. 1. Tolerated pressure of inert gas at an ambient pressure of 1.0 bar as a function of the half-value times for nitrogen and helium. •PN_2 calculated in correspondence with the tables of the US Navy; °PN_2 and *PHe determined experimentally in Zurich (compare Figs. 2–5). Identification of the half-value times of N_2 and He with the afflicted organs (sect. 3.4.5)

not been changed since 1959. The use of these tables is not recommended for routine use because they offer no adequate protection from decompression sickness, in particular damage to joints and bones.

In Zurich the PN_2 that is tolerated at 1.0 bar was determined with a larger number of test subjects; Tables 6 and 7 and Figs. 2–5 give detailed information [11]. These investigations indicate that the "slow tissues" with half-value times of 300–635 min for nitrogen tolerate a PN_2 of only 1.26–1.30 bar at an ambient pressure of 1.0 bar; if the PN_2 is more than 1.35 bar, pains in the joints occure more frequently. The values of PN_2 for the half-value times of 12–240 min for nitrogen correspond to those of the US Navy (Fig. 1).

3.4.3 Tolerated Pressure of Nitrogen at Overpressure

From the standard tables of the US Navy it is possible to calculate that at 1.0 bar a tissue with a half-value time for nitrogen of 37 min tolerates a PN_2 of 1.73 bar, a tissue with a half-value time for nitrogen of 53 min a PN_2 of 1.55 bar. After an exposure with an inspiratory PN_2 of 3.10 bar for 120 min, as for example when breathing air for 120 min at a depth of 30 m, the PN_2 in a tissue with a half-value time for nitrogen of 37 min amounts to 2.85 bar, in a tissue with a half-value time of 53 min, 2.60 bar. After such an exposure the ambient pressure may be reduced within

2–3 min to 1.9 bar. There is then for the half-value time for nitrogen of 37 min an overpressure of 0.95 bar, for the half-value time of 53 min an overpressure of 0.70 bar. This example shows that with a given half-value time the tolerated overpressure of nitrogen increases with increasing ambient pressure. This phenomenon has in principle been empirically determined and has wide practical significance for the composition of decompression tables when safety and economical decompression times are to be combined.

3.4.4 Differences Between Nitrogen and Helium and Experimental Bases for the ZH-L_{12} System

If not only the overpressure of the inert gas but also the excess volume of dissolved gas contributes importantly to symptoms of insufficient decompression, a higher pressure of helium than of nitrogen should be tolerated without symptoms. These

Table 6. Durations of stay at 3.92 bar (except for BO-180, which was at 4.41 bar), including compression time of 3 min. The composition of the gas breathed was identical with that in the chamber as long as pure oxygen was not breathed through a mask during decompression[a]

Trial	*n*	3.92 or 4.41 bar				Decompression		
		min	O_2	N_2	He	O_2	N_2	He
AA-73	28	73	0.21	0.79	–	0.21	0.79	–
AA-120	16	120	0.21	0.79	–	0.21	0.79	–
AO-120	31	120	0.21	0.79	–	1.0	–	–
AA-150	16	150	0.21	0.79	–	0.21	0.79	–
AA-320	36	320	0.21	0.79	–	0.21	0.79	–
AO-320	35	320	0.21	0.79	–	1.0	–	–
BB-23	24	23	0.21	0.19[b]	0.60	0.21	0.19	0.60
BB-35	19	35	0.21	0.01	0.78	0.21	0.01	0.78
BB-120	28	120	0.21	0.01	0.78	0.21	0.01	0.78
BA-120	16	120	0.21	0.01	0.78	0.21	0.78	0.01
BO-120	20	120	0.21	0.01	0.78	1.0	–	–
BO-180	43	180	0.11	0.17[b]	0.72	1.0	–	–
BA-Sat.	6	[c]	0.21	0.01	0.78	0.30	0.70	–
CO-120	22	45	0.21	0.01	0.78			
		+75	0.21	0.78	0.01	1.0	–	–
CO-300	22	150	0.21	0.01	0.78			
		+150	0.21	0.78	0.01	1.0		

[a] The 362 exposures are of 230 different subjects of the ages of 16–48 years, 10 of whom were women

[b] Partial pressure of nitrogen of 0.74 bar in the gas breathed is the same as that breathing air at normal atmospheric pressure. This is why at 3.92 or 4.41 bar only helium is absorbed and no nitrogen is released

[c] Durations of stay 48 h and 72 h, Capshell Experiment in the Mediterranean, with excursions in the open sea

Table 7. Length of decompression, first decompression step, number of subjects, frequency of symptoms of inadequate decompression and the affected organs; critical half-value times at the end of decompression. A: adequate decompression; B: inadequate decompression resulting from shortening the last step before reaching the pressure of 1.0 bar

Trial		Total decompression (min)	First step (bar)	No. affected no. of subjects	Organ	Critical ½ time (min)
AA-73	A	57	1.8	1/16	Skin	N_2 37–79
	B	39	1.8	5/12	Skin	
AA-120	A	114	1.9	1/16	Joints	N_2 79–146, 304
AO-120	A	43	1.9	2/23	Skin	N_2 53–79
	B	37	1.9	3/8	Skin	
AA-150	A	167	2.1	4/12[a]	Joints	N_2 304
	B	147	2.1	1/4	Skin/Joints	N_2 114–185, 304
AA-320	A	670	2.5	2/18	Joints	N_2 304–542
	B	525	2.5	9/18	Joints	
AO-320	A	170	2.5	1/19	Joints	N_2 304–458
	B	145	2.5	4/16	Joints	
BB-23	A	27	1.7	0/12		He 14–30
	B	18	1.7	6/12	Skin	
BB-35	A	80	2.1	0/19		He 55–70
BB-120	A	316	2.5	0/20		He 150–240
	B	232	2.5	3/8	Joints	
BA-120	A	170	2.5	0/12		He 115–190,
	B	145	2.5	2/4	Joints	N_2 304–503
BO-120	A	83	2.5	0/12		He 115–173
	B	65	2.5	3/8	Joints	
BO-180	A	173	2.5	0/34		He 150–240
	B	140	2.5	4/9	Joints	
BA-Sat	A	330	2.5	0/6		He 240
CO-120	A	35	2.5	0/16		He 43–55,
	B	27	2.5	5/6	Skin	N_2 114–146
CO-300	A	130	2.5	0/18		He 150–240,
	B	110	2.5	2/4	Joints	N_2 397–635

[a] In AA-150 the half-value times for nitrogen of 114–185 min were tested. For a half-value time of 304 min even total decompression time of 167 min is unsufficient

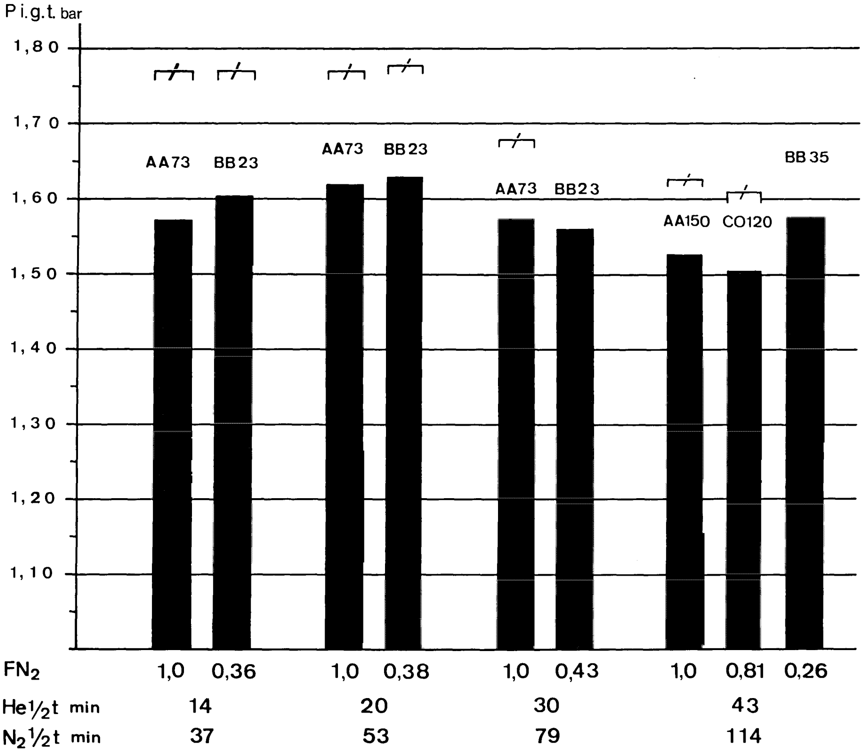


Fig. 2. Calculated pressure of the inert gas in tissue (P i.g.t.) and the fraction of nitrogen (FN_2) at the end of decompression at an ambient pressure of 1.0 bar, in the compartments with half-value times of 14–43 min for helium, corresponding to half-value times of 37–114 min for nitrogen.
⌐⁄¬P i.g.t. with symptoms affecting the skin following shortened decompression. (For AA-73 etc. see Tables 6 and 7)

relationships were examined systematically for the tissues with half-value times for helium of 14–240 min, corresponding with those for nitrogen of 37–635 min [11]. All exposures were accomplished with a proportion of oxygen of 0.21 in the breathing gas; the concentration of gas and the pressure in the chamber were controlled continuously. Pure oxygen was breathed through a full-face mask. During the experiments with air the temperature of the chamber varied between 21° and 22 °C, and with helium, between 28° and 30 °C.

The exposures were chosen so that the half-value times with different fractions of nitrogen from 1.0, i.e., nitrogen alone, to 0.25 could be evaluated. For 10 min every hour 80 W was performed on a bicycle ergometer. Because the pressure of the inert gas may exceed the tolerated value, at the end of the decompression certain half-value times, corresponding to the breathing gas and duration of exposure, are critical.

Table 6 presents information regarding exposure times and breathing gases. In the experiments with air (AA), nitrogen is absorbed by tissues with short half-value times during exposure at full pressure and then relinguished during decompression,

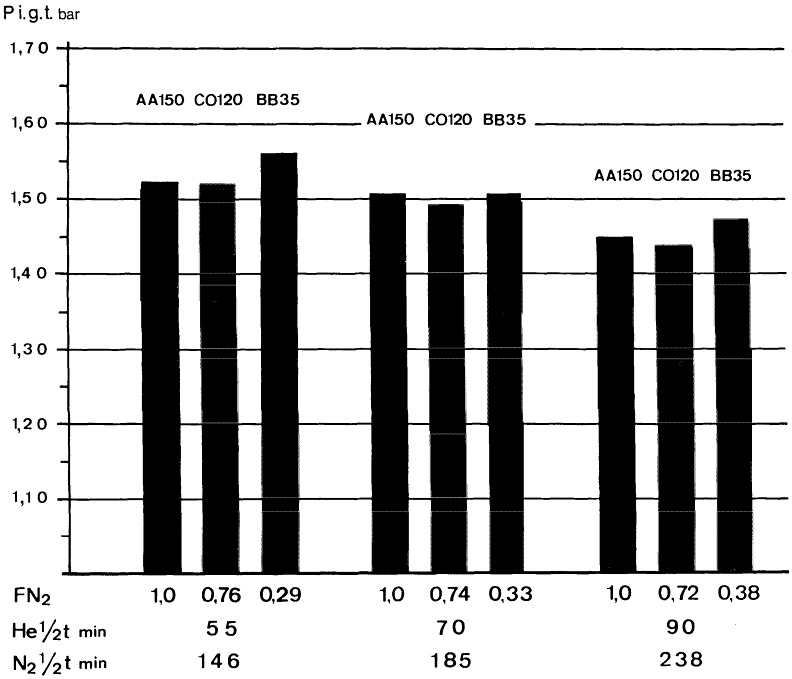
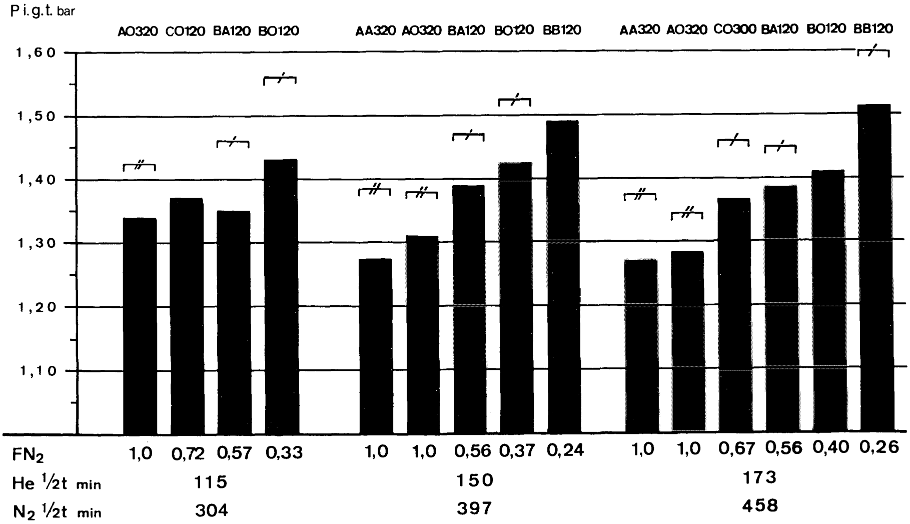


Fig. 3. Calculated pressure of the inert gas in tissues and the fraction of N_2 at the end of decompression at an ambient pressure of 1.0 bar, in the compartments with half-value times of 55–90 min for helium, corresponding to half-value times of 146–238 min for nitrogen. (For AA-150 etc. see Table 6)



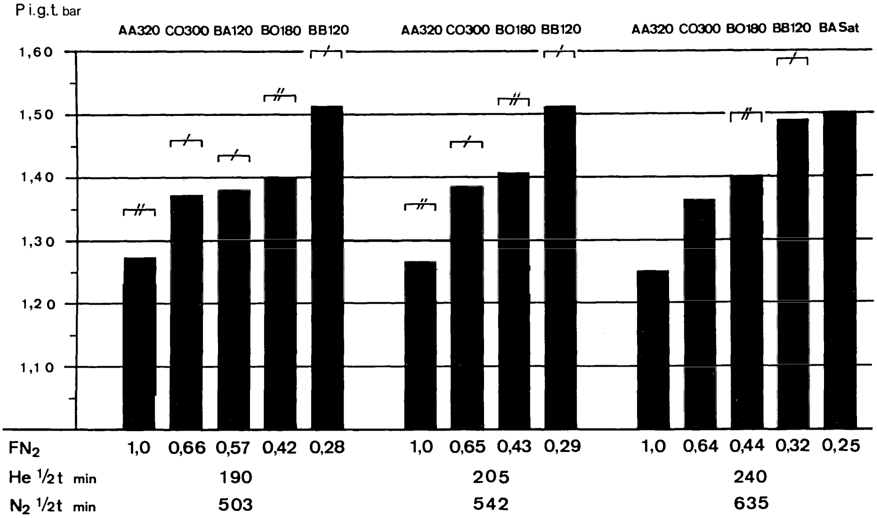


Fig. 5. Calculated pressure of the inert gas in tissues and the fraction of N_2 at the end of decompression at an ambient pressure of 1.0 bar, in the compartments with half-value times of 190–240 min for helium, corresponding to half-value times of 503–635 min for nitrogen. ┌/┐┌//┐ as in Fig. 4. (For AA-320 etc. see Tables 6 and 7)

but in those tissues with long half-value times it is still partly absorbed. During breathing of 100% oxygen, as in the AO, BO, CO experiments, inert gas is released in all compartments. With the exception of experiments BB-23 and BO-180, in the exposures to helium, at full pressure the body absorbs helium and simultaneously releases nitrogen. In the change of inert gas at full pressure, the CO-experiments, helium is absorbed and nitrogen is relinquished during the first phase, whereas during the second phase nitrogen is absorbed and helium released; during the following decompression with pure oxygen both inert gases are eliminated. A characteristic of experiments BA-120 and BA-Sat. was that at a pressure of 3.92 bar helium is absorbed and nitrogen relinquished, but then during decompression with air nitrogen is absorbed and helium released. These trials made it possible to ascertain whether the reciprocal movement of helium and nitrogen between lungs, blood, and tissues at constant pressure or during decompression influences the tolerance as shown by the occurrence of symptoms.

The reduction in pressure to the first decompresssion step was accomplished within 1.5 min; the later steps followed in correspondence with the factors given in Table 8. For critical decompression only the duration of the last step was shortened each time. Table 7 contains information regarding the decompression times, the fre-

◀ **Fig. 4.** Calculated pressure of the inert gas in tissues and the fraction of N_2 at the end of decompression at an ambient pressure of 1.0 bar, in the compartments with half-value times of 115–173 min for helium, corresponding to half-value times of 304–458 min for nitrogen. ┌/┐ = P i. g. t. with slight pains in the joints; ┌//┐ = P i. g. t. with serious pains in the joints following shortened decompression. (For AO-320 etc. see Tables 6 and 7) quency of symptoms, their localization, as well as the half-value times that are critical at the end of the decompression.

The values given in Figs. 2–5 correspond to the pressure of the inert gas at the end of the decompression. In the experiments with helium this value is the sum of the pressure of helium and that of nitrogen for the corresponding half-value times. Without any change in the course of decompression, with solely a curtailment of the last step, an increase in pressure of the inert gas was followed by an increased occurrence of symptoms of insufficient decompression. This result supports the concept that at no stage of decompression should the ambient pressure be less than that tolerated.

These experiments yielded for the tissues with half-value times of 14–70 min for helium, corresponding with those for nitrogen of 37–185 min, no obvious difference between the pressures of helium and nitrogen that were tolerated asymptomatically when a pressure of 1.0 bar was reached. However, a clear difference was demonstrated for the slow tissues with half-value times for helium of 115–240 min, corresponding with those for nitrogen of 304–635 min. The exposures with helium as the inert gas yielded an increased tolerance that was dependent upon the fraction of nitrogen; the various proportions of nitrogen make it possible to calculate the tolerated pressure of helium. If for the slow tissues the pressure of the nitrogen is multiplied by 1.25 and the product is added to the pressure of the helium, the result corresponds for the various experiments to a tolerated partial pressure of helium of 1.57–1.62 bar (Fig. 6). Conversely, if the PHe is divided by 1.25, the tolerated PN_2

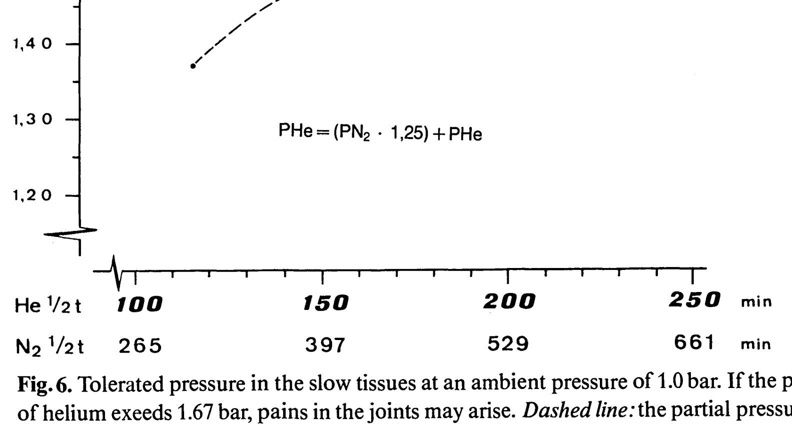


Fig. 6. Tolerated pressure in the slow tissues at an ambient pressure of 1.0 bar. If the partial pressure of helium exeeds 1.67 bar, pains in the joints may arise. *Dashed line:* the partial pressure of helium is for these half-value times less than the tolerated limit

amounts to 1.26–1.30 bar, corresponding to the lengthy exposures to air in experiments AO-320 and AA-320.
If one assumes a fat content of 12%–13% for the slow tissues, the volume of helium that is dissolved at an overpressure of 0.6 bar of helium corresponds to the volume of nitrogen that is dissolved at an overpressure of 0.3 bar of nitrogen (see Sect. 3.7 and Fig. 14).

The consideration of the solubility factors of other inert gases shows that for neon about the same tolerance is to be expected as for helium; for hydrogen, a tolerance similar to that for nitrogen; and for the heavy very readily soluble argon, the least tolerance. For the change of gas from helium to a more slowly diffusing gas, neon is preferred to nitrogen, although the gain in decompression time would be slight. Theoretically, the use of the other inert gases has no advantage in comparison with the well established use of helium and nitrogen. Our own experience concerns helium and nitrogen and to a lesser extent argon [19].

3.4.5 Identification of the Half-Value Times with Tissues

When the half-value time of a tissue is dependent foremost upon its perfusion rate, variations that time with physical activity are to be expected. This is especially true for the muscles and skin, and thus for the subcutaneous fatty tissue, too. For the joints and bones, a certain increase in the blood supply is to be during work and with it a somewhat faster equalization of the pressure of the inert gas [24].

If the circulation in an arm, for example, is inhibited by the cuff of a sphygmomanometer during decompression that is critical for the skin, symptoms such as red spots and swelling develop on this arm. Therefore, in experimental research on decompression and testing decompression tables, there is validity for the rule that during exposure to overpressure physical exercise be performed regularly, e.g., for 10 min every hour 80–100 W be produced on a bicycle ergometer. This leads to the idea, conversely, of slowing the decompression during sleep [26, 27].

For the brain and the spinal cord the short half-value times may be considered representative; obvious reasons prevent experiments in this region, but experience is gained from the analysis of dives of those who have had accidents. In agreement with our experience, the compartments with half-value times for helium of 55–90 min, corresponding to times for nitrogen of 146–238 min, are representative for the inner ear. If these compartments are decompressed insufficiently, symptoms of affliction of the inner ear (vertigo bends) can occur with loss of hearing, sensation of noise in the ear, dizziness, nausea, and vomiting [12]. Decompression sickness in this form requires a quick recompression to prevent permanent damage to the inner ear. The skin and muscles are represented by half-value times for helium of 14–30 min and for nitrogen of 37–79 min. The signs of insufficient decompression are itching, reddening, swelling, and for the muscles pains comparable to those of muscular soreness from unaccustomed exercise. The limits are of course flexible. If the half-value time of 43 min for helium, or that of 114 min for nitrogen, is concerned, symptoms affecting the skin and muscles as well as the inner ear may occur [23].

Joints and bones, the "slow tissues," have half-value times of 115–240 min for helium and 304–635 min for nitrogen. If the decompression is inadequate for these values, pains in the joints become more frequent. Recompression is also urgent in this type of decompression sickness to prevent definitive damage to the joints. Figure 1 illustrates the relation between half-value times and organs.

3.5 Calculation of Safe Decompression

3.5.1 Tolerated Pressure of Inert Gas as Dependent on Half-Value Time and Ambient Pressure

The knowledge of the pressure of inert gas that is tolerated when the normal pressure of 1 bar is attained does not suffice for the calcuation of decopression steps or of the speed of a continuous decompression. It is accepted generally and can be seen from recognized decompression tables that the tolerated pressure of inert gas decreases with increasing half-value time at a given ambient pressure, and that the ratio of the pressure of the inert gas in the tissue to ambient pressure at a given half-value time becomes smaller with increasing pressure of the inert gas. The reduction in the ratio of the pressure of the inert gas in the tissue to ambient pressure does not follow a rectilinear, but rather a curvilinear course. Our experience indicates that the difference between the pressure of the inert gas in the tissue and the tolerated ambient pressure, the "overpressure" or "excess" of nitrogen or helium, as long as the excess volume of dissolved gas is taken into consideration, increases approximately linearly with the ascending ambient pressure. Henessy and Hempleman suggested simplifying the calculations of decompression by means of linear functions [17]. In Zurich the experimentally determined tolerances were always correlated with the pressure of the inert gas for the dissimilar half-value times of nitrogen and helium and the numerical values always adapted to the new results. These experiential values allowed easy derivation of the coefficients for the calculation of a safe decompression while taking into acount 16 half-value times for both nitrogen and helium.

3.5.2 Twelve Pairs of Coefficients for Sixteen Half-Value Times of Helium and Nitrogen (ZH-L_{12})

For each half-value time the tolerated ambient pressure (Pamb. tol.) is caculated from the pressure of the inert gas in the tissue (P i.g.t.) as

$$\text{P amb.tol} = (\text{P i.g.t} - \text{a}) \cdot \text{b}.$$

The values for a and b are listed in Table 8. For compartments 1–9 the same values are valid for both nitrogen and helium, whereas for nitrogen compartments 10–16 have other values because of the lower tolerance of the slow tissues for nitrogen. Figure 7 shows the curves of the 12 pairs of coefficients; the numerical value of a is given by the selected unit of pressure, while b gives the slope of the curves.
Good manometers permit a reading to 0.1 bar. If the decompression takes place in a

Table 8. ZH-L_{12}. Twelve pairs of coefficients for 16 half-value times for helium and 16 half-value times for nitrogen

Compartment	1	2	3	4	5	6	7	8	9
He-½ t (min)	1	3	4.6	7	10	14	20	30	43
N_2-½ t (min)	2.65	7.94	12.2	18.5	26.5	37	53	79	114
Factor a, He, N_2	2.200	1.500	1.080	0.900	0.750	0.580	0.470	0.455	
Factor b, He, N_2	0.820	0.820	0.825	0.835	0.845	0.860	0.870	0.890	
Compartment	10	11	12	13	14	15	16		
He-½ t (min)	55	70	90	115	150	190	240		
N_2-½ t (min)	146	185	238	304	397	503	635		
Factor a, He	0.515		0.515	0.515					
Factor b, He	0.926		0.926	0.926					
Factor a, N_2	0.455		0.380	0.255					
Factor b, N_2	0.934		0.944	0.962					

If both helium and nitrogen are present in the compartments, factors a and b must be calculated in correspondence with the proportion of the gases, as in the example for compartments 13–16:

a $(He + N_2) = [(P_{He} \cdot 0.515) + (P_{N_2} \cdot 0.255)]/[P_{He} + P_{N_2}]$;

b $(He + N_2) = [(P_{He} \cdot 0.926) + (P_{N_2} \cdot 0.962)]/[P_{He} + P_{N_2}]$.

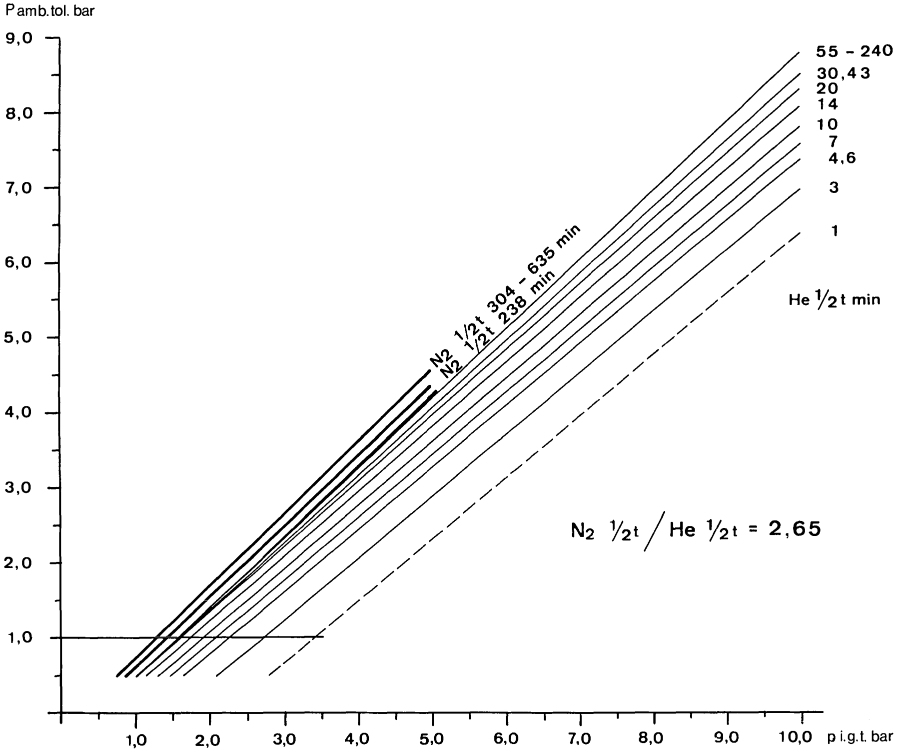


Fig. 7. ZH-L_{12}. Tolerated ambient pressure (P amb.tol.) dependent on the calculated pressure of inert gas in tissue (P i.g.t.) with half-value times for helium of 1–240 min. The curves for these half-value times of 1–43 min are also valid for the half-value times of 2.65–114 min for nitrogen. The curve for the half-value times of 146–185 min for nitrogen coincides in "the air range" with that for the half-value times of 55–240 min for helium. For the half-value times of 238 and 304–635 min the additional curves are appropriate (see Table 8)

hyperbaric chamber, steps of 0.1 bar can be maintained. If the tolerated ambient pressure is above 1.0 bar, the calculated value is rounded up to the first dezimal place (1.41 = 1.5 bar). Below 1.0 bar, it is rounded up to the second dezimal place (0.851 = 0.86 bar).

With the ZH-L_{12} system a continuous decompression can also be calculated without difficulty and a computer programmed for decompression calculations. The difference between the pressure of exposure to that of the first step of decompression increases with increasing pressure of exposure; this is true for short exposure times as well as for those lasting days. The dependence of the tolerated overpressure of the inert gas upon the half-value time and upon the pressure of the inert gas itself leads to the idea of adapting the rate of reduction of the pressure for the first decompression step to the total pressure and to the dominant half-value time. The standard tables of the US Navy for dives with air give a maximum rate of decrease in pressure of about 1.8 bar/min to the first decompression step; this rate is also valid for ascent and descent in excursion dives during saturation with helium.

The experiments in Zurich indicate that, during short exposures to oxyhelium in the range 21–26 bar, a rate of decrease in pressure of 3–4 bar/min is tolerated well approaching the first step. This rate is only possible, however, in a suitably equipped pressure chamber. For such conditions the following formula has proved successful: $= (P\,amb \cdot 0.2) + 0.6$.

Rate of ascent to the first level in bar/min.

This value is limited by a maximum rate of 3.0 bar/min for each of the compartments 1–5, of 2.0 bar/min for each of the compartments 6 and 7, and of 1 bar/min for each of the compartments 8–16.

For professional divers a change in pressure faster than 1.0 bar/min is usually not possible for technical reasons, and this rate may therefore be recommended for all hyperbaric exposures.

If the decompression is executed in a chamber, it may be continuous; if decompression in steps is preferred, differences in pressure of 0.1 bar should be maintained. For decompression in scuba diving in water intervals of 0.3 bar have proved successful.

3.5.3 Comparisons Between Decompression Using ZH-L_{12} and the US Navy and Royal Navy Tables After Dives with Air [22, 26]

For short dives with air as the breathing gas, which interest amateur divers, the ZH-L_{12} systems gives decompression times and steps similar to those of the US Navy and Royal Navy tables. The characteristic differences are evident in dives with a longer stay under water or at greater depths, that is on the border between conventional and exceptional dives with air. These differences concern more the course

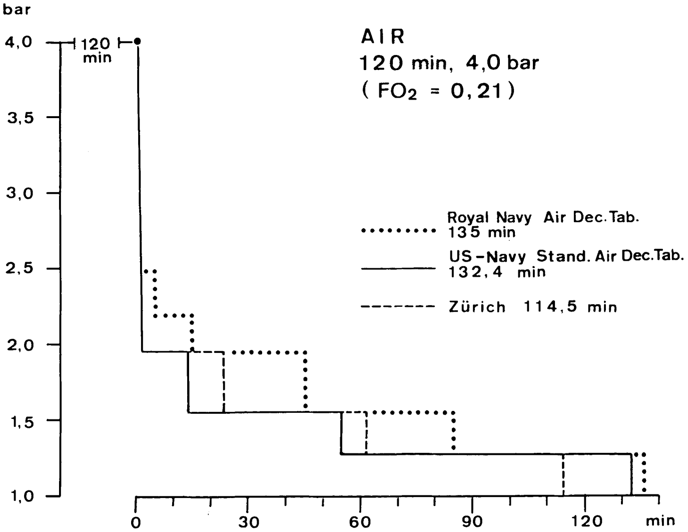


Fig. 8. Exposure with air for 120 min at 4.0 bar. Courses of decompression corresponding to the Royal Navy, the US Navy and ZH-L_{12} (see also Table 9)

and less the time of decompression, as seen from a comparison for a dive of 120 min to 30 m (4.0 bar) (Fig. 8).

The three systems use the same decompression steps at intervals of 3 m. The Royal Navy demands a first stop for decompression at 15 m and a second at 12 m; the stay at 9 m is notably longer than that of the US Navy, which has its first decompression stop at this level. The US Navy has its longest stop last at 3 m. The total duration of decompression is practically the same in the two navies. The procedure in Zurich also requires only three steps; however, the stay at 9 m is longer than that in the US Navy, but shorter than that in the Royal Navy. The total duration is only 114.5 min, but this course is only adequate for an exposure at exactly 4.0 bar. If a safety margin of a depth that effects a pressure of 0.2 bar is taken into account for the routine tables (Sect. 3.8.1), i.e., a short additional step at 12 m, supplements at 9 m and at 3 m are required, thus giving a total decompression of 142 min (Table 9).

The first decompression stage used by the US Navy is somewhat too fast for the tissues with a half-value time of 53 min for nitrogen. The US Navy decompressions follow in the range above 1.0 bar a higher ratio between the pressure of nitrogen in the tissue and the ambient pressure, which explains the rapid initial decompression that is typical of its tables. Graphs for the US Navy decompressions would then be depicted by lines proceeding more flat than those of Fig. 7. Thanks to the lengthy stay at 3 m, however, all the values of PN_2 at the end of the decompression are less than those indicated in Fig. 1 as tolerable. With the Royal Navy procedure, the beginning of the decompression is not critical, but at the end of the decompression the tolerated value is exceeded for a tissue with a half-value time of 146 min for nitrogen. For this half-value time the PN_2 is 1.56 bar, in the US Navy, 1.46 bar, and with ZH-L_{12}, 1.49 bar. With the Zurich procedure in comparison with that of the US Navy and that of the Royal Navy somewhat more safety is attained for the beginning of the decompression, and without the end of it becoming critical as it does with the Royal Navy procedure.

These same characteristic differences remain for a stay of 90 min at 39 m (4.9 bar), and for the extreme dives while breathing air that no longer correspond to routine dives – those with a stay of 60 min at 60 m (7.0 bar). The comparison of the decompression procedure in Table 9 shows the fast initial decompression of the US Navy with a long stay at the last step and the steps that start at greater depths in the Royal Navy, in whose tables the middle stops are longer whereas the stay at 3 m is notably shorter.

The fast initial decompression in extreme dives to 60 m while breathing air in correspondence with the the US Navy procedure is problematic for the tissues with half-value times of 12–36 min for nitrogen. Greater safety for the beginning of the decompression, as attained by the Royal Navy and ZH-L_{12} procedures, requires a longer stay at the last stop at 3 m. The PN_2 for a tissue with half-value time for nitrogen of 304 min at the end of the decompression is for the Royal Navy 1.36 bar, for ZH-L_{12}, and for the US Navy it is 1.29 bar. Thanks to the fast decompression until a depth of 9 m the slow tissues absorb less nitrogen during this phase than they do during the procedure used by the Royal Navy.

Table 9. Courses of decompression of the US Navy, the Royal Navy, and ZH-L_{12} after longer dives breathing air. (Atmospheric pressure at surface = 1.0 bar)

	Decompression stop (min)								Total time (min)
m	24	21	18	15	12	9	6	3	
30 m *120 min*									
US Navy	–	–	–	–	–	13	41	78	132
Royal Navy	–	–	–	5	10	30	40	50	135
ZH-L_{12} (4.2 bar)	–	–	–	–	10	24	36	72	142
39 m *90 min*									
US Navy	–	–	–	–	10	19	45	80	154
Royal Navy	–	–	5	5	25	40	45	50	170
ZH-L_{12} (5.1 bar)	–	–	–	10	14	24	40	79	167
60 m *60 min*									
US Navy[a]	–	–	5	13	17	24	51	89	199
Royal Navy[a]	5	5	10	25	35	45	45	50	220
ZH-L_{12} (7.2 bar)	8	6	10	14	21	26	42	149	276

[a] The US Navy and the Royal Navy do not recommend these decompressions for routine use; the data given are an example for and exceptional exposure. The ZH-L_{12} table includes for safety a supplement of 0.2 bar

Table 10. Experimental bases for the coefficients of ZH-L_{12}. Exposures while breathing air. These 116 exposures are not considered in Table 6

Exposure (bar)	Duration of compression (min)	Duration of stop (min)	Decompression to pressure (bar)	*n*
2.7–2.9[a]	3	300	0.97	21
3.92	3	48 h	0.97	8
4.0	3	117	0.85	16
4.0	3	117	0.79	15
3.0–4.5	2	65	0.70	16
4.2	3	57	0.70	12
4.2	3	117	0.70	12
1.0[b]	–	Saturated	0.47	16

[a] Breathing 50% O_2 and 50% N_2, diving in the watertank, 3 min decompression to surface (0.97 bar)

[b] Saturation at 1.0 bar, decompression in 15 min to 0.47 bar (see also Table 15)

3.6 Experimental Experiences with ZH-L_{12}

The research on decompression by the Hyperbaric Laboratory of the Medical Clinic of the University of Zurich has always been oriented toward practical experience. The aim was the realization of a practicable decompression with the largest possible assurance of safety. Experiments were conducted with voluntary human subjects, but none with animals. The continuity of personnel since the beginning made the consequent planning of the experiments easier. Tables 6, 7, 10–12, and 15 present information concerning the hyperbaric exposures that were especially important for the development of ZH-L_{12}. With oxygen and helium as the breathing gas, exposures to saturation, experiments with fast compression, and exposures of only some

Table 11. Experimental bases for the coefficients of ZH-L_{12}. Exposures breathing oxygen and helium. These 131 exposures are not considered in Table 6

Exposure (bar)	Duration of compression (min)	Duration of stop (min)	Decompression to pressure (min)	*n*
4.0	3	117	0.78	15
7.0	6	64	0.97	3
12.0	11	4	0.97	3
12.0	11	49	0.97	3
14.0	13	1	0.97	3
14.0	13	32	0.97	3
16.0	15	5	0.97	3
19.0	18	62	0.97	3
15.7	15	5	0.97	3
15.7	15	15	0.97	8
15.7	10	20	0.97	3
20.6	15	15	0.97	10
22.6	25	215	0.97	6
25.5	20	10	0.97	5
25.5	25	15	0.97	6
30.4	30	5	0.97	2
30.4	30	120	0.97	2
30.4	30	180	0.97	2
30.4	30	240	0.97	2
35.3	35	5	0.97	6
50.0	50	8	0.97	3
30.4	155	30	0.97	6
40.2[a]	255	45	0.97	3
35.3[a]	325	60	0.97	3
9.0	15	72 h	1.0	3
22.5	30	72 h	0.97–1.0	10
26.0	35	72 h	1.0	3
30.4	70	72 h	0.97–1.0	6
50.0[b]	700	48 h	0.97	3

[a] Following decompression to 30.4 bar and saturation at this pressure, excursions to 35.3 bar

[b] On the following day excursions for 120 min to 57.4 bar

Table 12. Experimental bases for the coefficients of ZH-L_{12}. Rapid compression, short stops, fast continuous decompression until the first step

Exposure (bar)	Duration of compression (min)	Duration of stop (min)	First step (bar)	Rate of ascent (bar/min)	*n*
15.7	15	5	11.2	1.0	3
15.7	15	15	10.9	3.5	8
15.7	10	20	9.0	1.4	3
19.0	18	62	14.2	1.0	3
20.6	15	15	16.6	4.0	10
25.5	20	10	21.5	4.0	5
25.5	25	15	17.9	3.0	6
30.4	30	5	26.4	4.0	2
35.3	35	5	30.4	4.9	6
50.0	50	8	45.1	4.9	3

minutes' duration at full pressure were executed up to a pressure of 50 bar. With air, the decompression to an ambient pressure of 0.70 bar, corresponding to that at 3 000 m above sea level, was of special interest.

3.6.1 Exposures with Air

It has already been mentioned (Sect. 3.5.3) that the decompressions calculated with ZH-L_{12} for short dives with air as the breathing gas were the same in their total duration as those of the standard tables of the US Navy and the Royal Navy. The procedure with slightly longer stays at the first decompression stops should have scarcely no unfavorable effect on the safety. The slow initial decompression is similar to the British practice. The comparison with these standard tables for air may be cited as proof that ZH-L_{12} offers adequately safe decompressions for short dives, with air as the breathing gas.

For long exposures with air, as are usual for caisson and tunnel workers and professional divers, ZH-L_{12} presents essentially longer durations of decompressions for exceptional and extreme exposures than are given by, for example, the tables of the US Navy. According to the factors for the slow tissues, saturation with air and a return to normal pressure (1.0 bar) is possible only after an exposure up to 1.7 bar. If saturation occurs at a pressure of 2.0 bar (a depth of 10 m in water), the decompression while breathing air requires 8 h, while breathing 100% oxygen, 4.5 h.

During the last 20 years few experiments with saturation with air have been performed in comparison with exposures with saturation with helium. In these experiments, pains in the joints occurred very frequently during decompression, an important argument for the belief that the tolerance of the slow tissues was less than had been assumed for a long time.

The low tolerance of the slow tissues to an overpressure of nitrogen is also important for conventional dives, if the ambient pressure decreases additionally after a pressure of 1.0 bar has been reached. Corresponding investigations in the hypobaric

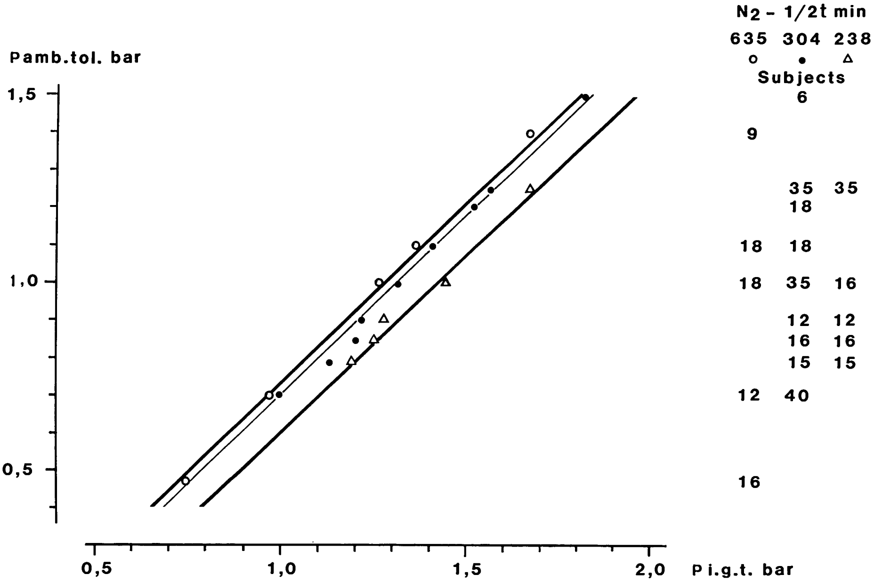


Fig. 9. Tolerated partial pressure of nitrogen for the half-value times of 238 and 304–635 min at ambient pressures of 0.47–1.5 bar. (See Tables 10 and 15)

range are the basis for decompression tables for dives in mountain lakes, but the tables also give guidance on the necessary stay at normal pressure before flying. The combination of overpressure and negative pressure also offers the possibility of testing the use of the linear system. Figure 9 shows with a larger number of experimental subjects a linear relation of the tolerated overpressure of nitrogen to the ambient pressure in the range of 0.47–1.5 bar for the half-value times of nitrogen of 238, 304, and 503–635 min. For some of these experiments the tolerance for the half-value time of 304 min was exceeded. In 7 of 31 experimental subjects slight, spontaneously vanishing pains in the joints occurred during a stay of 2 h at reduced ambient pressure (see Table 15, Sect. 3.10).

3.6.2 Exposures with Helium and with Mixed Gases

The simultaneous breathing of helium and nitrogen and the change from helium to nitrogen during decompression make it possible to test whether an equalization of pressure has to be considered that is for all tissues 2.65 times as fast with helium as with nitrogen. The change from helium to nitrogen makes it possible to shorten the duration of decompression because the helium, as a consequence of the larger pressure gradient, is released more rapidly than when oxygen and helium are breathed together, and because the equalization of pressure with nitrogen occurs more slowly for a given compartment.

Figure 10 shows the large differences between the duration of decompression after

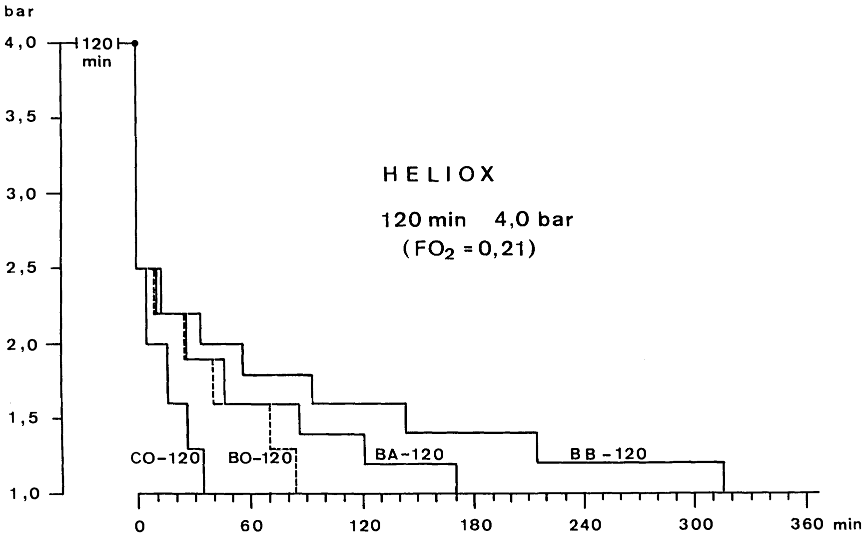


Fig. 10. Exposures with 21% O_2 and 78% He for 120 min at 4.0 bar. According to the gas breathed during decompression, very dissimilar courses of decompression are apparent. The first decompression step is at 2.5 bar for all decompressions. (For CO-120 etc. see Table 6 and Figs. 2–5)

an exposure of 120 min at 4.0 bar to oxygen and helium and a minimal contamination of the breathing gas with nitrogen (Table 7). If the change from breathing oxygen and helium to breathing air is made at the first decompression step, a sufficient decompression does not require 316 min, but only 170 min. If 100% oxygen is breathed instead of air, 83 min suffices. In experiment CO-120 the change to breathing air at full pressure was made after 45 min and then decompression was effected with 100% oxygen; with this sequence a decompression of 35 min suffices. It is shorter than decompression with 100% oxygen after breathing air for 120 min at 4.0 bar, which requires 45 min. Information concerning the half-value times that are critical at the end of decompression is given by Fig. 2–6. These experiments prove the usefulness of assuming for a every compartment or tissue with a given perfusion, rate that the equalization of pressure with helium will be 2.65 times as fast as with nitrogen.

In experiments BB-120 and BO-120 nitrogen is released during the entire exposure to overpressure. In experiment BA-120 at full pressure helium is absorbed and nitrogen released, but during decompression helium is eliminated from all compartments and nitrogen absorbed. Experiment CO-120 is characterized by the fact that at full pressure at first helium is absorbed and nitrogen released and then helium is released and nitrogen absorbed; finally, during decompression helium and nitrogen and eliminated simultaneously from all compartments. In experiment CO-300 the procedure was the same. With this length of exposure the slow tissues determine the decompression time, so that only a slight reduction in decompression time is made possible by the change from helium to nitrogen, as shown by a comparison with experiment AO-320 (Table 7). This experimental procedure proves that the ZH-L_{12} system is applicable also there is countercurrent diffusion of helium and nitrogen.

For the decompression of each compartment the sum of the pressure of helium and of nitrogen is always decisive.

The coefficients of the ZH-L_{12} system were tested for short and long half-value times up to those in the range of 57 bar. Each of the asterisks on the lines of Figs. 11 and 12 denotes a minimum of three different subjects for whom the half-value time of helium at decompression led to the pressure of inert gas indicated on the abscissa and who, at this pressure of the inert gas, were exposed to the ambient pressure indicated on the ordinate. The subjects showed at this point and for at least 6 h afterward no symptoms of an insufficient decompression.

The first decompression steps after saturation with helium, as shown in Table 13, are instructive [21, 27]. The rule for decompression after saturation dives that is recommended by the US Navy and also used by the British and French specifies that the rate of decrease in pressure after quickly reaching the first decompression step be dependent on the ambient pressure at an approximately constant partial pressure of oxygen. With this rule the decompression times for dives to great depths are two to three times as long as those with the Zurich system, but these much slower decompressions do not guarantee any greater safety from the occurrence of pains in the joints. In the US Navy Diving Manual pains in the joints of this kind after saturation dives are mentioned as "common" [26]. With the American rule the decom-

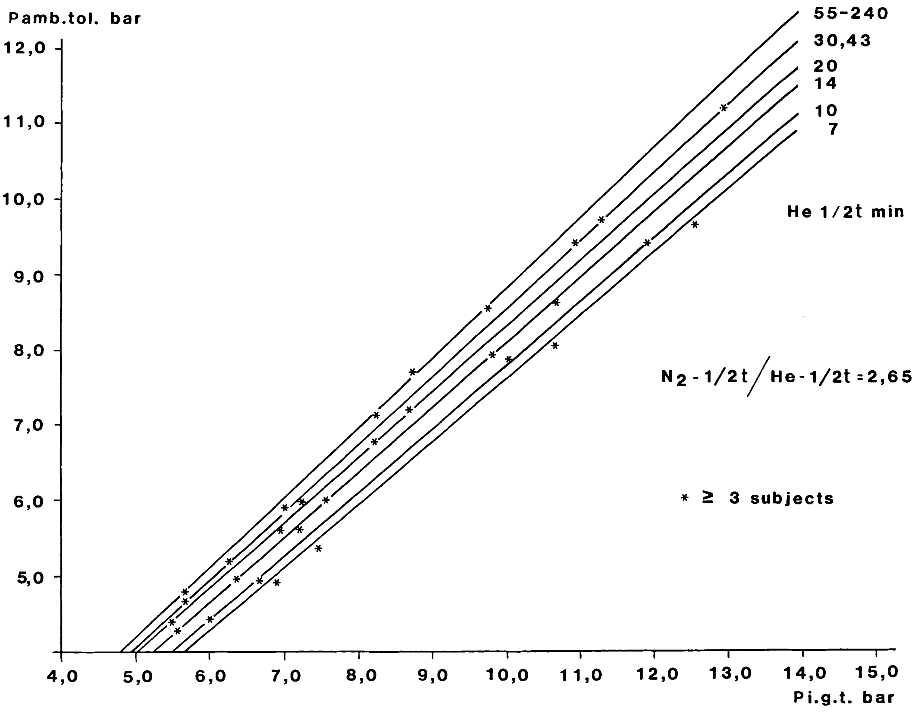


Fig. 11. ZH-L_{12}. Exposures with oxygen and helium. *Pressure of inert gas in the tissues with half-value times of 7–240 min for helium in at least three different subjects, at ambient pressure of 4.0–12.0 bar

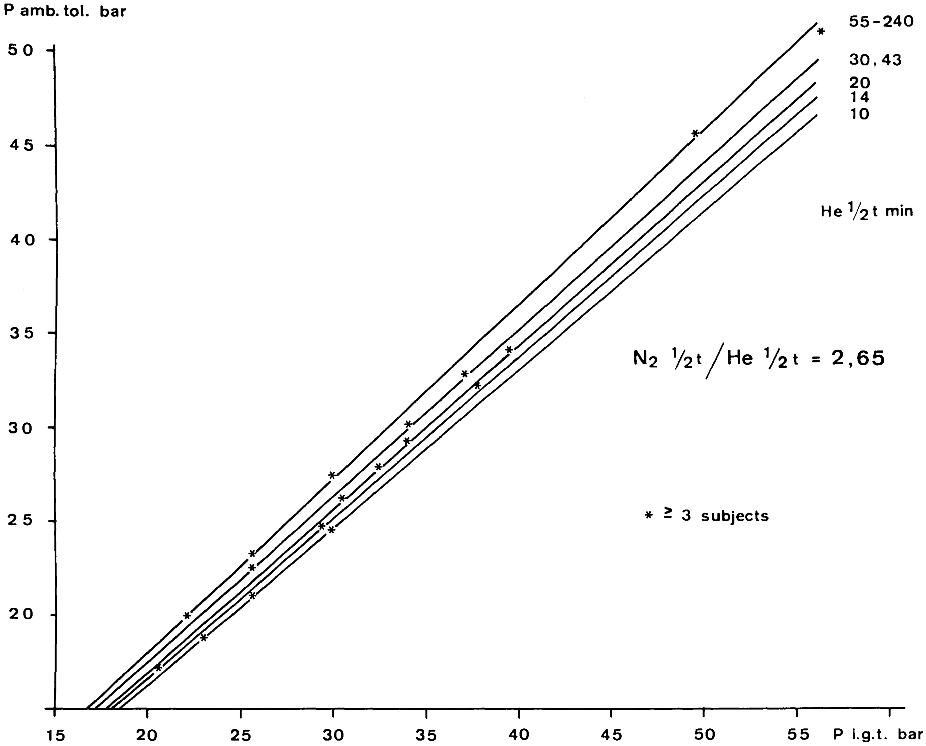


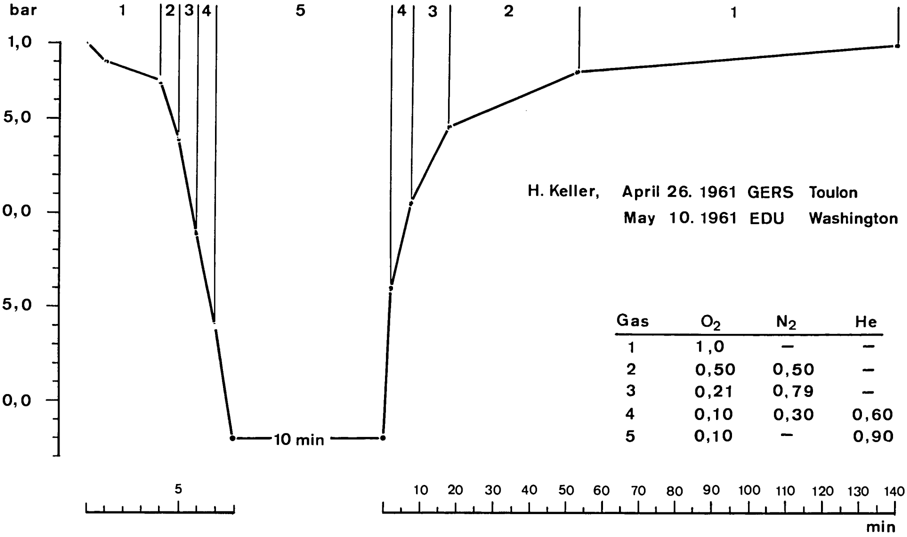
Fig. 12. ZH-L_{12}. Exposures with oxygen and helium. *pressure of inert gas in the tissues with half-value times of 10–240 min for helium in at least three different subjects, at an ambient pressure of 15–50 bar

Table 13. Saturation trials with oxygen and helium, first decompression stops; in the breathing gas, PO_2 0.4–0.6 bar, PN_2 0.7–0.8 bar; rate of ascent 1.0 bar/min

Pressure of exposure	bar	4.0	9.0	22.5	26.0	30.4	50.0
Pressure of inert gas	bar	3.4	8.5	22.0	25.5	29.9	49.5
Effective pressure at first decompression stop	bar	2.6	7.6	19.8	23.1	27.3	45.6
First stop in correspondence with ZH-L_{12}	bar	2.8	7.5	20.0	23.2	27.3	45.4
Number of subjects	*n*	6	3	10	3	6	3

pression is slower to an ambient pressure of about 2.5 bar, then from 2.5 to 1.0 bar, in the case of an increased partial pressure of nitrogen, faster than with the ZH-L_{12} system.

In 1961 Keller demonstrated two dives in the water-tanks of the French Navy in Toulon and of the US Navy in Washington. These comprised compression in 8 min to 22.0 bar, 10 min stay with light work in water, and continuous decompression to



Gas	O_2	N_2	He
1	1,0	–	–
2	0,50	0,50	–
3	0,21	0,79	–
4	0,10	0,30	0,60
5	0,10	–	0,90

Fig. 13. Exposures of 10 min at 22.0 bar. Course of compression and decompression

normal pressure in 140 min. The experts were impressed, especially by the short and obviously well-tolerated decompression. On 25 April 1961 Keller had already demonstrated a dive with a stay of 15 s at 30.4 bar with a decompression lasting only 31 min. These dives, which had been prepared in Zurich by means of the combination of overpressure and negative pressure in a small pressure chamber, involved exposures to a mixture of gases with a clever change in gases breathed during compression and decompression (Fig. 13). The calculation of these dives with the ZH-L_{12} system shows that the dives had essentially been in the safe range. Keller had risked only slight symptoms affecting the skin and light pains in the joints, which, however, did not occur.

3.7 Summary of the Arguments for the ZH-L_{12} System

With the ZH-L_{12} system the decompression can be calculated for exposures of a few minutes to those to saturation with inert gases.

This calculation takes into consideration solely the equalization of pressure with inert gases for a variety of half-value times and is based upon simple measured values such as pressure, time, and the fraction of inert gas in the breathing gas.

The coefficients for the calculation of the tolerated ambient pressure are based upon empirically determined values and can be adapted to new results without changing the system.

The system is applicable for every breathing gas that is composed of oxygen, nitrogen, and helium, whether or not nitrogen and helium are simultaneously or reciprocally absorbed or released or the equilibration of helium occurs at a constant pressure of nitrogen.

For conventional dives using air the system gives courses of decompression that, with roughly the same total length of decompression, lie between those of the US Navy and those of the Royal Navy.

With the system it is also possible to calculate decompression for less than normal ambient pressure; the coefficients are in agreement with the experience in aviation medicine of tolerances in fast ascents without a pressure cabin.

The system also takes into consideration the lower tolerance of the slow tissues toward nitrogen than toward helium. The half-value time of 90 min for helium corresponds to one of 238 min for nitrogen in whole blood, and to those of 115–240 min for helium and 304–635 min for nitrogen in a mixture of whole blood with 12.0% fat; for these half-value times ZH-L_{12} yields identical values for the excess volumes of gas that are dissolved (Fig. 14).

The linearity of the relation between ambient pressure and that pressure of inert gas in the tissue that is tolerated without symptoms of an inadequate decompression was tested for a wide range of half-value times of nitrogen and helium. It was also possible to take into consideration the partial pressure of nitrogen in tissue to an ambient pressure of 0.47 bar and the partial pressure of helium in tissue to an ambient pressure of 50.0 bar.

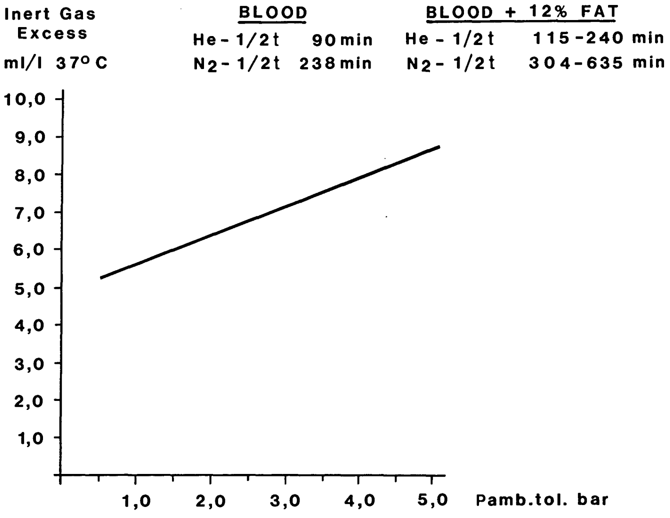


Fig. 14. ZH-L_{12}. Excess volume of the inert gas as function of the ambient pressure (P i.g.t. – P amb.tol.), coefficient of solubility. For the half-value times of 90 min for helium the values a = 0.555 and b = 0.918 were assumed

3.8 Rules for the Calculation of Decompression Tables

3.8.1 Decompression Tables and Individual Decompression

Decompression tables are based upon empirically determined and statistically more or less safe tolerances. They are valid for "normal" persons as well as simple conditions with regard to duration of compression and stay at full pressure. The adjustment of the tabular values to complicated exposures with frequent changes in pressure cannot be optimal, because for safety reasons the rules for adjustment always take into account an exposure that is longer than the actual one.

This unsatisfactory situation could be improved essentially by the use of a small computer that would show the diver continuously the tolerated ambient pressure and, for the decompression, the stay that is necessary at each and every step as well as the total decompression time. With such a device the rules for the use of decompression tables for repeated dives as well as special tables for dives at altitude would become unnecessary; it would be very useful, too, for dives repeated daily and those of some hours' duration. As long as only air is breathed and either air or pure oxygen during decompression, the technical and financial cost remain modest for such a small computer to calculate from the known values of pressure and time the decompression necessary at the effective exposure, using for example the ZH-L_{12} system. However, no such computer is on the market; it would, as the tables do, utilize collectively valid tolerances, but not individual ones.

Gas bubbles in the blood, and also partly in the tissues, can be demonstrated ultrasonically. This possibility leads to the idea of regulating the decompression individually with ultrasonic detection of the bubbles. One difficulty is the selection of positions that are appropriate for the detection. In the region of the cervical veins and carotid artery gas bubbles may be found frequently, especially with the considerable reduction in pressure to the first decompression step found in the rules of the US Navy, without symptoms of decompression sickness arising if decompression is then continued according to the table. This is as true for dives when breathing air as for the return from an excursion dive to the saturation level when breathing helium. Conversely, divers have often reported pain in the joints after long exposures and exposures to saturation, although no gas bubbles were recorded by sonography. Despite years of effort in various laboratories there has so far been no success in developing a method to analyze the number and size of the bubbles as a basis for a correlation with the risk of decompression sickness. However, such a correlation would be a precondition for an individual regulation of the decompression by means of sonography. For the moment decompression tables and rules for decompression remain indispensable.

3.8.2 Dives Using Air

The breathing of compressed air has for the calculation of decompression tables the advantage that the fraction of nitrogen in the breathing gas, 0.79, is known and constant. Exception would only exist in badly ventilated caissons and hyperbaric chambers whose use should, however, be prevented by appropriate regulations.

Decompression tables for dives with air should not be designed for conditions at sea level alone, but also for dives at above sea level. For the sport diver it is difficult to carry out decompression at steps of less than 2–3 m in the water, corresponding to differences of pressure of 0.2–0.3 bar. The internationally used interval of 3 m between steps has proved reliable.

The length of compression or descent should be freely determinable for sport diving, from which is derived the rule that the descent time should be used for the time of exposure at full pressure. With regard to depth a safety margin of 0.2 bar is reasonable. If an initial partial pressure of nitrogen of 0.75 bar in all tissues and an ambient pressure of 0.95 bar at the end of the decompression are taken into consideration, the table is usable for seawater as well as for fresh water up to 700 m above sea level.

If the decompression is effected in water, it is possible, before completing the last decompression step to emerge safely for the purpose of orientation for 1 min and then return to the decompression level.

For dives above sea level it is important to take into consideration whether the divers reach the mountain lake very quickly, for example, by helicopter, and then dive immediately, or whether they have been at the height for some time and so start their dives with a subnormal partial pressure of nitrogen in their tissues.

In Switzerland in 1973 decompression tables were developed for breathing air at five heights, the greatest at 3200 m above sea level, where the ambient pressure is 0.68 bar. These tables were then tested with controlled dives for 3 years in the Swiss Army and by the Lake Police before being published in 1976 [7]. Use of the ZH-L_{12} system has produced some changes and improvements for those exposures that particularly interest sport divers.

Decompression tables for repeated dives with air, for example, those of the US Navy, take 240 min as the longest half-value time of nitrogen, which is inadequate for dives that are repeated daily, as on diving vacations or by professional divers. For these conditions, the longer half-value times of nitrogen, with the lower tolerance toward nitrogen shown by the slow tissues, must also be taken into consideration.

Exposures of some hours, usual for professional divers and caisson and tunnel workers, require longer decompression time than are often used if permanent damage to joints and bones is to be prevented. If the exposure to overpressure, including that during decompression, is limited to 5–6 hours per day as well as to 5 days per week, prolongation of the decompression becomes unnecessary when intervals breathing air at normal pressure of 16 h between two working days and of 48 h over each weekend are maintained.

The ratio of working time at full pressure to duration of decompression may be improved markedly by enrichment of the breathing gas with oxygen and decompression with pure oxygen. At an ambient pressure of 3.0 bar while breathing 65% nitrogen and 35% oxygen the inspiratory partial pressure of nitrogen is 1.91 bar and that of oxygen 1.03. With this mixture of gases it is possible to work 4–5 h daily at 18–20 m; the subsequent decompression with pure oxygen requires only 20 min. At greater depths the working time is reduced, and for shorter working times a higher inspiratory partial pressure of oxygen is tolerated. For work at greater depths it is advantageous to have two periods of work daily with an interval between them of

3–4 at normal pressure. Table 23 in Appendix A gives information concerning the possibilities of daily periods of work in a range of 7–45 m depth when mixtures of nitrogen and oxygen are breathed. For the exposures to overpressure that are given in this table additional intervention dives without decompression have been taken into consideration.

Work with such mixtures of nitrogen and oxygen during daily exposures to overpressure proved its worth during the construction of the new Quai Bridge in Zurich. This method is much less costly than exposure to saturation and more comfortable for the divers.

3.8.3 Deep Diving Using Helium and Mixed Gases

In deep diving with helium as the inert gas the diver and his tender are transported to the working-place in a capsule. In the water he is connected with the capsule by a conduit cable for breathing gas, heating, energy, and communication. The decompression can take place in the capsule, but is predominantly carried out in a larger pressure chamber that is equipped for a stay of days or weeks and to which the transport capsule is affixed by a flange. Under these conditions it is possible to maintain exact descent times and course of decompression; decompression steps with differences in pressure of 0.1 bar are possible as well as continuous decompression.

The transport capsule and the pressure chamber are filled with air at normal pressure. If the nitrogen is not flushed out with helium for the dive, the inspiratory partial pressure of nitrogen remains constant at 0.75 bar during compression and exposure to full pressure, but decreases during decompression. The contamination with nitrogen is measurable during an exposure to overpressure, but not predictable in the calculation of the tables; analogously the fraction of oxygen in the mixture breathed is not exactly predictable. It is technically possible to achieve the desired mixture of helium and oxygen in the pressure chamber independent of pressure. Many diving companies prefer, however, to fill the chamber with a mixture of gases prepared in advance. For logistic reasons the number of mixtures of oxygen and helium is limited. These prerequisites explain why diving companies use their own decompression tables that have been developed for the particular needs from their own experience.

With a small computer the proper decompression can be calculated with the ZH-L_{12} system from the pressure, time, and measured composition of the gases. However, for reasons of safety, tables should be within reach at all times.

In collaboration with the diving company Sub Sea Oil Services, the following rules have proved valuable for the calculation of tables:

1. A safety margin equivalent to a pressure of 0.3 bar should be added to the depth.
2. The rate of compression should be 1.0 bar/min.
3. A partial pressure of helium corresponding to the intended mixture of gases should be considered, whereas for the partial pressure of oxygen a value that is 0.1 bar less and for the partial pressure of nitrogen a value that is 0.1 bar more should be included in the calculation.

In dives with helium as the inert gas the decompression time, especially after intervention dives (bounce-diving) with stays of up to 60 min, can be shortened considerably if, for example, from 4.0 bar (30 m) air is breathed. An additional reduction is possible by breathing pure oxygen from 2.0 bar. Thus there result for every dive four courses of decompression and a very voluminious table for the range of 60–180 m.

Because of the fast equalization of pressure with helium the slow tissues even limit the speed of final decompression in bounce-diving. Then, however, on the surface helium is released quickly when air is breathed. After an interval of 24 h while breathing air at normal pressure, the next dive with helium may be undertaken without a supplement for the decompression.

3.9 Saturation Diving and Excursions

The calculation of decompression with the ZH-L_{12} system is very simple because for helium only the half-value time of 240 min must be considered and for nitrogen, only that of 635 min; these times are somewhat variable for the slow tissues depending on physical activity. Formerly we took this into account in some cases by a somewhat slowed decompression during the night; the US Navy interrupts the decompression from midnight until 6:00 A.M. and from 2:00 until 4:00 P.M. The advantage of this interruption in regard to frequency of pains in the joints is doubtful. In the majority of exposures to saturation that were executed in or controlled from Zurich the course of decompression remained uninfluenced by the time of day. Because of the slower equalization of pressure with nitrogen, 2.65 times as long as with helium, saturation dives using nitrogen need markedly longer decompression than do those with helium (Table 14).

With ZH-L_{12} the limits for excursions from the saturation level can also be calculated. Without wearing thermally protective clothing stays of more than 2 h in water are an exception. For saturation dives with nitrogen as the inert gas, there is the simple rule that for an excursion that lasts 120 min the depth of the excursion is (the depth of saturation $\cdot 1.5) + 8$ m.

For example, at a saturation level of 10 m the maximal depth of the excursion is 23 m. From the depth of the excursion the ascent to the depth of saturation takes 2 min; after an interval of 120 min the next excursion of 120 min may be undertaken.

Table 14. Length of decompression after saturation with a PHe of 3.8 bar or a PN_2 of 3.8 bar, equivalent to the pressure at a depth of 30–32 m

		PHe 3.8		PN_2 3.8
First decompression stop (bar)		3.0	3.0	3.5
Composition of breathing gas during decompression	FO_2	0.21	0.21	0.21
	FHe	0.79	–	–
	FN_2	–	0.79	0.79
Length of decompression (h)		23	11	56

Decompression to normal pressure after an interval of 120 min, in conformity with the table, is calculated using the actual depth of saturation and a supplement of 5 m. From a saturation depth of 15 m, decompression requires 30 h if air is breathed from 10 m on.

These examples show that long exposures while breathing air and exposures to saturation with nitrogen are very uneconomical. In the range of 10–15 m depth of water, as explained in Sect. 3.8, the use of a mixture of oxygen and nitrogen is much more economical and offers greater safety against later damage to bones and joints (see Table 23).

The replacement of nitrogen by helium is reasonable in regard to time of decompression for exposures to saturation even at shallow depths; it demands, however, a large technical investment. Deep diving is not possible without helium as the inert gas and pressure chambers. The effective working time in water is always limited, so that the excursions from the depth of saturation have much practical importance. Because of the fast equalization of pressure with helium a differentiation commensurate with the duration of the excursion is necessary because the possible depth of excursion decreases with increasing duration:

Duration of excursion	to 60 min	to 120 min
Depth of excursion in meters	(Depth at saturation ·1.16) + 11 m	(Depth at saturation ·1.13) + 9 m
Duration of interval at saturation level	120 min	120 min

The decompression after the interval at the depth of saturation is in correspondence with the table for the effective depth at saturation plus 10 m.

An example: When at a saturation depth of 200 m the desired duration of the excursion to 243 m is 60 min, after an interval of 120 min at 200 m the next excursion may be undertaken or the decompression corresponding to saturation at 210 m may be initiated.

Between the saturation depth and the first step of decompression as many excursions and as long as are desired may be undertaken; no time limit exists for such excursions. The simple rules for excursions of the US Navy are based upon this principle [26]. From a saturation depth of 250 m it is possible to descend to 305 m for as long as desired and then ascend in 4 min again to 250 m; decompression then begins at 250 m. Figure 15 presents a comparison of that method with that of Zurich. The depth of excursion in Zurich is 301 m for two excursions of 60 min each with an interval of 120 min at 250 m. After a second interval of 120 min at 250 m, the decompression to correspond with a saturation depth of 260 m is begun. The depth of excursions of unlimited duration is only 280 m.

After 24 h of decompression, without taking into consideration the interruption of 8 h daily, by the US Navy rules a depth of 208 m is reached. With the ZH-L_{12} system depths of 171 m and 185 m are reached after 24 h. For saturation diving, the same result is shown as that from the comparison with the standard air-decompression

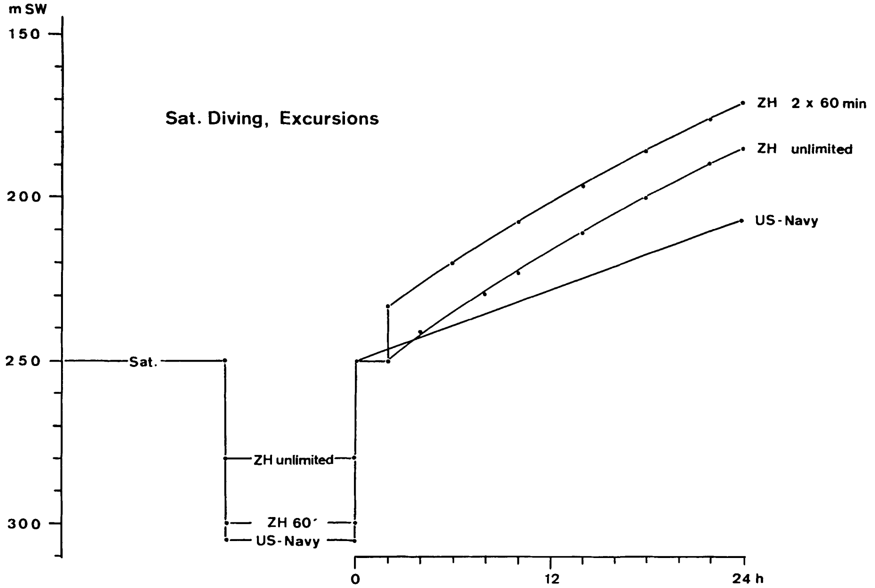


Fig. 15. Excursions during saturation with helium. Example: Saturation at 26.0 bar (250 m). The US Navy allows in excursion of unlimited duration to 305 m, which corresponds to the Zurich rule for two excursions of 60 min each. An excursion of more than 240 m is permitted to no deeper than 280 m. The subsequent decompression is faster with the ZH-L_{12} system than with the method of the US Navy. For a true comparison neither decompression is interrupted for periods of rest

tables of the US Navy, i. e., the difference between depth of exposure and the depth of the first stage of decompression is larger than that of the ZH-L_{12} system resulting in a slower decompression.

3.10 Flying After Diving

In a mountainous country such as Switzerland diving at a lower than normal ambient pressure is of practical importance for both professional and amateur divers. In the mountains it is also necessary to know the period of time that must have elapsed at the surface before the ambient pressure may be reduced additionally to travel over a pass. After every dive the same problem is posed for flying.

The results of a first comprehensive series of corresponding experiments with decompressions to a subnormal ambient pressure, were published in 1973 [14]. They made it possible to calculate decompression tables for dives with breathing air at 4 different ranges of altitudes to 3200 m above sea-level. These tables with rules for repeated dives and for the length of the interval at the surface before reducing the ambient pressure again have been tested by controlled dives in mountain lakes by Swiss army divers [7]. Not a single case of decompression sickness after a dive above sea level became known in Switzerland in 1973–1983 although more than a hundred dives are undertaken each year at altitudes of 1000 to 2000 m above sea level.

Decompression in accordance with the coefficients of the ZH-L_{12} system prescribes for dives above sea level courses which are somewhat different from those in the tables from 1976, but provides practically the same value for the excess of nitrogen at the end of the decompression when the surface is reached. The new courses of decompression were tested by supplementary experiments for exposures to air and also to helium.

Joints and bones have the least tolerance to an excess of inert gas; they also release this excess only very slowly. Therefore the pressure of the inert gas in the compartments with half-value times of 304–635 min for nitrogen and corresponding half-value times of 115–240 min for helium is decisive for the duration of the interval at the surface. Table 15 and Figs. 16–18 give information concerning the arrangement of the experiments and the decompressions which were performed. During the exposures to overpressure and during decompression subjects delivered 80 W for 10 min in each hour on the bicycle ergometer. After an interval at the surface lasting 60 min at 1.0 bar or 95 min at 0.9 bar in trial AA-60 and 200 min at 0.9 bar in trial AA-120.2 breathing air and having lunch, the pressure was reduced in 2–5 min to the given values and kept constant for 120–180 min. At the simulated altitude air was breathed and work was performed on the bicycle-ergometer during 10 min in each hour. In computing the "correct" decompression the value was again rounded, as mentioned in Table 8 (see Sect. 3.5.2).

The effective decompression in experiment AO-120 briefly exceeded the tolerated limits for the half-value time of 53–79 min for nitrogen and in experiment

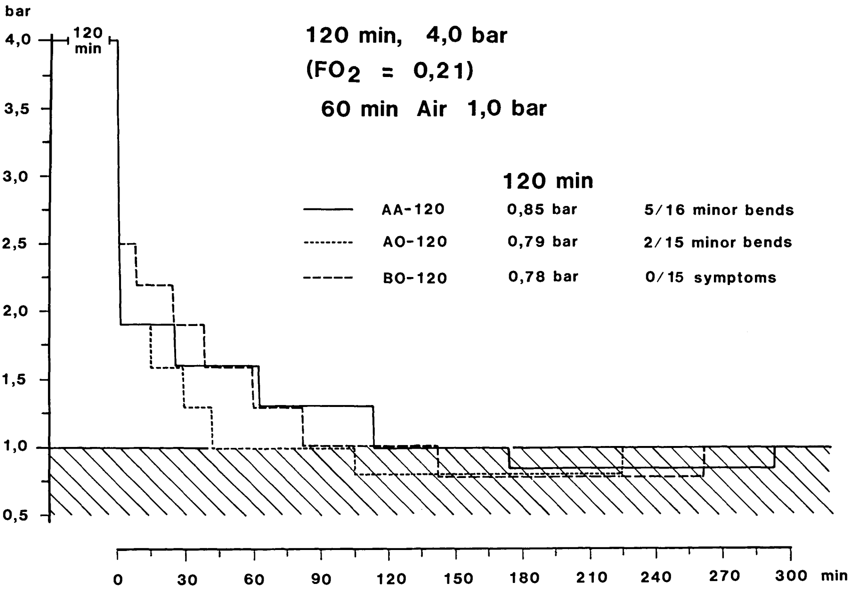


Fig. 16. Exposures with 21% O_2 and 79% N_2 or 78% He for 120 min at 4.0 bar. *AA-120* decompression breathing air, *AO-120* and *BO-120* decompression breathing 100% O_2 beginning at 2.5 bar. After breathing air at 1.0 bar for 60 min the ambient pressure is reduced for 120 min. (See Tables 10, 11 and 15)

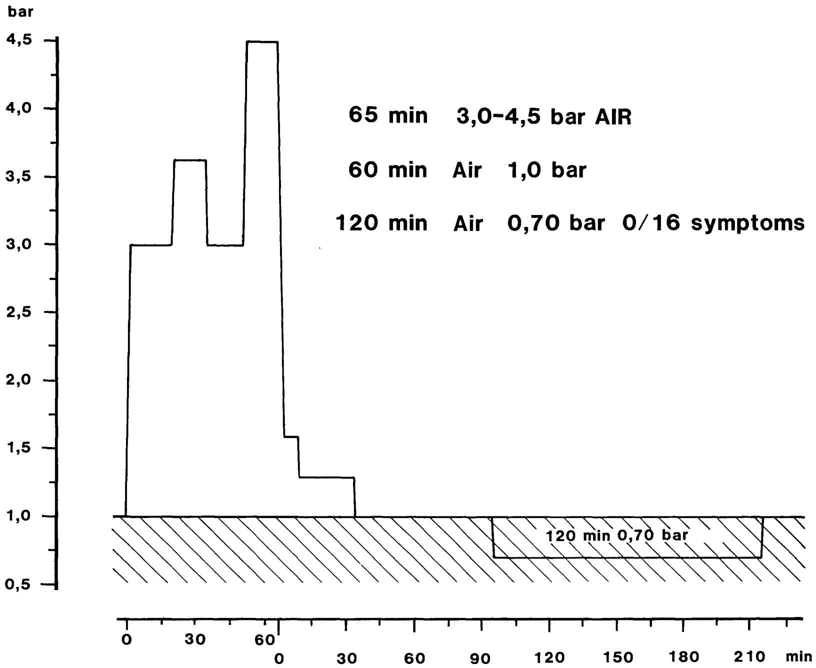


Fig. 17. Stage-wise exposure to breathing air 3.0–4.5 bar for 65 min. After breathing air at 1.0 bar for 60 min the ambient pressure is reduced to 0.70 bar for 120 min. (See Tables 10 and 15)

AA-120 briefly exceeded those of 79–114 min and that of 304 min. In both experiments, after the interval at the surface the ambient pressure was reduced significantly more than in correspondence with the half-value time for nitrogen of 304 min. Seven of the 31 subjects reported discrete pains in one shoulder or in the knees at reduced ambient pressure. The pains decreased spontaneously during a 120-min stay. In the other exposures to air and to helium, as indicated in Table 15 and Figs. 16–18 the reduction in the ambient pressure after the interval corresponded to the coefficients of the ZH-L_{12} system. In these experiments no symptoms of inadequate decompression occurred.

These results confirm the utilizability of the decompression method based on a linear relation between the tolerated overpressure of the inert gas in tissue and the ambient pressure, also above sea level (see Fig. 9). In the trials AA-60 and AA-65, the reduction of the ambient pressure was limited by the half-value time of 304 min for nitrogen and in the trial AA-120.2 by the half-value time 397–635 min. The well-tolerated reduction of the ambient, pressure to 0.47 bar after saturation with air at 1.0 bar confirms these results.

The tolerance of the slow tissues to an overpressure of helium is significantly greater than to an overpressure of nitrogen (Sect. 3.4.4). Additionally, at the surface helium is released faster than nitrogen, so that for dives using oxyhelium and a minimal amount of nitrogen significantly shorter intervals at the surface are needed than after air dives. In the experiment BO-120 at 4.0 bar helium is taken up and ni-

Table 15. Experimental bases for the coefficients of ZH-L_{12}

Decompression to subnormal ambient pressure after saturation with air at 1.0 bar (A-Sat. 1.0) and after hyperbaric exposures breathing air of oxyhelium

Trial	*n*	bar	min	O_2	N_2	He	Decompression			bar	Symptom
							min	O_2	N_2		
A-Sat. 1.0	16	1.0	Sat	0.21	0.79	–	15	0.21	0.79	0.47	0/16
AA-120	16	4.0	120	0.21	0.79	–	114	0.21	0.79	1.0	1/16[b]
AO-120	15	4.0	120	0.21	0.79	–	43	1.0	–	1.0	0/15
AA-65[a]	16	3.0–4.5	65	0.21	0.79	–	36	0.21	0.79	1.0	0/16
AA-60	12	4.2	60	0.21	0.79	–	61	0.21	0.79	0.90	0/12
AA-120.2	12	4.2	120	0.21	0.79	–	176	0.21	0.79	0.90	0/12
BO-120	15	4.0	120	0.21	0.01	0.78	82	1.0	–	1.0	0/15

Inert gas pressure of the leading compartment after breathing air at 1.0 bar for 60 min, at 0.9 bar for 95 min (AA-60), or at 0.9 bar for 200 min (AA-120.2).

Trial	N_2 ½ t min	PN_2 bar	He ½ t min	PHe bar	Decompression		Altitude	
					correct bar	performed bar	min	Symptoms
A-Sat. 1.0	*635*	0.750	–	–	*0.48*	*0.47*	120	0/16
AA-120	238	1.260	–	–	0.84			
	304	1.206	–	–	*0.92*	*0.85*	120	5/16[b]
	397	1.142	–	–	0.86			
AO-120	238	1.186	–	–	0.77			
	304	1.132	–	–	*0.85*	*0.79*	120	2/15[b]
	397	1.068	–	–	0.79			
AA-65	238	1.042	–	–	0.63			
	304	0.993	–	–	*0.71*	*0.70*	120	0/16
	397	0.949	–	–	0.67			
AA-60	238	1.026	–	–	0.61			
	304	0.992	–	–	*0.71*	*0.70*	120	0/12
	397	0.955	–	–	0.68			
AA-120.2	*397*	1.003	–	–	*0.72*			
	503	0.992	–	–	*0.71*	*0.70*	180	0/12
	635	0.966	–	–	0.69			
BO-120	304	0.514	115	0.673	0.74			
	397	0.556	*150*	0.680	*0.79*			
	503	0.586	*190*	0.649	*0.80*	*0.78*	120	0/15
	635	0.616	*240*	0.598	*0.79*			

[a] See the profile in Fig. 17

[b] Minor bends in the shoulder or the knee, decreasing or disappearing at constant pressure at altitude

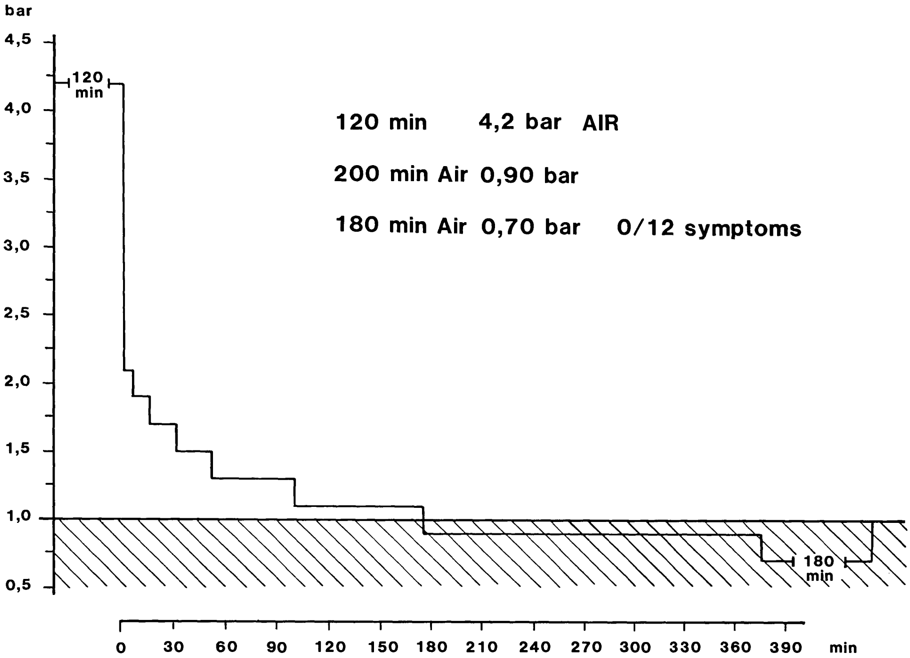


Fig. 18. Exposure to air at 4.2 bar for 120 min and decompression with breathing air. After breathing air at 0.90 bar vor 200 min the ambient pressure is reduced to 0.70 bar for 180 min (see Tables 10 and 15)

trogen is simultaneously released. During the decompression breathing pure oxygen both inert gases are released. During the following interval at the surface breathing air, helium continues to be released and nitrogen is taken up. At reduced ambient pressure both gases are again released. This example shows that a countercurrent diffusion of helium and nitrogen between the lungs and the blood as well as between the blood and the tissues does not reduce the tolerance as long as an equalization of pressure for helium is used which is 2.65 times as fast for a given compartment (Sect. 3.6.2). In the experiment BO-120 the fraction of nitrogen in the leading compartment, with a half-value time of 190 min for helium and the corresponding half-value time of 503 min for nitrogen, is 0.41 at the end of the decompression and is then 0.47 at the end of the interval at the surface with breathing air for 60 min (see Table 15).

The intervals that are recommended in the Figs. 19 and 20 include a safety margin. For the dive AA-120 a surface interval of 90 min is given to reduce the pressure to 0.92 bar. After a saturation dive with helium where the fraction of nitrogen at the end of decompression is 0.50, a surface interval of 180 min is required before reducing the ambient pressure to 0.79 bar in correspondence with Fig. 19. In the BO-120 experiment 60 min sufficed. The supplements also took the variations in atmospheric pressure at a given altitude into consideration.

For aircraft with and without pressurized cabins the pressure corresponding to one at 2500–3000 m above sea level is important. After saturation with helium with

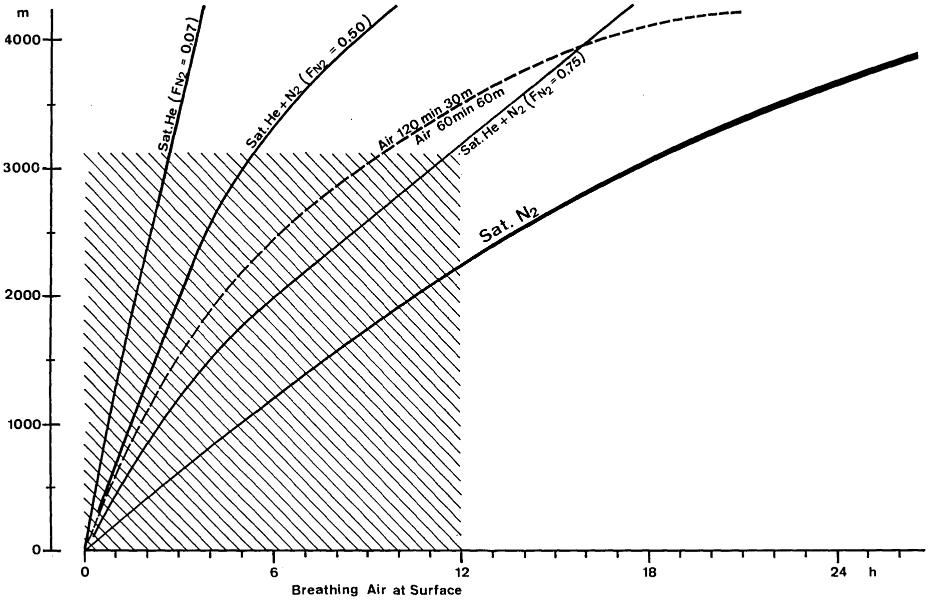


Fig. 19. Flying after dives. The length of the necessary interval at the surface depends on the duration of the dive and on the breathing gas; the slow tissues have a limiting effect. Helium is released fast when breathing air, nitrogen, only slowly. Dives of 120 min to 30 m with air or 60 min to 60 m require a longer interval at the surface with air than do dives with saturation by helium and a proportion of nitrogen of 0.5 in the slow tissues. The permitted altitude above sea level is added to that at which the dive took place

a very small fraction of nitrogen in the slow tissues, a condition that occurs breathing a mixture of oxygen and helium during the whole exposure, ascent to 3000 m above seal level may be undertaken even after a surface interval of 3 hours. If, however, there is saturation with nitrogen, a surface interval of 18 hours is needed. If in diving with mixed gases air is breathed during the decompression, the pressure of nitrogen in all tissues increases markedly. If the nitrogen fraction at the end of the decompression is 0.75, the interval at the surface before ascending to 3 000 m above sea level should last 12 hours. Air dives to a depth of 30 m lasting 120 min as well to 60 m and lasting 60 min require the same surface interval before ascent to 3000 m above sea level may be undertaken without risk of pains in the joints.

For dives at subnormal ambient pressure a somewhat longer decompression time is needed for a given depth and bottom time than at normal ambient pressure (see Table 24.3). The ZH-L_{12} system is based on a linear relationship between the tolerated overpressure of inert inert gas in tissue and the ambient pressure. Breathing air with the decreasing ambient pressure yields a linear reduction in the tolerated excess of nitrogen and in the gradient between the pressure of nitrogen in tissue and in inspired air. The part of this pressure gradient that is important for the equalization of the inert gas pressure increases exponentially with decreasing ambient pressure. The atmospheric pressure does not decrease linearly with increase in altitude. These conditions explain why the curves in Figs. 19 and 20 are not only valid at sea

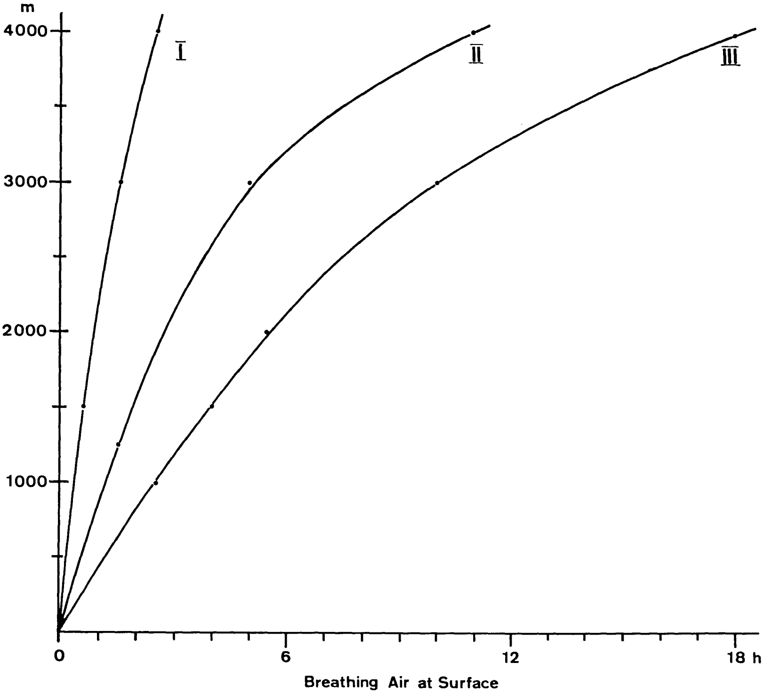


Fig. 20. Flying after dives for sport divers. *I*, Single dives without decompression, but more than 12 m deep, at 0–700 m above sea level or more than 9 m deep at higher altitudes. *II*, Single dives without decompression, not more than 12 m deep at 0–700 m above sea level or not more than 9 m deep at higher altitudes, as well as single dives with decompression up to 120 min. *III*, Dives of more than 120 min, repeated dives, diving vacations

level, but also for dives in mountain lakes. For these dives the height above sea level that is allowed after the surface interval is added to that at which dive is done.

Experiment AA-120.2 illustrates this situation. After an exposure to breathing air at 4.2 bar for 120 min, decompression to 1.0 bar takes 120 min. Then if an interval of 200 min is interposed the ambient pressure may be reduced to 0.80 bar. In this experiment the ambient pressure was in fact reduced to 0.9 bar in 176 min. After an interval of 200 min at 0.9 bar the ambient pressure was reduced to 0.70 bar without symptoms of inadequate decompression appearing.

The rules that were recommended in 1982 by The United Kingdom Diving Medical Advisory Committee for flying after diving prescribe very long surface intervals. After every kind of dives breathing mixed gases an interval of 12 hours at the surface is demanded before ascent to 2400 m above sea level is possible. For air dives lasting more than 4 hours, just as with saturation dives with air, a surface interval of 48 hours is recommended. These rules are not based, however, on limits that determined systematically by experiment; they also consider neither the experience of aviation medicine nor the experience accumulated in Switzerland in regular dives in mountain lakes for 10 years. Unnecessarily long intervals or unnecessary limitations on altitude during flying may cause risks when a diver must be transported despite unfavorable weather.

3.11 Testing Decompression Tables

No internationally binding rules for testing decompression tables exist. The confidence in the available tables is supported by the reputation of the institutions that recommend them, such as the US Navy and the Royal Navy. The tables that are preferred by some sport divers, the old tables of the French Navy (GERS) give, however, sometimes somewhat shorter, but also occasionally somewhat longer decompression times than those of the US Navy. In all these tables the results of hyperbaric experiments and experience with actual dives have been taken into account. Even with the inclusion in these tables of additional safety factors, the experimentally established tolerance levels have not been fully exploited. For these safety supplements there also exist no generally recognized rules, although there is certainly general agreement that tables of this kind are valid for healthy divers only. Especially in the presence of impairment of the circulatory system, symptoms of insufficient decompression may occur even with the use of very safe decompression tables.

The ZH-L_{12} system, with which decompression can be calculated for every exposure to an inert gas, was widely tested experimentally with nitrogen and helium. In these experiments the real duration of compression and bottom time as well as the real composition of the breathed were used. The decompression in each case paralleled exactly that calculated within ± 0.1 bar.

To calculate the tables intended for real dives, the time for descent was included in that of the stay at greatest pressure, the full pressure for diving with air increased by 0.2 bar, that for diving with helium, by 0.3 bar (compare Sects. 3.8.2 and 3). Testing the tables for helium is best carried out during training dives for professional divers. The tables for helium developed in Zurich have been used by the Sub Sea Oil Services since 1970, while tables corresponding to the ZH-L_{12} system have been edited in 1981.

4 Decompression Sickness

4.1 Pathogenesis

Gas bubbles that lead to a capillary obstruction and then to an ischemically conditioned hypoxia are the initial cause of decompression sickness. The obstruction may be classified as one of two kinds:

(1) arterial gas embolism as a consequence of either a central rupture of the lung (burst lung) or explosive decompression (blow up);

(2) formation of gas bubbles in tissues (autochthonous gas bubbles).

The precondition for the pulmonary barotrauma is an impaired flow of gas out of the alveoli through the respiratory tract when the ambient pressure is reduced. The duration and degree of the exposure to overpressure as well as the speed of ascent are less important (see Sect. 3.2.2). If the ambient pressure decreases more than 2 bar/min, so many gas bubbles may form in the arterial blood that disturbances of vision and unconsciousness may occur. It is also possible for this to occur in brief exposures to high pressure at depths of more than 30 m (see Sect. 3.4.1).

Gas bubbles form in the tissues during decompression when the difference between the inert gas pressure in tissue and the ambient pressure exceeds the tolerable limits. Autochthonous gas bubbles in the various organs are only possible, as a result of the different rates of blood supply to the organs and the varying half-value times, with corresponding times of exposure. With an explosive decompression, a "blow-up" after exposure to high pressure that requires decompression, gas bubbles can ensue simultaneously in the arterial blood and in the tissues, so that arterial gas embolism and autochthonous gas bubbles combine to cause decompression sickness.

The symptomatology of decompression sickness is determined by the organ that is affected by the capillary obstruction. In the development of clinically relevant decompression sickness, the increase in volume of the gas bubbles in the capillaries is of great importance. In addition, there are secondary factors such as platelet aggregation, intravasal coagulation, and above all the formation of a perifocal edema with hemorrhage and displacement of fluid into the extravasal space. Different opinions exist regarding the gravity of these secondary factors, but there is agreement that recompression, which reduces the volume of the gas bubbles, and hyperoxia are the most important therapeutic measures. Voluminal substitution with plasma expanders and the prescription of steroids and aggregation inhibitors are additional measures that are useful in some cases, but which cannot replace recompression if the decompression sickness is affecting the nervous system, inner ear, and joints.

After the formation of the gas bubbles and before the appearance of the first definite symptoms of decompression sickness, there is a time of latency, which for the slow tissues, e.g., the joints, may be some hours. This variable time of latency makes difficult an exact determination of the critical moment of the preceding decompression, thus giving rise to the concept that it is always the initial phase with the largest reduction of pressure that is the cause of even those symptoms that arise much later. With the decompression that often lasts a number of days after saturation dives, very frequently there are no untoward symptoms for some days, then finally, however, pains in the joints are noted. This experience supports the opposing concept that every phase of decompression can be critical. It follows that the ambient pressure at every phase of the decompression must not fall below the minimum tolerated ambient pressure, which is dependent on the various half-value times.

4.2 Symptomatology

4.2.1 Decompression Sickness of the Central Nervous System

The causes of decompression sickness of the central nervous system include a gas embolism after barotrauma of a lung, explosive decompression (exceeding the maximum speed of ascent), and not maintaining the steps and times of decompression outside the limits for "dives without decompression".

The symptoms appear a short time after the event that has led to the formation of gas bubbles. The neural status shows mostly multifocal lesions, and if the brain is affected, confusion, vertigo, unconsciousness, and disturbances of vision are preeminent. Disturbances of motility and of sensation and paralyses, including disturbances of micturition, are symptoms of damage to the spinal cord. Damage to the inner ear is indicated by tinnitus, loss of hearing, vertigo, and vomiting.

Barotrauma of the lungs by itself often causes only light pulmonary symptoms. With an explosive decompression, with the possibility of gas bubbles and fat particles being carried by the systemic circulation to the lungs, pulmonary symptoms ensue facultatively, with dyspnea, cyanosis, pain in the chest upon breathing, and somewhat bloody expectoration.

Decompression sickness affecting the brain, spinal cord, and inner ear requires the fastest possible recompression so that permanent damage will be avoided. Lasting paralyses and symptoms of an affliction of the inner ear can usually be attributed to a lack of recompression or inadequacy of its duration and of the pressure at which it was executed. The most serious decompression sickness is that affecting the central nervous system and is frequent among amateur divers, seldom among professional divers.

4.2.2 Decompression Sickness of the Skin, Muscles, Bones, and Joints

The cause of this decompression sickness is the presence of gas bubbles in the organs as a consequence of inadequate decompression. In comparison with the central nervous system, the bones and joints require little blood, and the equalization of pressure with that of the inert gas occurs very slowly. This is why the sickness afflicts foremost professional divers and caisson workers, who are exposed to overpressures for hours or even days.

Decompression sickness of the skin exhibits itself with itching, red spots, and swellings. Stiffness of the muscles and soreness like that after sudden and protracted exercise indicate damage to muscles. These symptoms often arise only some hours after exposure to overpressure. Pains in the joints, above all the knees, hips, shoulders, and elbows, indicate damage to the joints and bones. With this form of "light" decompression sickness, which often arises only after some hours, recompression is urgently required to avoid enduring and incapacitating arthroses.

With extensive damage to the subcutaneous fatty tissue and the fatty bone marrow, gas bubbles and fat droplets can enter the lungs with the blood and then enter the systemic circulation from the lungs; in this way a very dangerous condition may develop [10].

4.3 Treatment

In an emergency the layman and the nonspecialized physician must be able to execute the treatment. A prerequisite is that at least the diving instructors and professional divers are trained appropriately. The recompression must be based on easily recognizable symptoms of decompression sickness. A standardization of this kind has proved its worth in the military domain.

The published therapy tables for recompression, e.g., those of the US Navy, are concerned with decompression sickness of the central nervous system, bones, and joints after conventional dives while breathing compressed air. The maximum pressure of recompression is 5.0 bar, which is as a rule sufficient for decompression sickness after dives to 50 m. Air is breathed during recompression. Over the last 10 years two tendencies have developed: the combination of recompression with enrichment of the breathing gas with oxygen, and in cases where symptoms of affliction of the central nervous system persist, the recompression is continued for several days. Both tendencies presuppose generously conceived pressure chambers that are impervious to oxygen.

Recompression to 5.0 bar is insufficient for a more or less complete remission of the symptoms in cases of decompression sickness of the central nervous system after an "extreme" dive while breathing air, i.e., breathing nitrogen as the inert gas at depths of more than 50 m. In such cases recompression with oxygen and helium at 8.0–9.0 bar, corresponding to a depth of 80–90 m, is indicated. The duration of treatment is not increased, since the nitrogen is released at full pressure when a mixture of oxygen and helium is breathed. When this method is used, the concentration of oxygen in the chamber must be measured continuously. The advantages of recompression with helium certainly exist, also for the "conventional" range with air, that is, for recompression at 5.0 bar. Since, however, air is nearly always used for recompression at this level, the experience with oxygen and helium only concerns individual cases.

For the conventional range with air as the breathing gas, the US Navy uses six different therapy tables. The difference between these and the four tables developed in Switzerland for this range is essentially relevant only in the case of persisting symptoms of damage to the central nervous symptom. In Zurich a longer treatment is provided for this situation, namely one of 48 h (Table 17 (II B), in contrast to only 38 h, as indicated by Table 4 of the US Navy. For the treatment of decompression sickness of the central nervous system after dives to depths of more than 50 m while breathing air, an additional therapy table with the indication for recompression to 90 m and breathing oxygen and helium was developed in Zurich. This table is also appropriate for recompression at pressures of less than 9.0 bar.

4.3.1 General Rules

For treatment in cases of diving accidents the following procedure has proved reliable:

1. Reanimation and attendance to external injuries; if spontaneous breathing is lacking, recompression may take place only after intubation and artificial respiration.
2. Protection against hypothermia is necessary.
3. With decompression sickness there is always danger of hypovolemia; for prophylaxis of the hypovolemic shock 8–10 ml human albumin/kg body weight should be given i.v.
4. In the presence of unconsciousness because of cerebral edema, 100 mg prednisolone is administered i.v.
5. The treatment center is notified and transportation of the patient is arranged.
6. If symptoms affecting the brain and/or spinal cord are present, or if there is severe pain in the joints, recompression is imperative.

Table 16. Treatment of decompression sickness with cerebral and/or spinal symptoms after dives down to 12 m with air

Therapy Table I: Recompression in a few minutes with a pressure of 1.9 ba (19 m)

	Breathing gas		
bar	Air (min)		100% oxygen (min)
1.9	15		
1.5	30		
1.2	60	or	30[a]
0.9	60	or	60
0.7	90	or	60
0.5	120	or	60
0.3	120	or	30
0			

8 h 15 min with air
4 h 45 min with pure
oxygen from 12 m

---

[a] Breathing pure oxygen is interrupted every hour by breathing air for 5 min

7. If there is pneumothorax, especially tension pneumothorax, without other symptoms of decompression sickness, puncture for relief and suction drainage should be performed with no recompression.

During treatment in the pressure chamber, rupture of a lung can occur with a gas embolism into the central nervous system, so that symptoms afflicting the brain or spinal cord arise. In this case recompression should take place at the full pressure of the therapy table that is used and kept constant for 3 h; immediately afterward decompression like that following saturation dive is effected. If the rupture occurs while breathing pure oxygen, no symptoms of an arterial gas embolism arise.

4.3.2 Decompression Sickness of the Central Nervous System

Dives not Exceeding 12 m. When decompression sickness with symptoms of injury to the central or spinal part of the nervous system occurs after diving to shallow

Table 17. Treatment of decompression sickness with cerebral and/or spinal symptoms after dives to 13–50 m with air

Therapy Table II: Recompression in a few minutes with a pressure of 5.0 bar (50 m)

A

After 30 min practically free of symptoms

	Breathing gas		
bar	Air min		100% oxygen min
5.0	30		
4.5	10		
4.0	15		
3.5	15		
3.0	15		
2.5	30		
2.1	60		
1.8	90		
1.5	120		
1.2	120	or	60[a]
1.0	120	or	60
0.8	120	or	60
0.6	180	or	30
0.4	180	or	30
0.2	120	or	15
0.2	120	or	15
0			

20 h 25 min with air
10 h 40 min with pure oxygen from 12 m on

B

After 30 min improved, but still with symptoms

	Breathing gas				
bar	Air min		100% oxygen min		Air min
5.0	90				
4.5	20				
4.0	30				
3.5	30				
3.0	45				
2.5	60				
2.1	120				
1.8	180				
1.6	240				
1.4	240	or	60	+	30
1.2	300	or	60	+	30
1.0	300	or	60	+	60
0.8	300	or	60	+	60
0.6	300	or	–		240
0.4	240	or	–		240
0.3	240	or	–		240
0.2	120	or	–		120
0					

47 h 35 min with air
34 h 35 min with pure oxygen from 14 m on

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[a] In II A breathing pure oxygen is interrupted every hour by breathing air for 5 min

depths, it is usually from an arterial gas embolism into the central nervous system following barotrauma of the lungs. Recompression to a pressure of 1.9 bar (19 m) for 15 min and then immediate decompression in correspondence with Therapy Table I (Table 16) is adequate. This table is also adequate in the case of inner ear disorders following barotrauma of the middle ear.

Dives to 13–50 m and Dives to Extreme Depths. These patients undergo recompression at 5.0 bar, corresponding to the pressure at 50 m, for 5 min. Further treatment ist determined, in correspondence with Therapy Table II (Table 17), by the improvement the symptoms affecting the nervous system.

In the case of a deep dive to, for example, 70 m when breathing air, recompression is with oxygen and helium at 9.0 bar (90 m).

If the chamber is not flushed, the partial pressure of nitrogen is the same as that at normal atmospheric pressure, 0.75 bar, which has been taken into consideration for

Table 18. Treatment of decompression sickness with cerebral and/or spinal symptoms after dives to depths of more than 50 m with air

Therapy Table III: Recompression with oxygen and helium with a 9.0 bar (90 m) the breathing gas at full pressure containing 8–10% oxygen and 82–84% helium[a]

	Breathing gas				Breathing gas		
bar	min	% O_2	bar	min	% O_2	min	%O_2
9.0	180	8	3.0	90	20		
8.5	10	8	2.8	120	20		
8.0	10	8	2.5	120	20		
7.5	15	8	2.2	120	20		
7.1	15	8	1.9	120	20		
6.7	15	8	1.6	120	20		
6.4	20	8	1.4	60	100	+ 30	20
6.1	20	8	1.1	60	100	+ 30	20
5.8	20	8	0.8	60	100	+ 30	20
5.5	20	8	0.6	60	100	+ 60	20
5.2	20	8	0.3	–	–	120	20
5.1	20	8	0				
5.0	20	15					
4.8	30	15	32 h 25 min				
4.6	60	15					
4.2	60	15					
3.8	60	15					
3.5	60	15					
3.3	90	15					

[a] It is not necessary to flush the pressure chamber with oxygen and helium before beginning the recompression.

The concentration of oxygen in the pressure chamber must be measured regularly; deviations of ±2% are acceptable. The temperature of the chamber should be 28–30 °C.

Therapy Table III can replace Therapy Table II for dives to a depth of 50 m. To do this, recompression is at 5 bar, after which, following a stay of 120–180 min, the pressure is reduced to 4.8 bar (48 m); the subsequent decompression accomplished in accordance with Therapy Table III

Table 19. Treatment of decompression sickness with cerebral and/or spinal symptoms. Treatment starts more than 48 h after symptoms first appeared

Therapy Table IV: Recompression in a few minutes with a pressure of 1.5 bar (15 m)

Pressure bar	Breathing gas 100% oxygen min
1.5	60[a]
1.0	60
0.8	30
0.6	30
0.4	30
0.2	30
0	
4 h	

[a] Breathing pure oxygen is interrupted every hour by breathing air for 5 min.
This treatment can be applied with an interval of 4 h twice in every 24 h

Therapy Table III (Table 18); the proportion of oxygen should be 8%. The pressure is kept constant equal to that at 90 m for 2–3 h. The proportion of oxygen is increased at 50 m to 15%, at 30 m to 20%. Between 14 and 6 m pure oxygen is breathed with interruptions.

This table can also be used for recompression at 5.0 bar, i. e., for recompression after a conventional dive to 50 m when breathing air. In this case, after a stay of 2–3 h at 50 m breathing 15% oxygen, it is possible to return to 48 m and then continue the decompression in correspondence with the Therapy Table III (Table 18).

If more than 48 h pass after the appearance of serious decompression sickness with neural impairment, the recoverability of the nervous tissue is of foremost importance. The gas bubbles have by then disappeared. In cases of this kind recompression at 5.0 or 9.0 bar achieves no rapid improvement, but recovery may be accelerated with the use of hyperbaric oxygen in correspondence with Therapy Table IV (Table 19). Individual observations suggest that better restitution is achieved with the use of hyperbaric oxygen in the treatment of the patients suffering from this type of decompression sickness than with a recompression lasting some days, corresponding to Therapy Table II B.

In 1979 an amateur diver had an accident during a dive to 40 m near the Maledive Islands. Partial paralysis of the arms and legs developed. Recompression to 50 m and then 60 m was begun about 15 h after the dive and brought no improvement. During the following treatment for 39 h in correspondence with Therapy Table IV of the US Navy a subtotal tetraplegia developed. The patient was always fully conscious and demanded that he be transferred to Zurich. He was flown by the Swiss Air Rescue Service, at normal pressure, to Zurich, which required 19 h. The therapy in correspondence with Therapy Table IV began 103 h after the dive, 48 h after the termination of the first treatment. The therapy with hyperbaric oxygen over 5 days yielded a spectacular improvement; 3 weeks later only a disturbance of fine motoric function and of the sensitivity in the region of the right arm as well as a slight spasticity of both legs were still evident. All of these symptoms regressed extensively in the course of the following years. The same treatment was used for a similar case with complete success. This patient was transported by aircraft at normal pressure from the Red Sea to Zurich 48 h after the dive.

4.3.3 Decompression Sickness of the Joints and Bones

Pains in the joints can arise toward the end of decompression following dives with air that last some hours and also some hours thereafter. Severe pains are an unconditional indication for recompression. If the pains lessen markedly as early as 10 min after recompression at 1.0 bar, decompression is begun in correspondence with Therapy Table V A (Table 20). If the pains persist or even increase, recompression is continued with an additional 1.5 bar, to the pressure at 25 m, and then the treatment is carried out in correspondence with Therapy Table V B.

Tabelle 20. Treatment of decompression sickness with pains in the joints (bends), difficulties at the end of decompression or later

Therapy Table V: Recompression in a few minutes with a pressure of 1.0 bar (10 m)

A				B			
Notable improvement after 10 min				No or only slight improvement after 10 min			
				Additional recompression at 1.5 bar			
	Breathing gas				Breathing gas		
Pressure bar	Air min		100% oxygen min	Pressure bar	Air min		100% oxygen min
1.0	10			2.5	10		
0.9	60	or	60[a]	1.9	15		
0.7	90	or	60	1.5	30		
0.5	120	or	60	1.2	60	or	30[a]
0.3	120	or	30	0.9	60	or	60
0				0.7	90	or	60
				0.5	120	or	60
				0.3	120	or	30
				0			
6 h 40 min with air 3 h 40 min with pure oxygen from 9 m on				8 h 35 min with air 5 h 5 min with pure oxygen from 12 m on			

[a] Breathing pure oxygen is interrupted every hour by breathing air for 5 min

4.3.4 Decompression Sickness After Deep Diving with Helium

In deep diving with oxygen and helium and with mixed gasses, decompression is always carried out in a pressure chamber. In contrast to amateur diving, professional divers can begin recompression without delay, but the divers and the supervisory personnel must be competent to interpret the symptoms of decompression sickness correctly.

The rules and tables for treatment of decompression sickness after exposure to overpressure while breathing air are usuable in an analogous sense for corresponding incidents in deep diving. Symptoms of central nervous origin in the presence of an arterial gas embolus caused by barotrauma of the lungs require recompression by 5.0 bar and breathing of oxygen and helium, at whatever depth the symptoms have arisen. The symptoms will subside quickly. In "bounce diving", after waiting for 60–120 min at a pressure that is increased by 5.0 bar, the decompression is begun in correspondence with the table for a stay of 180 min at the corresponding depth. If there has been a dive with saturation, the corresponding decompression table is valid. It is conceivable that, with a rupture of a lung, during decompression gas from the lungs will pass into the blood and then the symptoms of an arterial gas embolism arise. In this case too, recompression by an additional 5.0 bar is undertaken and the pressure is kept constant for 3 h, after which decompression follows corresponding to saturation at the pressure of recompression.

Explosive decompression occurs in deep diving only when there is a technical failure that leads to a sudden loss of pressure in the transport capsule or the pressure chamber. In such cases, which are fortunately very infrequent, there should be an immediate recompression to the pressure at the beginning of the sudden decrease or, if this is not known with certainty, to the full pressure of the preceding dive. Then, after a wait of 60–120 min decompression is carried out corresponding to that of a saturation dive. These general directives are somewhat theoretical since these procedures are not always possible if there is a technical fault in the pressure chamber.

Pains in the joints are relatively frequent in deep diving with helium and oxygen in contrast to the decompression sickness of the central nervous system. As a rule an increase in recompression by 1.0 bar suffices for a marked decrease of the pains; if they persist, an additional increment of the pressure by 1.5 bar is applied. After 10 min, decompression commensurate with saturation at the depth of recompression is begun with an addition of 30 min per step, or with a corresponding slowing in continuous decompression. After 8–12 h, as a rule, the normal decompression that follows saturation can be maintained again.

The additional recompression by 1.0 bar or by 2.5 bar proceeeds, independent of the depth, best with helium and a proportion of oxygen as foreseen for the actual depth. Also when the pains in the joints occur at the end of the decompression, after air has already been breathed, recompression with oxygen and helium is preferable; air can be used, but then only with a prolongation of 30 min for every decompression step as given by the decompression table for saturation dives with helium that is meant to be used with a final decompression with air.

4.4 Transport of the Injured Diver

In Switzerland some lake police corps, the army, and the Swiss Air Rescue Service have at their disposal mobile pressure chambers to contain one person that can be connected to the large pressure chamber in Zurich. Their organization and use are based upon an instructive experience: In 1969 paralysis of the legs appeared in two divers after short dives while breathing air. The symptoms of the first diver disappeared after recompression by 5.0 bar in the pressure chamber for one person and did not recur after treatment that lasted 5 h. The second diver experienced recidivation of the paralysis a short time after similar treatment. He then underwent recompression in the small chamber again and was transported over the Alps to Zurich, which took 4 h. In Zurich the patient was transferred at an pressure of 3.1 bar through an air-lock into the large chamber and then treated essentially in correspondence with Therapy Table II B while breathing air. After 2 days he left the chamber with no paralysis. For some years only a slight hypesthesia in the lower lumbar and upper sacral segments could be detected.

This experience showed that in decompression sickness of the central nervous system recompression while breathing air that lasts only some hours is adequate only exceptionally. The example shows additionally, however, that the small chamber for one person is excellent for the initiation of the recompression, as long as the patient is breathing spontaneously. Chambers for two persons offer no decisive advantages. They are too small for reanimation with some hours of artificial respiration, and too heavy to be transported by a rescue helicopter or a long-range rescue aircraft like the Lear Jet.

The area covered by the Swiss Air Rescue Service is not limited to Switzerland. Because its service is guaranteed to continue without interruption, it seemed reasonable to centralize the reporting of divers who had accidents and the organization of the transport by air or by road, with and without a pressure chamber, with the Swiss Air Rescue Service. This also ensures that experienced personnel are always available. For a country the size of Switzerland with about 5000 amateur divers, two treatment centers each with a pressure chamber for several persons suffice.

5 Appendix: Calculation of Low-Risk Decompression and Decompression Tables

5.1 Calculation of Inert Gas Pressure in Tissues

Abbreviations and Symbols

P amb. = ambient pressure in bar,
PI i.g. = inspiratory pressure of the inert gas,
F i.g. = proportion of the inert gas in the breathing gas,
t_O = beginning of the exposure at time 0,
t_E = duration of exposure in min,
½ t = half-value time in min,
P i.g.t. = pressure of the inert gas in the tissue with a given half-value time,
0.063 bar = pressure of water vapor in the inspired breathing gas at a body temperature of 37 °C.

Formulae

$$\text{PI i.g.} = (\text{P amb.} - 0.063) \cdot \text{F i.g.}$$

The pressure of the inert gas in the tissue with a given half-value time after a given time of exposure (t_E) is given by

$$\text{Pi.g.t.}(t_E) = \text{Pi.g.t}(t_O) + \left[\text{PIi.g.} - \text{Pi.g.t}(t_O)\right] \cdot \left[1 - e^{-k \cdot t_E}\right] \text{ or}$$
$$\cdot \left[1 - e^{-0.69315 \cdot t_E / ½t}\right].$$

whereby the value of the last expression in parentheses, a function of the time of exposure and the half-value time, may be obtained readily from Table 21.

An example:

t_E = 10 min	½ t	5 min	20 min	79 min
		10/5	10/20	10/79
	=	2.0	0.5	0.127
Table 21		0.75	0.293	0.0845

The difference in pressure of the inert gas is multiplied by the value obtained from the table and the product is added to the initial pressure of the inert gas at time 0, as shown by the examples in Table 22.

Table 21. The ratio of the duration of exposure to the half-value time as a fraction of the difference in pressure of the inert gas

	0	1	2	3	4	5	6	7	8	9
0.0		0.007	0.014	0.021	0.027	0.034	0.041	0.047	0.054	0.061
0.1	0.067	0.073	0.081	0.086	0.092	0.099	0.105	0.111	0.117	0.123
0.2	0.129	0.136	0.141	0.147	0.153	0.159	0.165	0.171	0.176	0.182
0.3	0.188	0.193	0.199	0.204	0.210	0.215	0.221	0.226	0.232	0.237
0.4	0.242	0.247	0.253	0.258	0.263	0.268	0.273	0.278	0.283	0.288
0.5	0.293	0.298	0.303	0.307	0.312	0.317	0.322	0.326	0.331	0.336
0.6	0.340	0.345	0.349	0.354	0.358	0.363	0.367	0.372	0.376	0.380
0.7	0.384	0.389	0.393	0.397	0.401	0.405	0.410	0.414	0.418	0.422
0.8	0.426	0.430	0.434	0.438	0.441	0.445	0.449	0.453	0.457	0.460
0.9	0.464	0.468	0.472	0.475	0.479	0.482	0.486	0.490	0.493	0.496
1.0	0.500	0.503	0.507	0.510	0.514	0.517	0.520	0.524	0.527	0.530
1.1	0.533	0.537	0.540	0.543	0.546	0.549	0.553	0.556	0.559	0.562
1.2	0.565	0.568	0.571	0.574	0.577	0.580	0.583	0.585	0.588	0.591
1.3	0.594	0.597	0.600	0.602	0.605	0.608	0.610	0.613	0.616	0.618
1.4	0.621	0.624	0.626	0.629	0.632	0.634	0.637	0.639	0.642	0.644
1.5	0.646	0.649	0.651	0.654	0.656	0.659	0.661	0.663	0.666	0.668
1.6	0.670	0.672	0.675	0.677	0.679	0.681	0.684	0.686	0.688	0.690
1.7	0.692	0.694	0.697	0.699	0.701	0.703	0.705	0.707	0.709	0.711
1.8	0.713	0.715	0.717	0.719	0.721	0.723	0.725	0.726	0.728	0.730
1.9	0.732	0.734	0.736	0.738	0.739	0.741	0.743	0.745	0.747	0.748
2.0	0.750	0.752	0.754	0.755	0.757	0.759	0.760	0.762	0.764	0.765
2.1	0.767	0.768	0.770	0.772	0.773	0.775	0.776	0.778	0.779	0.781
2.2	0.782	0.784	0.785	0.787	0.788	0.790	0.791	0.793	0.794	0.796
2.3	0.797	0.798	0.800	0.801	0.803	0.804	0.805	0.807	0.808	0.809
2.4	0.811	0.812	0.813	0.815	0.816	0.817	0.818	0.820	0.821	0.822
2.5	0.823	0.824	0.826	0.827	0.828	0.829	0.830	0.832	0.833	0.834
2.6	0.835	0.836	0.837	0.839	0.840	0.841	0.842	0.843	0.844	0.845
2.7	0.846	0.847	0.848	0.849	0.850	0.851	0.852	0.853	0.854	0.855
2.8	0.856	0.857	0.858	0.859	0.860	0.861	0.862	0.863	0.864	0.865
2.9	0.866	0.867	0.868	0.869	0.870	0.871	0.872	0.872	0.873	0.874
3.0	0.875	0.876	0.877	0.878	0.878	0.879	0.880	0.881	0.882	0.883
3.1	0.883	0.884	0.885	0.886	0.887	0.887	0.888	0.889	0.890	0.890
3.2	0.891	0.892	0.893	0.893	0.894	0.895	0.896	0.896	0.897	0.898
3.3	0.899	0.899	0.900	0.901	0.901	0.902	0.903	0.903	0.904	0.905
3.4	0.905	0.906	0.907	0.907	0.908	0.909	0.909	0.910	0.910	0.911
3.5	0.912	0.912	0.913	0.913	0.914	0.915	0.915	0.916	0.916	0.917
3.6	0.918	0.918	0.919	0.919	0.920	0.920	0.921	0.921	0.922	0.923
3.7	0.923	0.924	0.924	0.925	0.925	0.926	0.926	0.927	0.927	0.928
3.8	0.928	0.929	0.929	0.930	0.930	0.931	0.931	0.932	0.932	0.933
3.9	0.933	0.934	0.934	0.934	0.935	0.935	0.936	0.936	0.937	0.937
4.0	0.938	0.938	0.938	0.939	0.939	0.940	0.940	0.941	0.941	0.941
4.1	0.942	0.942	0.943	0.943	0.943	0.944	0.944	0.944	0.945	0.945
4.2	0.945	0.946	0.946	0.947	0.947	0.947	0.948	0.948	0.949	0.949
4.3	0.949	0.950	0.950	0.950	0.951	0.951	0.951	0.952	0.952	0.952
4.4	0.953	0.953	0.953	0.954	0.954	0.954	0.955	0.955	0.955	0.956
4.5	0.956	0.956	0.957	0.957	0.957	0.957	0.958	0.958	0.958	0.959

Table 21 (continued)

	0	1	2	3	4	5	6	7	8	9
4.6	0.959	0.959	0.959	0.960	0.960	0.960	0.960	0.961	0.961	0.961
4.7	0.962	0.962	0.962	0.962	0.963	0.963	0.963	0.963	0.964	0.964
4.8	0.964	0.964	0.965	0.965	0.965	0.965	0.966	0.966	0.966	0.966
4.9	0.967	0.967	0.967	0.967	0.967	0.968	0.968	0.968	0.968	0.969
5.0	0.969	0.969	0.969	0.970	0.970	0.970	0.970	0.970	0.970	0.971
5.1	0.971	0.971	0.971	0.971	0,972	0.972	0.972	0.972	0.972	0.973
5.2	0.973	0.973	0.973	0.973	0.974	0.974	0.974	0.974	0.974	0.974
5.3	0.975	0.975	0.975	0.975	0.975	0.976	0.976	0.976	0.976	0.976
5.4	0.976	0.977	0.977	0.977	0.977	0.977	0.977	0.977	0.978	0.978
5.5	0.978	0.978	0.978	0.978	0.979	0.979	0.979	0.979	0.979	0.979
5.6	0.979	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.981	0.981
5.7	0.981	0.981	0.981	0.981	0.981	0.981	0.982	0.982	0.982	0.982
5.8	0.982	0.982	0.982	0.982	0.983	0.983	0.983	0.983	0.983	0.983
5.9	0.983	0.983	0.984	0.984	0.984	0.984	0.984	0.984	0.984	0.984
6.2	0.986									
6.5	0.989									
6.7	0.990									
7.0	0.992									
7.5	0.994									
8.0	0.996									
9.0	0.998									

Table 22. Pressure of the inert gas in the tissue, with a given half-value time and the ambient pressure that is tolerated:

$$P\,\text{amb. tol.} = (P\,\text{i.g.t.} - a)\cdot b \quad \text{(see p.27).}$$

Examples

$t_E = 60$ min; PI i.g. = 3.11 bar; at t_0, in all tissues, $PN_2 = 0.75$ bar.

For the examples only those compartments and their half-value times that are important for the first step of compression have been considered.

	A PIN_2 3.11 bar PIHe 0 bar				**B** PIN_2 0 bar PIHe 3.11 bar				**C** PIN_2 0.75 bar PIHe 2.36 bar			
Compartment no.	3	4	5	6	5	6	7	8	5	6	7	8
N_2 ½t	12.2	18.5	26.5	37	26.5	37	53	79	26.5	37	53	79
He ½t	4.6	7	10	14	10	14	20	30	10	14	20	30
PN_2 (t_E)	3.03	2.86	2.62	2.34	0.16	0.24	0.34	0.44	0.75	0.75	0.75	0.75
PHe (t_E)	–	–	–	–	3.06	2.95	2.72	2.33	2.32	2.24	2.07	1.77
P i.g.t.	3.03	2.86	2.62	2.34	*3.22*	*3.19*	3.06	2.77	3.07	2.99	2.82	2.52
P amb. tol. 1st step	*1.7*	*1.7*	1.6	1.5	2.1	*2.3*	*2.3*	2.1	2.0	*2.1*	*2.1*	1.9

A, only oxygen and nitrogen in the breathing gas

B, only oxygen and helium in the breathing gas. Because helium is absorbed more rapidly than nitrogen is released, the pressure of the inert gas (PHe + PN_2) in compartments 5 and 6 is higher than the ambient pressure. With the same exposure time of 60 min, the ambient pressure can be reduced only to 2.3 bar and not to 1.7 bar as in A

C, the breathing gas contains, in addition to helium, nitrogen at a pressure of 0.75 bar, corresponding to the initial partial pressure of nitrogen in all the tissues. Only helium is absorbed while the partial pressure of the nitrogen is constant

Table 23. Daily repeated exposures to overpressure with no additional decompression time

Total pressure = $PIN_2 + PIO_2$.

By enriching the breathing gas with oxygen the descent to greater depths than with use of air alone is made possible. The given PIO_2 is valid for the breathing gas during work and takes the duration of exposure into consideration.

The pressure is changed by 1 bar/min; after the first decompression step has been reached, pure oxygen is breathed.

During each interval an additional dive of 10 min may be undertaken with the same or a lower PIN_2, without decompression. After each such additional exposure, the full duration of the interval while breathing air at a pressure of 1.0 bar must be maintained.

The length of the interval between 2 days of work must be not less than 12 h, and after 5 days of work, not less than 48 h.

PIN_2 bar	PIO_2 bar	
1.30	0.4	Unlimited duration, with no decompression.
1.50	0.7	Daily 6 h with no decompression.
1.90	1.1	Daily 270 min or 2 times 150 min with 3 h interval breathing air at 1.0 bar; decompression: 20 min pure oxygen at 1.3 bar.
2.40	1.5	Daily 2 times 100 min with 3 h interval breathing air at 1.0 bar; decompression: 25 min pure oxygen at 1.3 bar.
3.00	1.5	Daily 2 times 80 min with 4 h interval breathing air at 1.0 bar; decompression: 10 min pure oxygen at 1.6 bar, 20 min pure oxygen at 1.3 bar.
3.50	1.5	Daily 2 times 60 min with 4 h interval breathing air at 1.0 bar; decompression: 10 min pure oxygen at 1.9 bar, 15 min pure oxygen at 1.6 bar, 15 min pure oxygen at 1.3 bar.
4.00	1.5	Daily 2 times 40 min with 4 h interval breathing air at 1.0 bar; decompression: 5 min pure oxygen at 2.2 bar, 5 min pure oxygen at 1.9 bar, 15 min pure oxygen at 1.6 bar, 15 min pure oxygen at 1.3 bar.

5.2 Decompression Tables for Dives with Air at Various Altitudes (Tables 24.1–24.6)

Heights above sea level (m)	0–700	⩾700–1500	⩾1500–2500	⩾2500–3500
Pressure (bar)	1.03–0.93	0.93–0.84	0.84–0.74	0.74–0.65
Pressure at the surface at the end of decompression (bar)	0.95	0.86	0.76	0.67

General Rules. Because of the risk of nitrogen narcosis, diving to more than 40 m may not be undertaken without some security being given from the surface. For diving instructors the limit is increased to 50 m.

Decompression Tables. The tables have been compiled with a safety factor of 2 m for the depth of the dive; therefore, for a dive to 32 m decompression is carried out in correspondence with the table for 30 m. For intermediate stays at the bottom, the next length of stay should be used; thus for a stay of 35 min at 30 m decompression is undertaken as for a stay of 40 min.

With repeated dives time supplements for the bottom time must be considered; the values for repetitive dives are marked for every dive with a letter. The supplements are determined from Tables 24.1 and 24.2.

If diving is done daily, the total time of diving, whereby the intervals at the surface are included in the total, should not exceed 6 h in any 24 h.

Examples for Repeated Diving

1. No Decompression Dives. After a stay of 53 min at 18 m ascent to the surface may be effected in a bare 2 min without a stop for decompression. If the stay at 18 m has been only 20 min, the diver is in Repetitive Group C, which can be found in Table 24.2. He may dive again for 32 min to a depth of 18 m and then return to the surface without a stop for decompression.

2. Dives with decompression. After a first dive with a stay of 50 min at 30 m, following decompression the diver is in Repetitive Group G. After an interval of 60 min at the surface Repetitive Group D is applicable with an addition of 18 min for a second dive to the same depth. After a stay of 32 min at 30 m, decompression must be accomplished in correspondence with a stay of 50 min at the bottom. At the end of decompression, Repetitive Group G is again applicable; if the stay at 30 m is 50 min, decompression must be accomplished as for a stay at the bottom of 70 min.

Table 24.1. Table of intervals at the surface

Repetitive group at the end of the interval at the surface											
L	K	J	H	G	F	E	D	C	B	A	„0“
L	160	240	300	400	530	600	700	800	1000	1200	48
	K	120	150	210	270	330	420	480	560	660	34
		J	45	70	90	120	160	210	300	420	24
			H	30	45	60	90	150	180	260	17
				G	25	45	60	75	100	130	12
					F	20	30	45	75	90	8
						E	10	15	25	45	4
							D	10	15	30	3
								C	10	25	3
									B	20	2
										A	2

Repetitive group at the beginning of the interval at the surface

Duration of the intervals in minutes, for group “0”, in hours. This table is valid for up to 3500 m above see level.

For step-wise descent and ascent, the depth and duration of the first dive ascertain the repetitive group with an addition of time calculated for the depth that is averaged over the entire duration of the dive. An example is given by 20 min at 18 m is in Group C, plus 15 min at 24 m, plus 15 min at 18 m, and plus 15 min at 35 m, yielding 65 min at an average depth of 22.8 m, for which the supplement in Group C is 20 min for 21 m. The decompression will be as for a stay of 90 min at a depth of 21 m.

Table 24.2. Time supplements for repetitive dives

Repetitive group	Depth attained in the repetitive dives (m)																	
	9	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60
L	450	300	240	180	160	140	120	110	100	90	80	75	75	65	60	60	55	50
K	430	270	200	150	100	100	90	75	70	65	55	55	50	50	45	40	40	40
J	410	220	150	100	80	75	70	60	55	50	40	40	40	40	35	35	30	30
H	300	150	100	90	75	60	55	50	50	45	35	35	30	25	25	25	20	20
G	145	115	80	65	55	45	40	35	30	25	25	23	23	20	20	18	15	15
F	115	100	75	60	50	40	35	30	25	23	20	18	17	16	15	14	13	12
E	90	75	45	40	35	30	25	23	22	20	18	16	14	12	11	10	10	10
D	70	50	35	30	25	23	20	18	17	16	15	14	12	10	9	8	7	6
C	45	30	25	20	20	20	18	16	14	12	10	10	9	8	7	7	6	5
B	30	25	20	18	15	12	10	10	9	8	7	7	6	6	5	5	5	5
A	20	18	15	14	12	10	9	7	6	6	6	6	5	5	5	5	5	5

The time supplements are valid for up to 3 500 m above sea level.

Table 24.3. Air decompression table (0–700 m above sea level)

Depth m	Bottom time min	Time to first stop min : s		Decompression stops m min								Total ascent time min : s		Repetitive group
				24	21	18	15	12	9	6	3			
9	300											1	0	H
12	120											1	10	G
	150	0	50								9	9	50	G
	180	0	50								14	14	50	H
	210	0	50								18	18	50	H
	240	0	50								24	24	50	J
	270	0	50								29	29	50	K
	300	0	50								34	34	50	K
15	75											1	30	G
	90	1	10								6	7	10	G
	120	1	10								20	21	10	G
	140	1	10								25	26	10	H
	160	1	10								31	32	10	H
	180	1	10								38	39	10	H
	200	0	50							2	43	45	50	J
	220	0	50							5	46	51	50	K
	240	0	50							6	49	55	50	K

Table 24.3 *(continued).* Air decompression table (0–700 m above sea level)

Depth m	Bottom time min	Time to first stop min : s		Decompression stops m min								Total ascent time min : s		Repetitive group
				24	21	18	15	12	9	6	3			
18	53											1	50	F
	60	1	30								4	5	30	F
	70	1	30								9	10	30	G
	80	1	30								16	17	30	G
	90	1	30								23	24	30	G
	100	1	30								28	29	30	G
	110	1	10							1	31	33	10	H
	120	1	10							3	33	37	10	H
	130	1	10							7	35	43	10	H
	140	1	10							10	38	49	10	H
	150	1	10							13	41	55	10	J
	160	1	10							15	44	60	10	J
	170	1	10							17	46	64	10	K
	180	1	10							19	48	68	10	K
	190	1	10							20	50	71	10	K
	200	1	10							21	52	74	10	K
21	35											2	10	E
	50	1	50								6	7	50	F
	60	1	50								13	14	50	G
	70	1	50								23	24	50	G
	80	1	30							3	28	32	30	G
	90	1	30							7	31	39	30	H
	100	1	30							10	33	44	30	H
	110	1	30							15	36	52	30	H
	120	1	30							20	39	60	30	J
	130	1	30							23	43	67	30	J
	140	1	30							26	46	73	30	K
	150	1	30							29	48	78	30	K
	160	1	10						2	29	51	83	10	L
	170	1	10						5	30	52	88	10	L
	180	1	10						7	33	73	114	10	L
24	25											2	30	E
	40	2	10								6	8	10	F
	50	2	10								15	17	10	G
	60	1	50							3	23	27	50	G
	70	1	50							8	29	38	50	G
	80	1	50							13	32	46	50	H
	90	1	50							18	33	52	50	H
	100	1	30						1	24	38	64	30	H
	110	1	30						4	26	43	74	30	J
	120	1	30						6	29	46	82	30	J
	130	1	30						10	29	49	89	30	K
	140	1	30						13	30	52	96	30	L
	150	1	30						16	33	61	111	30	L
	160	1	30						18	36	94	149	30	L

Table 24.3 *(continued)*. Air decompression table (0–700 m above sea level)

Depth m	Bottom time min	Time to first stop min :	s	Decompression stops m min								Total ascent time min :	s	Repetitive group
				24	21	18	15	12	9	6	3			
27	22											2	40	E
	30	2	20								4	6	20	F
	40	2	10							1	12	15	10	F
	50	2	10							4	22	28	10	G
	60	2	10							10	28	40	10	G
	70	1	50						1	16	32	50	50	H
	80	1	50						4	21	34	60	50	H
	90	1	50						8	25	39	73	50	H
	100	1	50						11	28	44	84	50	J
	110	1	50						15	29	49	94	50	K
	120	1	50						19	30	52	102	50	L
	130	1	30					1	23	33	55	113	30	L
	140	1	30					3	24	38	94	160	30	L
30	20											3	0	D
	25	2	40								4	6	40	E
	30	2	20							2	6	10	20	F
	40	2	20							5	16	23	20	G
	50	2	10						1	10	26	39	10	G
	60	2	10						3	16	31	52	10	H
	70	2	10						7	21	34	64	10	H
	80	2	10						12	25	40	79	10	J
	90	1	50					1	15	29	45	91	50	J
	100	1	50					4	19	29	50	103	50	K
	110	1	50					6	23	32	51	113	50	L
	120	1	50					9	24	37	79	150	50	L
33	17											3	20	D
	25	2	40							2	6	10	40	F
	30	2	40							4	10	16	40	F
	40	2	20						2	7	22	33	20	G
	50	2	20						4	14	30	50	20	G
	60	2	20						8	20	33	63	20	H
	70	2	10					2	13	25	39	81	10	J
	80	2	10					4	16	29	45	96	10	K
	90	2	10					8	20	29	51	110	10	K
	100	2	10					12	23	33	53	123	10	L
	110	2	10					14	26	38	95	175	10	L
36	15											3	40	D
	20	3	0							2	4	9	0	E
	25	3	0							4	7	14	0	F
	30	2	40						2	5	14	23	40	G
	40	2	40						4	10	26	42	40	G
	50	2	20					1	8	16	33	60	20	H
	60	2	20					4	12	23	37	78	20	H
	70	2	20					7	15	28	44	96	20	K
	80	2	20					12	19	29	50	112	20	K

Table 24.3 *(continued).* Air decompression table (0–700 m above sea level)

Depth m	Bottom time min	Time to first stop min	: s	Decompression stops m min								Total ascent time min	: s	Repetitive group
				24	21	18	15	12	9	6	3			
	90	2	10				2	14	24	33	53	128	10	L
	100	2	10				5	16	26	39	102	190	10	L
39	12											3	50	D
	15	3	40								4	7	40	E
	20	3	20							3	6	12	20	F
	25	3	0						2	4	11	20	0	G
	30	3	0						3	6	17	29	0	G
	40	2	40					2	6	13	29	52	40	G
	50	2	40					4	10	20	33	69	40	H
	60	2	20				1	7	15	27	41	93	20	J
	70	2	20				3	11	19	29	49	113	20	K
	80	2	20				5	14	23	33	52	129	20	L
	90	2	20				9	16	26	39	95	187	20	L
42	10											4	10	D
	15	3	40							2	4	9	40	E
	20	3	20						1	4	7	15	20	F
	25	3	20						3	5	14	25	20	G
	30	3	0					2	3	8	22	38	0	G
	40	2	40				1	3	8	16	31	61	40	G
	50	2	40				2	6	13	24	37	84	40	H
	60	2	40				4	9	17	29	46	107	40	K
	70	2	40				7	13	22	31	51	126	40	K
	80	2	20			2	10	15	26	38	84	177	20	L
45	10	4	10								2	6	10	E
	15	3	50							3	5	11	50	E
	20	3	40						3	4	10	20	40	F
	25	3	20					2	3	6	17	31	20	G
	30	3	20					3	5	10	25	46	20	G
	40	3	0				2	5	9	18	34	71	0	H
	50	3	0				5	7	15	27	41	98	0	K
	60	2	40			2	6	12	20	29	50	121	40	K
	70	2	40			3	10	14	25	35	57	146	40	L
	80	2	40			6	12	19	26	42	130	237	40	L
48	10	4	30								4	8	30	E
	15	3	50						1	4	5	13	50	F
	20	3	40					1	3	5	13	25	40	F
	25	3	40					3	4	8	21	39	40	G
	30	3	20				2	3	6	13	28	55	20	G
	35	3	20				3	4	8	17	32	67	20	H
	40	3	0			1	3	6	12	22	34	81	0	H
	50	3	0			2	6	9	16	29	45	110	0	K
	60	3	0			4	8	14	23	31	52	135	0	K
	70	2	40		1	7	11	17	26	40	100	204	40	L

Table 24.3 *(continued).* Air decompression table (0–700 m above sea level)

Depth m	Bottom time min	Time to first stop min : s		Decompression stops m min								Total ascent time min : s		Repetitive group
				24	21	18	15	12	9	6	3			
51	10	4	30							1	4	9	30	E
	15	4	10						2	4	7	17	10	F
	20	3	50					2	4	5	15	29	50	G
	25	3	40				1	4	5	9	25	47	40	G
	30	3	40				3	4	7	15	30	62	40	G
	35	3	20			1	4	5	10	20	33	76	20	H
	40	3	20			2	5	7	13	25	38	93	20	J
	50	3	0		1	4	7	12	19	29	49	124	0	K
	60	3	0		2	6	10	15	25	36	60	157	0	L
	65	3	0		3	7	12	17	26	40	106	214	0	L
54	10	4	50							2	5	11	50	E
	15	4	30						3	4	8	19	30	F
	20	4	10					3	4	6	18	35	10	G
	25	3	50				3	3	6	12	27	54	50	G
	30	3	40			2	3	5	8	17	32	70	40	G
	35	3	40			3	4	6	12	23	35	86	40	J
	40	3	20		1	3	5	9	15	27	41	104	20	K
	50	3	20		2	5	8	14	22	29	52	135	20	K
	60	3	20		5	7	12	17	26	39	103	212	20	L
57	10	5	10							3	5	13	10	E
	15	4	30					1	4	4	11	24	30	F
	20	4	10				2	3	4	8	22	43	10	G
	25	3	50			1	3	4	6	15	29	61	50	G
	30	3	50			3	3	6	9	20	33	77	50	H
	35	3	40		2	3	4	8	14	25	39	98	40	K
	40	3	40		3	3	6	10	16	29	45	115	40	K
	50	3	20	1	4	6	9	15	24	34	52	148	20	K
	55	3	20	2	5	7	11	17	26	39	95	205	20	L
60	10	5	10						1	4	5	15	10	E
	15	4	50					2	4	5	13	28	50	F
	20	4	30				3	3	5	9	25	49	30	G
	25	4	10			2	4	4	8	16	31	69	10	H
	30	3	50		2	3	4	6	12	22	35	88	50	J
	35	3	50		3	3	6	8	16	27	42	108	50	K
	40	3	40	1	3	5	7	12	19	29	48	127	40	K
	45	3	40	2	4	5	9	14	23	32	52	144	40	L
	50	3	40	3	4	7	11	16	26	37	82	189	40	L
	55	3	40	4	5	8	14	19	26	42	133	254	40	L
63	10	5	20						2	4	6	17	20	F
	15	4	50				1	3	4	6	15	33	50	G
	20	4	30			1	3	4	6	11	27	56	30	G
	25	4	10		1	3	3	6	8	18	33	76	10	H
	30	4	10		3	3	5	7	14	24	38	98	10	J
	35	3	50	2	3	4	6	10	16	29	46	119	50	K
	40	3	50	3	3	5	8	13	22	29	51	137	50	L
	45	3	50	4	4	7	10	15	25	35	56	159	50	L
	50	3	50	5	5	8	13	18	26	41	114	233	50	L

Table 24.4. Air decompression table (701–1 500 m above sea level)

Depth m	Bottom time min	Time to first stop		Decompression stops m min							Total ascent time		Repetitive group
		min	s	18	15	12	9	6	4	2	min	s	
9	180										1	0	G
12	90	1	0								1	10	G
	100	1	0							2	3	0	G
	110	1	0							6	7	0	G
	120	1	0							10	11	0	G
	130	1	0							13	14	0	G
	140	1	0							15	16	0	G
	150	1	0							17	18	0	H
15	63										1	30	F
	70	1	10							4	5	10	G
	80	1	10							9	10	10	G
	90	1	10							15	16	10	G
	100	1	10							20	21	10	G
	110	1	10							24	25	10	G
	120	1	10							27	28	10	H
18	43										1	50	F
	50	1	40							2	3	40	F
	60	1	40							9	10	40	G
	70	1	40							17	18	40	G
	80	1	40							24	25	40	G
	90	1	20						3	27	31	20	G
	100	1	20						5	30	36	20	H
	110	1	20						9	31	41	20	H
	120	1	20						13	33	47	20	H
21	30										2	10	E
	40	1	50							3	4	50	F
	50	1	50							11	12	50	G
	60	1	40						1	20	22	40	G
	70	1	40						5	25	31	40	G
	80	1	40						9	29	39	40	H
	90	1	40						14	30	45	40	H
	100	1	30					6	17	32	56	30	H
	110	1	30					6	19	36	62	30	H
24	25										2	20	E
	30	2	10							3	5	10	E
	35	2	10							5	7	10	F
	40	2	0						1	9	12	0	F
	50	2	0						3	18	23	0	G
	60	2	0						8	25	35	0	G
	70	1	50					2	12	29	44	50	H
	80	1	50					6	15	30	52	50	H
	90	1	50					10	18	34	63	50	H
	100	1	30				2	12	20	39	74	30	H

Table 24.4 *(continued).* Air decompression table (701–1500 m above sea level)

Depth m	Bottom time min	Time to first stop min : s		Decompression stops m min							Total ascent time min : s		Repetitive group
		min	s	18	15	12	9	6	4	2	min	s	
27	18										2	20	E
	25	2	30							3	5	30	E
	30	2	20						1	5	8	20	F
	35	2	20						2	10	14	20	F
	40	2	20						3	14	19	20	G
	50	2	10					2	7	24	35	10	G
	60	2	10					5	11	29	47	10	G
	70	1	50				1	9	15	30	56	50	H
	80	1	50				4	11	19	35	70	50	H
	90	1	50				8	14	20	40	83	50	J
30	16										3	0	E
	20	2	50							3	5	50	E
	25	2	40						1	5	8	40	F
	30	2	40						3	8	13	40	F
	35	2	20					1	4	14	21	20	G
	40	2	20					2	6	19	29	20	G
	45	2	20					4	7	24	37	20	G
	50	2	10				1	5	10	27	45	10	G
	60	2	10				3	9	14	30	58	10	H
	70	2	10				7	11	19	35	74	10	H
	80	2	10				12	14	20	41	89	10	J
33	14										3	20	E
	20	2	50						1	4	7	50	E
	25	2	40					1	3	6	12	40	F
	30	2	40					2	4	12	20	40	G
	35	2	20				1	3	5	18	29	20	G
	40	2	20				2	4	7	24	39	20	G
	45	2	20				3	5	11	27	48	20	G
	50	2	20				4	7	12	30	55	20	H
	60	2	20				8	11	18	32	71	20	H
	70	2	10			2	13	14	20	40	91	10	J
36	11										3	40	D
	15	3	20							4	7	20	E
	20	3	10						3	5	11	10	F
	25	3	0					2	3	10	18	0	G
	30	2	40				2	3	4	16	27	40	G
	35	2	40				3	4	6	23	38	40	G
	40	2	40				4	5	11	26	48	40	G
	45	2	20			1	5	8	12	30	58	20	H
	50	2	20			1	8	10	15	30	66	20	H
	60	2	20			4	12	12	20	38	88	20	J
39	10										3	50	D
	15	3	30						1	4	8	30	E
	20	3	20					2	3	6	14	20	F
	25	3	0				2	3	3	13	24	0	G

Table 24.4 *(continued).* Air decompression table (701–1 500 m above sea level)

Depth m	Bottom time min	Time to first stop min	: s	Decompression stops m min 18	15	12	9	6	4	2	Total ascent time min	: s	Repetitive group
	30	3	0				3	4	6	20	36	0	G
	35	2	40			1	4	5	10	25	47	40	G
	40	2	40			2	6	6	12	30	58	40	H
	45	2	40			3	8	9	15	31	68	40	H
	50	2	40			5	9	11	18	34	79	40	H
	55	2	40			6	12	13	18	40	91	40	J
42	15	3	50						3	4	10	50	F
	20	3	20				1	3	3	8	18	20	G
	25	3	20				3	3	5	16	30	20	G
	30	3	0			2	4	4	8	24	45	0	G
	35	3	0			3	5	6	12	28	57	0	H
	40	2	40		1	3	8	9	14	30	67	40	H
	45	2	40		1	5	9	12	17	33	79	40	H
	50	2	40		2	6	13	14	20	38	95	40	J
45	10	4	20							3	7	20	D
	15	3	50					2	3	4	12	50	F
	20	3	40				3	3	4	12	25	40	F
	25	3	20			2	3	4	6	20	38	20	G
	30	3	20			3	5	5	10	27	53	20	G
	35	3	0		1	4	6	9	12	30	65	0	H
	40	3	0		2	5	9	11	16	31	77	0	H
	45	3	0		3	6	12	12	20	37	93	0	J
48	10	4	20						1	4	9	20	D
	15	3	50				1	2	3	6	15	50	F
	20	3	40			1	3	3	4	15	29	40	G
	25	3	40			3	4	4	8	23	45	40	G
	30	3	20		2	3	6	6	12	29	61	20	H
	35	3	20		3	4	8	10	15	31	74	20	H
	40	3	0	1	3	6	11	12	19	35	90	0	J
	45	3	0	2	4	8	14	15	20	41	107	0	J
51	10	4	40						2	4	10	40	E
	15	4	10				2	3	3	7	19	10	G
	20	3	50			2	4	4	5	17	35	50	G
	25	3	40		1	4	5	5	9	26	53	40	H
	30	3	40		3	4	7	8	13	30	68	40	H
	35	3	20	1	4	5	10	11	18	32	84	20	H
	40	3	20	2	5	7	13	14	19	39	102	20	J
54	10	4	50					1	3	4	12	50	E
	15	4	30				3	3	3	10	23	30	G
	20	4	10			3	4	4	6	21	42	10	G
	25	3	50		3	3	6	6	11	28	60	50	H
	30	3	40	2	3	5	8	10	15	31	77	40	H
	35	3	40	3	4	6	12	12	20	36	96	40	J

Table 24.5. Air decompression table (1 501–2 500 m above sea level)

Depth m	Bottom time min	Time to first stop min : s		Decompression stops m min							Total ascent time min : s		Repetitive group
				18	15	12	9	6	4	2			
9	135										1	0	G
12	82										1	10	G
	90	1	0							2	3	0	G
	100	1	0							7	8	0	G
	110	1	0							11	12	0	G
	120	1	0							15	16	0	G
	130	1	0							18	19	0	H
	140	1	0							21	22	0	H
	150	1	0							23	24	0	H
15	55										1	30	G
	60	1	20							2	3	20	G
	70	1	20							7	8	20	G
	80	1	20							14	15	20	G
	90	1	20							20	21	20	G
	100	1	20							25	26	20	H
	110	1	20							29	30	20	H
	120	1	20							33	34	20	H
18	40										1	50	F
	50	1	40							5	6	40	G
	60	1	40							12	13	40	G
	70	1	40							22	23	40	G
	80	1	20						1	28	30	20	H
	90	1	20						4	32	37	20	H
	100	1	20						8	33	42	20	H
	110	1	20						14	35	50	20	H
	120	1	20						16	39	56	20	H
21	30										2	10	E
	40	1	50							5	6	50	G
	50	1	50							14	15	50	G
	60	1	40						2	24	27	40	G
	70	1	40						7	29	37	40	G
	80	1	40						11	32	44	40	H
	90	1	30					2	15	34	52	30	H
	100	1	30					5	18	38	62	30	H
	110	1	30					7	21	42	71	30	J
24	23										2	20	E
	30	2	10							4	6	10	F
	35	2	10							7	9	10	G
	40	2	0						1	12	15	0	G
	50	2	0						4	22	28	0	G
	60	1	50					1	9	29	40	50	H
	70	1	50					3	13	33	50	50	H
	80	1	50					8	16	35	60	50	H
	90	1	50					11	20	40	72	50	J
	100	1	30				3	14	21	45	84	30	K

Table 24.5 *(continued).* Air decompression table (1 501–2 500 m above sea level)

Depth m	Bottom time min	Time to first stop min : s		Decompression stops m min							Total ascent time min : s		Repetitive group
				18	15	12	9	6	4	2			
27	17										2	40	D
	25	2	30							4	6	30	F
	30	2	20						1	7	10	20	G
	35	2	20						2	13	17	20	G
	40	2	10					1	4	17	24	10	G
	50	2	10					3	8	27	40	10	H
	60	2	10					6	12	33	53	10	H
	70	1	50				2	10	16	35	64	50	H
	80	1	50				5	12	20	41	79	50	J
	90	1	50				9	15	21	46	92	50	K
30	15										3	0	D
	20	2	50							4	6	50	E
	25	2	40						2	5	9	40	F
	30	2	20					1	3	11	17	20	G
	35	2	20					2	4	17	25	20	G
	40	2	20					3	6	23	34	20	G
	45	2	10				1	4	9	28	44	10	H
	50	2	10				2	5	12	31	52	10	H
	60	2	10				4	10	15	34	65	10	H
	70	2	10				9	12	20	40	83	10	J
33	12										3	20	D
	15	3	10							3	6	10	D
	20	2	50						2	4	8	50	F
	25	2	40					1	3	8	14	40	G
	30	2	40					3	3	15	23	40	G
	35	2	20				1	3	6	23	35	20	G
	40	2	20				2	5	8	28	45	20	H
	45	2	20				4	6	11	31	54	20	H
	50	2	20				5	8	13	34	62	20	H
	60	2	10			1	9	12	19	38	81	10	J
36	10										3	40	D
	15	3	20							4	7	20	E
	20	3	10						4	5	12	10	F
	25	3	0					3	3	12	21	0	G
	30	2	40				2	3	5	20	32	40	G
	35	2	40				3	5	7	27	44	40	G
	40	2	20			1	4	6	11	31	55	20	H
	45	2	20			1	6	8	14	33	64	20	H
	50	2	20			2	8	11	16	35	74	20	H
	60	2	20			4	14	14	20	43	97	20	J
39	9										3	50	D
	15	3	30						2	4	9	30	E
	20	3	20					2	3	8	16	20	G
	25	3	0				2	3	4	16	28	0	G
	30	3	0				4	4	6	25	42	0	G

Table 24.5 *(continued)*. Air decompression table (1 501–2 500 m above sea level)

Depth m	Bottom time min	Time to first stop min : s		Decompression stops m min							Total ascent time min : s		Repetitive group
				18	15	12	9	6	4	2			
	35	2	40			2	4	6	10	30	54	40	H
	40	2	40			3	6	7	13	33	64	40	H
	45	2	40			4	8	10	17	34	75	40	H
	50	2	40			5	11	12	19	40	89	40	J
42	10	4	0							3	7	0	D
	15	3	40					1	3	4	11	40	F
	20	3	20				1	3	3	11	25	20	G
	25	3	20				4	4	5	20	36	20	G
	30	3	0			2	4	5	9	28	51	0	G
	35	3	0			3	6	7	12	32	63	0	H
	40	2	40		1	4	8	10	16	33	74	40	H
	45	2	40		2	5	10	12	19	39	89	40	H
	50	2	40		2	7	14	14	20	44	103	40	J
45	10	4	20							4	8	20	D
	15	3	50					2	3	5	13	50	F
	20	3	40				3	3	4	14	27	40	G
	25	3	20			2	4	4	6	25	44	20	G
	30	3	20			4	5	6	11	30	59	20	H
	35	3	0		2	4	7	9	14	33	72	0	H
	40	3	0		3	5	9	12	18	37	87	0	J
48	10	4	20						1	4	9	20	E
	15	3	50				1	3	3	7	17	50	G
	20	3	40			1	3	4	4	18	33	40	G
	25	3	40			3	4	5	9	27	51	40	H
	30	3	20		2	4	6	7	13	32	67	20	H
	35	3	20		3	5	9	10	17	34	81	20	H
	40	3	0	1	4	6	12	13	20	41	100	0	J
51	10	4	40						3	4	11	40	E
	15	4	10				2	3	3	10	22	10	G
	20	3	50			2	4	4	5	22	40	50	G
	25	3	40		2	3	5	6	11	29	59	40	H
	30	3	40		3	5	7	9	14	34	75	40	H
	35	3	20	2	3	6	11	11	20	38	94	20	H
	40	3	20	3	4	8	14	15	21	44	112	20	J
54	10	4	50					1	3	4	12	50	F
	15	4	30				3	4	4	13	28	30	G
	20	3	50		1	3	4	4	7	25	47	50	G
	25	3	50		3	4	6	6	13	31	66	50	H
	30	3	40	2	3	5	9	11	16	34	83	40	H
	35	3	40	3	4	7	13	13	20	42	105	40	J

Table 24.6. Air decompression table (2501–3500 m above sea level)

Depth m	Bottom time min	Time to first stop min : s		Decompression stops m min							Total ascent time min : s		Repetitive group
				18	15	12	9	6	4	2			
9	125										1	0	G
12	76										1	10	G
	90	1	0							5	6	0	G
	100	1	0							10	11	0	G
	110	1	0							15	16	0	G
	120	1	0							18	19	0	H
	130	1	0							21	22	0	H
	140	1	0							24	25	0	H
	150	1	0							26	27	0	H
15	55										1	30	G
	60	1	20							4	5	20	G
	70	1	20							10	11	20	G
	80	1	20							18	19	20	G
	90	1	20							24	25	20	G
	100	1	20							29	30	20	H
	110	1	20							33	34	20	H
	120	1	10						3	34	38	10	H
18	38										1	50	F
	50	1	40							7	8	40	G
	60	1	40							16	17	40	G
	70	1	40							25	26	40	G
	80	1	20						3	30	34	20	H
	90	1	20						7	33	41	20	H
	100	1	20						12	33	46	20	H
	110	1	20						16	37	54	20	J
	120	1	10					1	20	40	62	10	J
21	25										2	10	F
	40	1	50							7	8	50	G
	50	1	50							18	19	50	G
	60	1	40						3	27	31	40	G
	70	1	40						9	31	41	40	H
	80	1	40						14	34	49	40	H
	90	1	30					4	17	36	58	30	H
	100	1	30					7	20	41	69	30	J
24	20										2	20	E
	25	2	10							3	5	10	E
	30	2	10							5	7	10	F
	35	2	0						1	9	12	0	G
	40	2	0						2	14	18	0	G
	50	2	0						5	25	32	0	G
	60	1	50					2	11	30	44	50	H
	70	1	50					5	15	33	54	50	H
	80	1	50					10	18	37	66	50	J
	90	1	30				1	13	21	43	79	30	J

Table 24.6 *(continued)*. Air decompression table (2510–3500 m above sea level)

Depth m	Bottom time min	Time to first stop min : s		Decompression stops m min							Total ascent time min : s		Repetitive group
				18	15	12	9	6	4	2			
27	17										2	40	E
	20	2	30							3	5	30	E
	25	2	30							5	7	30	F
	30	2	20						2	8	12	20	G
	35	2	20						3	14	19	20	G
	40	2	10					1	4	21	28	10	G
	45	2	10					2	7	26	37	10	G
	50	2	10					3	10	29	44	10	H
	60	1	50				1	7	14	34	57	50	H
	70	1	50				3	12	18	37	71	50	J
	80	1	50				8	13	22	43	87	50	J
30	15										3	0	D
	20	2	50							5	7	50	E
	25	2	40						2	7	11	40	G
	30	2	20					1	3	13	19	20	G
	35	2	20					2	5	20	29	20	G
	40	2	10				1	3	7	26	39	10	G
	45	2	10				1	5	10	30	48	10	H
	50	2	10				3	6	13	32	56	10	H
	60	2	10				6	11	17	36	72	10	H
	70	2	10				11	13	22	43	91	10	J
33	12										3	20	D
	15	3	10							3	6	10	E
	20	2	50						2	5	9	50	F
	25	2	40					2	3	10	17	40	G
	30	2	20				1	3	4	17	27	20	G
	35	2	20				2	4	6	25	39	20	G
	40	2	20				3	5	10	30	50	20	H
	45	2	20				5	6	13	33	59	20	H
	50	2	20				6	10	15	34	67	20	H
	60	2	10			2	11	12	21	41	89	10	J
36	10										3	40	D
	15	3	10						1	4	8	10	E
	20	3	0					1	3	6	13	0	G
	25	2	40				1	3	3	14	23	40	G
	30	2	40				3	3	6	23	37	40	G
	35	2	40				4	5	9	29	49	40	H
	40	2	20			1	5	7	12	33	60	20	H
	45	2	20			2	7	9	16	34	70	20	H
	50	2	20			3	9	12	19	37	82	20	H
39	8										3	50	D
	10	3	40							2	5	40	D
	15	3	30						2	5	10	30	F
	20	3	20					3	3	9	18	20	G
	25	3	0				3	3	4	19	32	0	G

Table 24.6 *(continued).* Air decompression table (2 501–3 500 m above sea level)

Depth m	Bottom time min	Time to first stop min : s		Decompression stops m min							Total ascent time min : s		Repetitive group
				18	15	12	9	6	4	2			
	30	2	40			1	4	4	8	27	46	40	G
	35	2	40			2	5	6	12	31	58	40	H
	40	2	40			3	7	9	15	33	69	40	H
	45	2	40			5	8	12	19	36	82	40	H
	50	2	20		1	5	13	13	21	42	97	20	J
42	10	4	0							3	7	0	D
	15	3	40					1	3	5	12	40	F
	20	3	20				2	3	3	13	24	20	G
	25	3	0			1	4	4	6	23	41	0	G
	30	3	0			3	4	5	11	30	56	0	H
	35	3	0			4	6	8	13	34	68	0	H
	40	2	40		1	5	9	11	18	35	81	40	H
	45	2	40		2	6	12	12	22	41	97	40	J
45	10	4	10						1	4	9	10	D
	15	3	50					3	3	6	15	50	F
	20	3	40				3	4	4	16	30	40	G
	25	3	20			2	4	5	8	26	48	20	G
	30	3	0		1	4	5	7	12	32	64	0	H
	35	3	0		2	4	8	10	17	33	77	0	H
	40	3	0		3	6	11	12	21	39	95	0	J
48	10	4	20						2	4	10	20	E
	15	3	50				2	3	3	9	20	50	G
	20	3	40			1	4	4	6	20	38	40	G
	25	3	20		1	3	5	5	10	30	57	20	H
	30	3	20		2	4	7	8	14	34	72	20	H
	35	3	0	1	3	5	10	12	19	37	90	0	H
	40	3	0	2	4	7	14	14	21	44	109	0	J
51	10	4	40						3	4	11	40	F
	15	4	10				3	3	4	12	26	10	G
	20	3	50			3	4	4	6	25	45	50	G
	25	3	40		2	4	5	7	12	31	64	40	H
	30	3	20	1	3	5	8	11	16	34	81	20	H
	35	3	20	2	4	6	12	13	21	41	102	20	J
54	10	4	50					2	3	4	13	50	F
	15	4	10			1	4	4	4	14	31	10	G
	20	3	50		1	4	4	5	8	27	52	50	G
	25	3	50		4	4	6	8	13	33	71	50	H
	30	3	40	2	4	5	10	12	19	37	92	40	H

6 Literature

La Plongée, the diving book of the French Navy, published in 1955, and the *US Navy Diving Manual,* published in 1959, were the most important references available in 1960 in Zurich for the preparation of the first experiments concerning deep diving. The decompression tables for dives with air were analyzed in relation to the pressure of inert gas in tissues with short half-value times and in relation to the tolerated ambient pressure. The values obtained were extrapolated for the then extreme range of 20–30 bar. For the calculation of the equalization of pressure with simultaneous presence and sequential presence of nitrogen and helium in the breathing gas, a new method was developed. The concept stayed unchanged for the experimental research on decompression for the next 24 years. The results of other experimental groups, which had not carried out comparable experiments, did not influence the development of the Swiss practice of decompression. All the empirical factors that are important for this method were determined experimentally in Zurich. These particular circumstances may excuse the fact that in addition to the standard works, in the main only the experimental works of the Laboratory of Hyperbaric Physiology of the Medical Clinic of the University of Zurich are cited.

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7 Subject Index

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