Preface

Textbooks of physiology and medicine are related essentially to an atmospheric pressure which does not fluctuate by as much as four per cent over the entire lifetime of the average individual. A great deal of caution is therefore needed in transposing those principles to other pressures when a simple extrapolation is seldom adequate, so that much rethinking of the biological sciences is needed when man enters these unusual environments. Not only is man's basic physiology altered under hyperbaric conditions but the simple act of changing pressure introduces many of the greatest potential hazards which have all too often resulted in death or permanent disablement of divers, caisson workers, aviators and hospital chamber personnel. While only the very simplest of these potential hazards are well understood, many of the others can be avoided—as can nitrogen narcosis by substituting other gases for nitrogen in the air to be breathed. However, unless a man is never to return to his normal atmosphere then, at some stage of any pressure excursion, he must experience decompression and must therefore consider the possibility of decompression sickness. Apart from acts of carelessness, this has proved to be by far the greatest occupational health hazard to those who work in compressed air or breathe other gases at elevated pressures.

These dangers have been exacerbated within the last few years by the very deep diving now required in support of offshore oil recovery as the world demand for energy forces the development of less accessible sources. Diving is still an essential 'tool' in this industry and yet the practical need for very deep diving—and hence the appropriate means of preventing decompression sickness—has far outstripped our understanding of the subject.

Many nations have expressed concern at the alarming death rate among deep-sea divers and have tried to combat the problem by legislation but it is difficult to lay down laws about decompression procedures, at least, when there is no knowing what is correct in the first place. At best, there are a few theories and many more empirical approaches devised to fill the immediate operational needs until some general consensus of opinion emerges. Towards this end the United States' Government, through several of its energy and health-related agencies, has recently produced a 'national plan for the safety and health of divers in their quest for subsea energy'. This was compiled by committees of international experts selected by the Undersea Medical Society, one for each of fourteen areas of concern where more work is needed in protecting the health of divers. Top priority was voted for the report concerned with the 'exchange of inert gases, oxygen and carbon dioxide' but while it was flattering to be chairman of that committee, it reflected a rather depressing fact. Most workers in this field are unaware of the vast amount of very fundamental work on gas transfer and bubble formation which has been completed and yet whose description remains buried in obscure papers or the publication of which was overshadowed by more spectacular reports of record depths or decompression rates.

When entering the field, many designers of decompression procedures tend to 'dive' straight into a new calculation method with little heed for the fundamentals and produce massive

books of tables which they then proceed to test with varying degrees of success—but at great expense. If any such table results in the bends, the schedules are usually so complex that it is impossible to single out any one of the many factors which might have caused the failure. Hence there is a need to go back and look at some of the basic experiments such as those of Al Behnke and the classical approach of Val Hempleman in studying just one isolated decompression rather than viewing a whole profile in attempting to see the forest for the trees. Moreover, the classical papers of J. S. Haldane have often not been read with the detail they deserve by those that use his method. One wonders how few have ever read the works of this outstanding physiologist beyond his 1908 decompression paper in the Cambridge Journal of Hygiene.

This book is intended to bring together much of that obscure fundamental work which present designers of tables, even if aware of its existence, have too little time to dig out for themselves. This is introduced in relation to its bearing on table formulation after presenting much of the purely factual information on decompression sickness divorced from theoretical interpretation. Many chapters on decompression sickness have been contributed to several books which are now available on hyperbaric and diving physiology. However, with each author contributing only one chapter, they have a tendency to emphasize their own interpretation or model rather than to devote such limited space to the broad picture. Although I have succumbed to this temptation in the last chapter, the rest of the book is intended to present the fundamentals with the continuity with which a single author should be able to convey the information.

Other aspects of hyperbaric physiology are only mentioned in so far as they relate to decompression and the emphasis is placed upon the issues relevant to formulating preventive measures rather than a uniform coverage of the subject. This includes a critical survey of preventive methods in which several 'sacred cows', such as the decompression ratio, are reviewed most rigorously.

I am particularly grateful to Drs. Edward L. Beckman, Val Hempleman and Al Behnke for their comments and much stimulating discussion of the text. For their painstaking efforts in helping to produce and check the manuscript, I am indebted to Mrs. Susan Arena and Mr. Bruce D. Butler. Finally I should like to mention the late Dr. Hugh D. LeMessurier for captivating my interest in the bends during those early days at Adelaide.

Decompression sickness is a subject which can be deceptive in the depth and very wide range of scientific disciplines needed to appreciate the intellectual challenge it offers. It is hoped that this book will make some small contribution towards our understanding of it.

August 1976 Brian A. Hills

List of Symbols

A, A'	area, surface area per unit volume.
a	capillary radius.
B, B'	excess gas pressure in bubble, nucleus.
$2b$	intercapillary spacing.
C, C_{N_2}	overall content of general gas, N_2.
c	constant defined in text (Equation 64).
c_{N_2}, etc.	concentration of dissolved nitrogen, etc.
D	diffusion coefficient.
D_a, D_f, D_c	diffusion coefficient in aqueous tissue, fatty tissue, cells.
d	equivalent thickness of unstirred boundary layer.
E	bulk modulus.
F	Helmoholtz free energy.
F_{IN_2}, F_{IHe}, F_i	fraction of N_2, He and general inert gas in inspired mix.
f	fraction of fat in tissue.
f'	frequency.
G	Gibbs free energy.
$\dot{g}$	rate of gas transfer.
H	depth.
i_1, i_2	constants.
J, K, L, W, Z	various constants defined in text.
M	decompression ratio.
M'	ratio: gas tension/absolute pressure.
M_0	metabolic gas consumption/production
m, m'	constants defined in text (Equations 80, 27).
P	general absolute pressure.
P_{N_2}, P_{O_2}, P_{CO_2}, P_{He}	tissue tension of N_2, O_2, CO_2, He.
P_{AO_2}, P_{AN_2}	alveolar partial pressure of O_2, N_2
P_{vO_2}, P_{vCO_2}	venous tensions of O_2, CO_2.
P'_{N_2}, P'_{He}	tissue tensions of N_2, He after 'dumping'.
P_u	hydrostatic pressure applied.
P_w	water vapour pressure.
p	general gas tension.
p_i, p_a, p_v, p_m	general, arterial, venous, maximum inert gas tension.
$\dot{Q}$	blood perfusion rate.
$\dot{q}$	transfer rate.
R	universal gas constant.
R_n	coefficients.
r	radial co-ordinate.
r_b, r_n	radius of bubble, nucleus.
S, S_a, S_f, S_c	solubility—general, in aqueous, in fat, in cells.
S_{N_2}, S_{He}, S_i	solubility of N_2, He, general inert gas.
s	specific heat.
T	absolute temperature.
t	time.
U	velocity of sound.
u	gradient—see text (Equation 72).
V	volume.
v	volume of separated gas.
X	cumulative fraction of cases.
x	thickness.
α, β_1, β_2, σ'	constants as defined in text (Equation 68).
α_n, etc.	roots of auxiliary equation.
γ	surface tension.
δ_f, δ_g	pressure differential from

	fluid, gas.
δ_t	pressure differential—pain threshold.
ε	coefficient defined in text (Equation 6).
η	viscosity.
κ	thermal conductivity.
λ	blood/tissue partition coefficient.
μ	shape factor of cell.
μ_I, μ_{II}	chemical potentials.
Ξ	permeability of cell membranes.
Π	osmotic pressure.
Π_n	excess O_2 partial pressure for convulsions at t_n after constant exposure.
ρ	density.
σ	reflexion coefficient.
τ	uptake interval/'bottom' time.
χ	clearance of tracer.

Chapter 1
Introduction

Long before the evolutionary process began to shape man to his present form, his forebears had already adapted to life in the atmosphere—a gaseous environment in which terrestrial composition and pressure do not vary to any appreciable extent. Knowledge of mammalian physiology—and hence medicine—essentially relates to normal atmospheric pressure. If pressure is greatly increased, then another realm prevails in which most aspects of previous knowledge need to be revised and many thoughts modified in the light of practical experience. Even such common clinical practices as administering an anaesthetic need to be reviewed, since a dose considered 'normal' at normal pressure can prove fatal under hyperbaric (high pressure) conditions.

While it might seem wise to try to answer most of these questions before exposing men to abnormal pressures, this has not proved expedient in practice. Apart from the few individuals who have pioneered deep diving or high flying out of sheer bravado and for exploration, there is the strong economic incentive for men to apply their skills to the various jobs which need to be performed under these potentially hostile conditions.

Occupations which involve a change of pressure in transporting the man to his work-site include divers, their attendants in diving bells, pilots (together with other aircrew in non-pressurized aircraft), astronauts, caisson or tunnel workers, certain hospital personnel and the patients whom they accompany during hyperbaric oxygen therapy. In emergency situations the crew must also be included, together with the passengers, of pressure-adjusted aircraft and submarines and other 'submersibles' designed to operate with cabin atmospheres close to normal. These days perhaps the largest single section of the population to experience pressure change are the amateur SCUBA (Self-Contained Underwater Breathing Apparatus) divers seeking a more exhilarating form of recreation in exploring an exotic underwater world. Their numbers are now estimated as several million compared with several thousand professional deep-sea divers and maybe 2,000–3,000 tunnel workers.

Because operational requirements provided much of the early incentive to study hyperbaric physiology—and decompression sickness in particular—it becomes difficult to describe the development of these subjects without first outlining the histories of the pressure-related occupations.

Diving

Breath-hold

Man has probably practised breath-hold diving, in some form, from the stage in his development when he became adept at swimming and then realized its advantages in recovering food, shells and sponges from the ocean floor.

The first recorded accounts of diving describe military exploits. Xerxes is said to have used divers in combat and for recovering treasure from sunken Persian ships (Herodotus, 460 B.C.), while Alexander the Great used divers to destroy the boom defences of Tyre in 332 B.C. Breath-hold divers have been used in naval warfare ever since and in commerce, there are still such notable groups as the armaghs of Korea and Japan who dive for oysters and

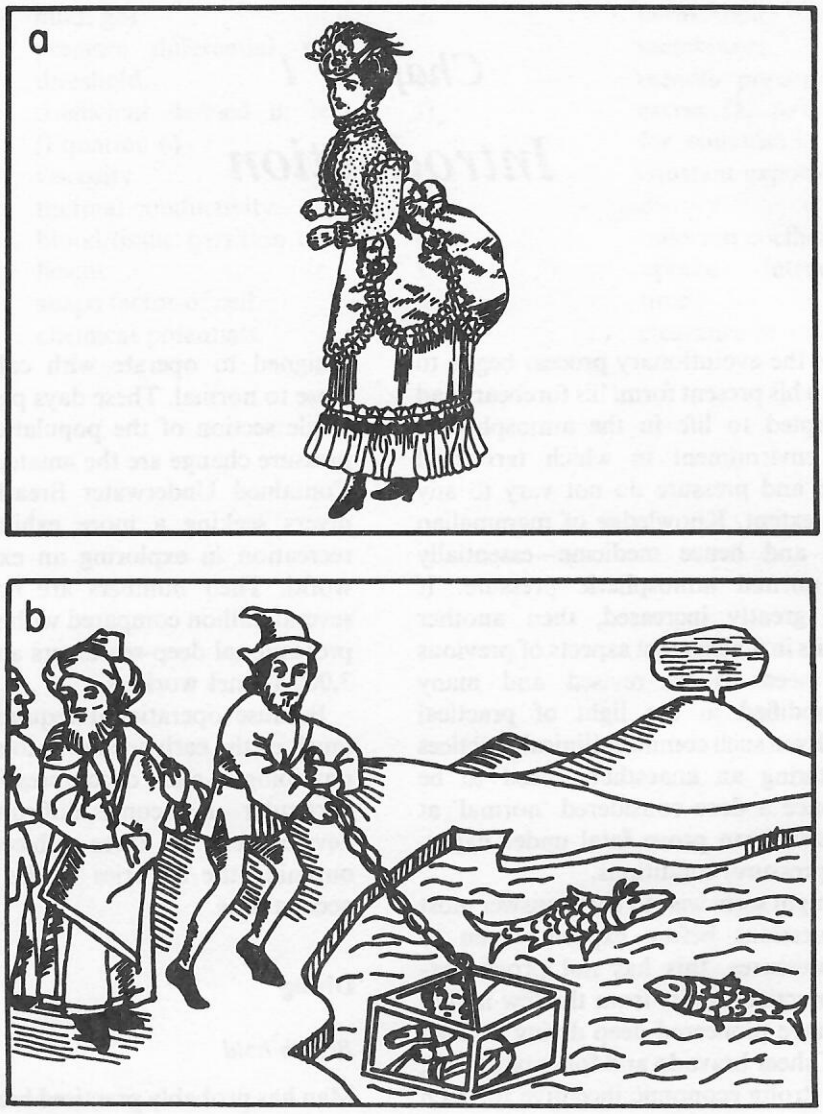

Fig. 1(a) 'The bends' is a term derived from the 'Grecian bend'—a fashionable gait in vogue among the young ladies at the time (1869 onwards) when compressed-air workers partially incapacitated by decompression sickness tended to assume a similar stoop. (Reproduced from Cunnington, Cunnington and Beard, *A Dictionary of English Costume*, 1960, by permission of the publishers: A. & C. Black Limited.) (b) An etching based upon a 15th-century print by an Indian artist portraying Alexander the Great going underwater to inspect the work of his divers in removing the boom defences of Tyre during the siege of 332 B.C.

the sponge fishermen of the Eastern Mediterranean. However, unlike the marine mammals which dive, man has a much lower inherent oxygen reserve and is, therefore, forced to surface by the depletion of body oxygen (hypoxia); although the urge to inspire is determined more by the simultaneous accumulation of carbon dioxide (hypercapnia). These simple physiological considerations limit the submergence of a trained breath-hold diver to about one to two minutes at 80–100 feet.

In diving deeper, the greater exertion needed

to return to the surface is exacerbated by the greater effort required to overcome the more negative buoyancy induced by the increased compression of the natural gas cavities of the body (lungs, nasal sinuses and middle ear). The depth range, or the time on the bottom, can be extended by avoiding energy expenditure in descent. By clutching a heavy rock to assist their descent, the Japanese can reach 80 feet compared with the Korean armaghs who actively swim to their fishing depth which therefore seldom exceeds 50 feet. This practice is taken to its limit by the 'rock-holding' diver who starts his ascent by releasing the rock the moment he reaches the bottom reserving most of his available oxygen, therefore, for the ascent to the surface. The record for this type of dive which stood at 240 feet of sea water (fsw) for many years (Schaefer *et al.*, 1968) has very recently been extended to 318 fsw. Other factors which can limit safe breath-hold descent are described later but these severe 'hypoxic' limitations have long been the incentive for supplying the diver with a further source of oxygen and a means of ridding him of his carbon dioxide.

Extended oxygen availability

Diving mammals such as the sea-lion have adapted to this problem in at least two ways: not only do they have a relatively large volume of blood but its oxygen content can be reduced to relatively lower levels than is tolerable in man. Another ingenious method of extending oxygen availability is used by certain insects which re-breathe from a bubble that they take underwater and which is attached to their bodies by surface forces—a process termed plastron respiration (Thorpe and Crisp, 1947).

To overcome the 'hypoxic' limitations to breath-hold diving, man adopted a similar principle in his first attempts to extend submergence time. Aristotle describes a diving bell in which Alexander the Great descended

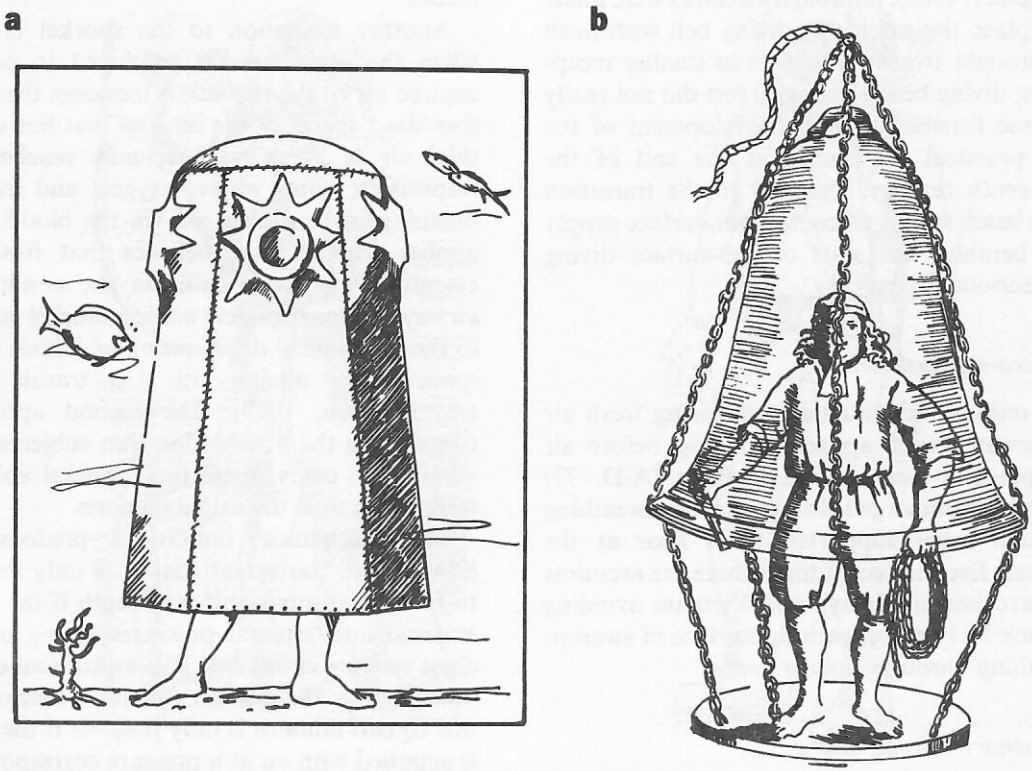

Fig. 2 Inverted receptacles used to trap a pocket of air underwater and the forerunners of diving bells: (a) the 'walking diving bell' tested by Franz Kessler around 1615 and (b) that of Sturmius, 1678

into the ocean; and goat-skins filled with air were used by free-swimming divers maybe three thousand years before modern SCUBA was designed.

Primitive diving bells were essentially inverted receptacles which enabled the occupant to re-breathe the trapped air until it became too foul for survival. They suffered from the particular disadvantage that the air volume decreased with depth (in accordance with Boyle's law) so that the diver had to retreat farther into the bell as the descent progressed in order to keep his head above the rising level of water (fig. 2). When this restricted his reach unduly he had to make breath-hold excursions from this compressed-air haven in order to perform his task.

Compression did not change the quantity of available oxygen but it did reduce the gas volume in which to dilute expired carbon dioxide the partial pressure of which is the prime humoral factor in controlling breathing (Lanphier, 1969). Although attempts were made to replace the gas in the diving bell with fresh air brought from the surface in smaller receptacles, diving below about 60 feet did not really become feasible until the development of the first practical air pumps at the end of the eighteenth century. This led to the transition from batch supply to continuous surface supply and heralded the start of sub-surface diving as a serious endeavour.

Surface-supplied diving

The military advantages of inspiring fresh air underwater were appreciated long before air compressors were invented; Pliny (A.D. 77) described submerged Roman soldiers breathing through tubes supported by a float at the surface. Even in recent times there are accounts of terrorists in Malaya and Vietnam avoiding capture by lying beneath the surface of swamps breathing through hollow reeds.

Pulmonary considerations

The supply of fresh air at normal pressure via a non-collapsible tube involves the principle of the 'snorkel' as used in present-day submarines. Submersible vessels which operate with cabin pressures near to normal, however, are rigid and designed to resist implosion by the ocean. By comparison, man is a collapsible structure and can only inspire fresh air by expanding his overall volume, having to work to overcome the pressure differential across his chest wall in addition to overcoming frictional forces. This work of breathing increases greatly for each few inches that the centre of pressure of the lungs is lowered beneath the surface of the water until, at three to four feet, the inspiratory effort becomes too great. Most people free from pulmonary disease can suck in air against a maximum head of four feet of water and blow out against three feet. Allowing about two feet from the centre of pressure of the chest wall to the top of the head, this means that most individuals immersed vertically cannot breathe through a snorkel if submerged more than about 12 inches.

Another limitation to the snorkel is that, when the same tube is employed to convey expired air to the surface, it increases the effective 'dead-space' of the lung so that less of the tidal air is 'fresh' and actually reaches the respiratory zone where oxygen and carbon dioxide can be exchanged via the blood. This applies whether one believes that fresh air essentially displaces gases in the conducting airways, (approximately adding snorkel volume to the anatomical dead-space), or dilutes dead-space gas by mixing with it in transit (Hills and Kuonen, 1973). The second approach can explain the observation that subjects have survived in cases where their snorkel volumes were larger than their tidal volumes.

The mechanical limitations predominate, however, to the extent that it is only feasible to breathe at any significant depth if the mean external and internal pressures acting on the chest wall are equalized. This means that diving much below the surface for more than about one to two minutes is only possible if the diver is supplied with air at a pressure corresponding to his ambient depth. The work of breathing then simply becomes that of overcoming the

resistance of the airways of the lung to the tidal flow of air plus the other frictional factors inherent in its structure and operative in normal respiration. At least, this is the case provided the diver is not wearing a stiff 'wet suit' which resists expansion of the chest wall and he is surrounded by air to the level of his diaphragm. If the centre of pressure of his lungs is a vertical height h below his mouth, then the diver does less work of breathing and feels more comfortable if the air is supplied at a pressure $(P + h)$. If he is then inverted, however, as may occur with a SCUBA diver swimming downwards, he may be overinflated by $2h$—a value which could approach the three-foot limit for expiration. For this reason various devices have been invented to allow for diver orientation in minimizing respiratory fatigue—one of the more recent and ingenious being the cardioid valve (O'Neill, 1970).

Before outlining the principle of SCUBA, however, historical place of preference must be given to the conventional 'hard-hat' diver (fig. 3b).

The hard-hat diver

The first air compressors were simply hand-operated bellows fitted with non-return valves; but these early 'hand-pumps' provided the vital need in diving of maintaining a pocket of fresh air against the ocean pressure. Moreover they could be used at any depth up to the pressure capability of the pump without need for any close control of its output. Merely by leaving the air pocket open to the water, excess air simply bubbled out from beneath the retainer rim irrespective of its rate of supply, leaving the pocket at the ambient pressure. In doing so, it also replenished the pocket with oxygen

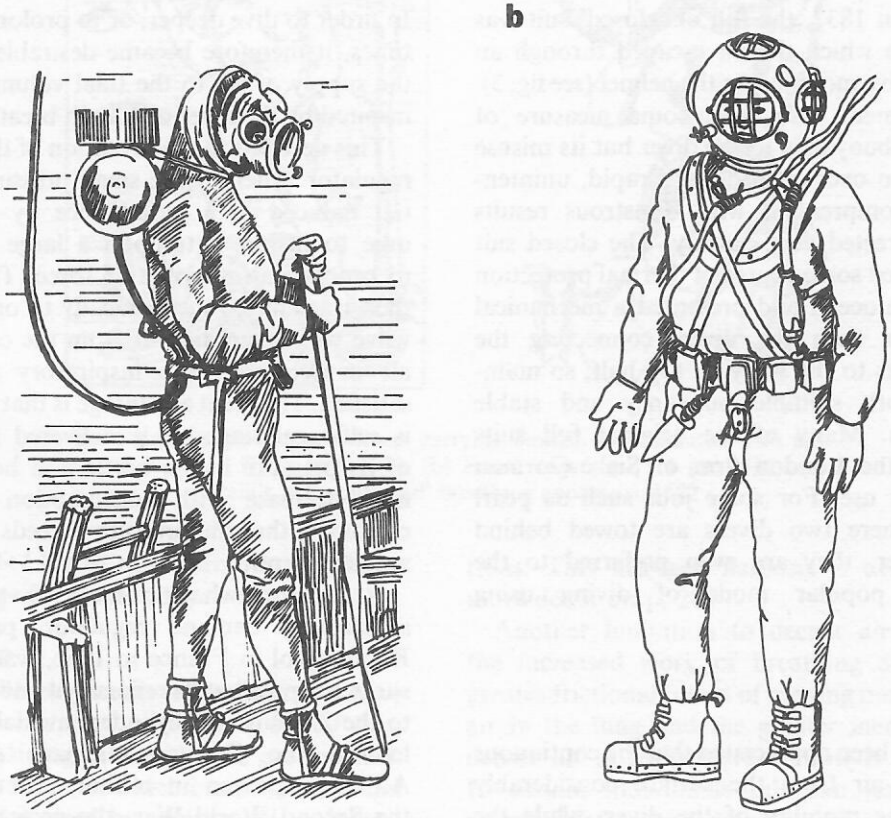

Fig. 3(a) The first demand regulator designed by Rouquayrol in 1866 for surface supply.
(b) The traditional hard-hat diver with surface supply

while simultaneously removing unwanted carbon dioxide.

In the first practical deep-sea outfit designed by Siebe in England in 1819, this 'retainer' for the air pocket was a metal helmet attached to a jacket open at the waist. The air flushing the suit simply bubbled out from around the bottom and the fact that the chest wall of the diver was surrounded by air avoided problems of breathing against the head of water between the centre of pressure of the lungs and the mouthpiece as used in later and more sophisticated outfits.

These 'half-suits' are still used in some parts of the world with little change but they constitute a hazard to the diver who loses his balance. Even within the last decade there are records of native 'islanders' in the Timor Sea who have fallen over on the ocean bottom and drowned within their own helmet despite a continuous and adequate supply of fresh air.

Hence, in 1837, the full or 'closed' suit was invented in which the air escaped through an exhaust valve mounted on the helmet (see fig. 3). Its adjustment also gave some measure of control of buoyancy to the diver but its misuse often led to over-inflation and rapid, unintentional decompression with disastrous results unless corrected very quickly. The closed suit also afforded some degree of thermal protection against the ocean and presented a mechanical link, other than the diver, connecting the heavy boots to the buoyant top half, so maintaining both suitable buoyancy and stable orientation. Many of the original full suits made by the London firm of Siebe-Gorman are still in use. For some jobs such as pearl fishing, where two divers are towed behind each lugger, they are even preferred to the currently popular mode of diving using SCUBA.

SCUBA

It has long been appreciated that the continuous supply of air from the surface considerably restricts the mobility of the diver, while the hose can impose a 'drag' if there is any appreciable current. Attempts to enable the man to swim, carrying with him the pocket of ambient-pressure air, have been made since ancient times (fig. 4) but the limited capacity of these early devices was a major restriction until a way was found to provide air already compressed at the surface which the diver could then carry to depth.

James, in England, in 1825, used an iron reservoir worn around the waist to store the compressed air, while the first containers resembling present-day air bottles were shown in the apparatus designed by Sicard in France in 1853. These devices, however, provided a continuous flow of air to the diver and hence a volume well in excess of that actually inspired. While this had previously posed little problem with surface supply, it very soon depleted the gas store of these early designs of SCUBA. At the end of the nineteenth century, air storage capacity was still severely limited by a maximum bottle working-pressure of around 500 psi. In order to dive deeper, or to prolong exposure times, it therefore became desirable to restrict the supply of air to the tidal volumes actually inspired by the diver with each breath.

This need led to the invention of the 'demand regulator' whereby the small pressure differential induced in a mouthpiece by the diver's urge to inspire acts upon a large diaphragm to produce an appreciable force. This force is then transmitted mechanically to open a small valve which supplies air from the compressed-air source until the inspiratory demand is satisfied. The great advantage is that the process is self-regulating; air is delivered irrespective of its pressure in the bottle and however this may decrease with consumption—provided, of course, that the pressure exceeds that of the ambient depth.

It is somewhat ironical that the first satisfactory demand regulator, patented by Rouquayrol in France in 1866, was used with surface supply but its refinement and adaptation to the 2,000 psi air cylinders available by 1943 led to the Cousteau-Gagnan 'Aqua-lung'. Although proven in military combat during the Second World War, the perfection of the demand regulator has made SCUBA diving comparatively safe and its commercial avail-

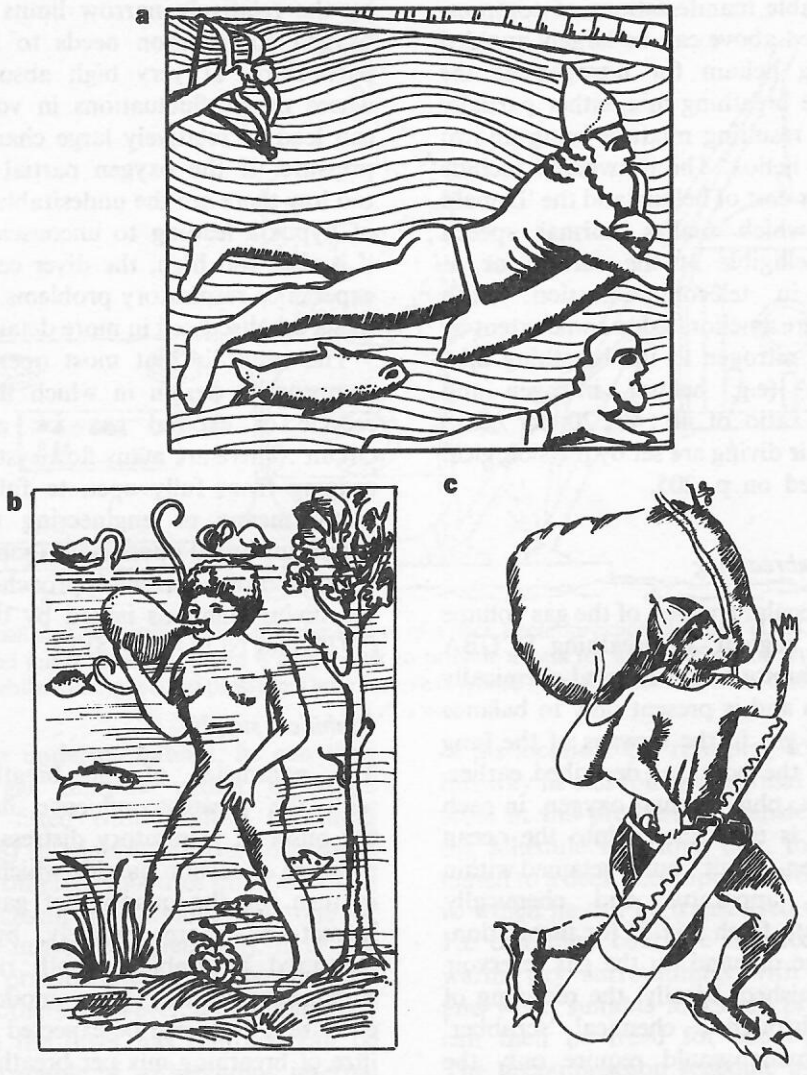

Fig. 4 Early self-contained divers carrying animal skins inflated with air. (a) An Assyrian frieze (900 B.C.). (b) From Vegetius, 1511 (or 1532). (c) Borelli's 'self-contained' breathing apparatus, 1582

ability in 1947 led to the enormous popularity which this sport enjoys today.

Heliox diving

Successive developments of equipment have led to deeper diving until, at 200–300 feet, the first physiological limitations are reached. It is a depth range in which brain function can be severely impaired by compressed-air intoxication—or 'rapture of the deep' as translated from one of the more romantic French descriptions. This nitrogen narcosis is described in more detail on p. 204.

Another limitation to deeper air diving is the increased work of breathing due to the greater frictional forces of moving more viscous air in the lung and the greater inertia of the denser air in regions where flow is turbulent. In certain individuals this can lead to the retention of carbon dioxide with the unfortunate consequences of hypercapnia summarized on p. 206.

The undesirable manifestations of compressed air described above can be largely avoided by substituting helium for nitrogen as the inert gas in the breathing mix, either partially or totally, the resulting mixture being known colloquially as heliox. The drawbacks include the much higher cost of helium and the 'Donald Duck' voice which makes normal speech virtually unintelligible at the surface or to other divers in telecommunication. Both disadvantages are ameliorated to some extent by retaining some nitrogen in the breathing mix, as in 'Trimix' (e.g. helium, nitrogen and oxygen in the ratio of 40 : 40 : 20 per cent.) The limits for air diving are set by physiological factors discussed on p. 205.

Closed-circuit rebreathing

The major molecular fraction of the gas volume carried by the regular air-breathing SCUBA diver is inert, cannot be assimilated chemically by body tissues and is present only to balance the pressure of gas in the airways of the lung against that of the ocean as described earlier. If this inert gas, plus residual oxygen, in each expired breath is not exhaled into the ocean as bubbles ('open-circuit') but is retained within the breathing apparatus and chemically reconstituted into fresh mix fit for inspiration, then the volume demand on the gas reservoir is greatly diminished. Ideally, the recycling of expired mix through a chemical 'scrubber' for carbon dioxide would require only the metabolic oxygen demand of the body to be supplied from a high-pressure bottle after the first breath at a new depth.

Unfortunately, this ideal fully 'closed-circuit' system is not so simple to realize in practice. The difficulties arise largely from controlling the composition of the mix in a system where the pressure is changing and leaks may be significant relative to the total recirculating gas volume. Electronic methods successful in sensing oxygen composition under laboratory conditions have yet to be proved adequate in controlling the composition of breathing mix under the much more exacting conditions of diving in the ocean. This situation is exacerbated by the relatively narrow limits within which oxygen composition needs to be controlled, particularly at very high absolute pressures where minor fluctuations in volume fraction can lead to relatively large changes in partial pressure. If the oxygen partial pressure falls too low there are the undesirable consequences of hypoxia leading to unconsciousness while, if it rises too high, the diver can convulse or experience respiratory problems. These phenomena are discussed in more detail in Chapter 8.

The result is that most operators select a compromise design in which there is partial recycle of expired gas—i.e. a 'semi-closed circuit'. There are many flow systems, however, ranging from fully open to fully closed and many means of engineering the breathing apparatus based upon each; (good descriptions of some of the current approaches are given in the diving manuals issued by the U.S. Navy (1974) and NOAA (1975)).

Umbilical supply

The parameter of the breathing medium with the greatest influence in determining the onset of respiratory distress is the partial pressure of carbon dioxide which is controlled, in turn, by the quantity of gas flushing the helmet—or, more precisely, by the volume measured at ambient depth rather than at standard pressure. At a moderate level of exercise a diver can be expected to inspire one litre of breathing mix per breath. At 1000 feet (31·3 ATA) this would require 31·3 litres or 1·1 cubic feet of free mix at surface pressure. Even with partial recycling and a supply at 2000 psi (137 ATA), it does not take many breaths to exhaust any bottle which a diver can be expected to carry with him. It is now common practice in very deep diving, therefore, for the diver to be supplied from a remote gas reservoir often located on a submersible decompression chamber (SDC) or on the diving bell from which he is working. This involves an umbilical hose and therefore reintroduces some of the restrictions in mobility imposed by the life-line of the original hard-hat diver. Once a diver returns to his SDC,

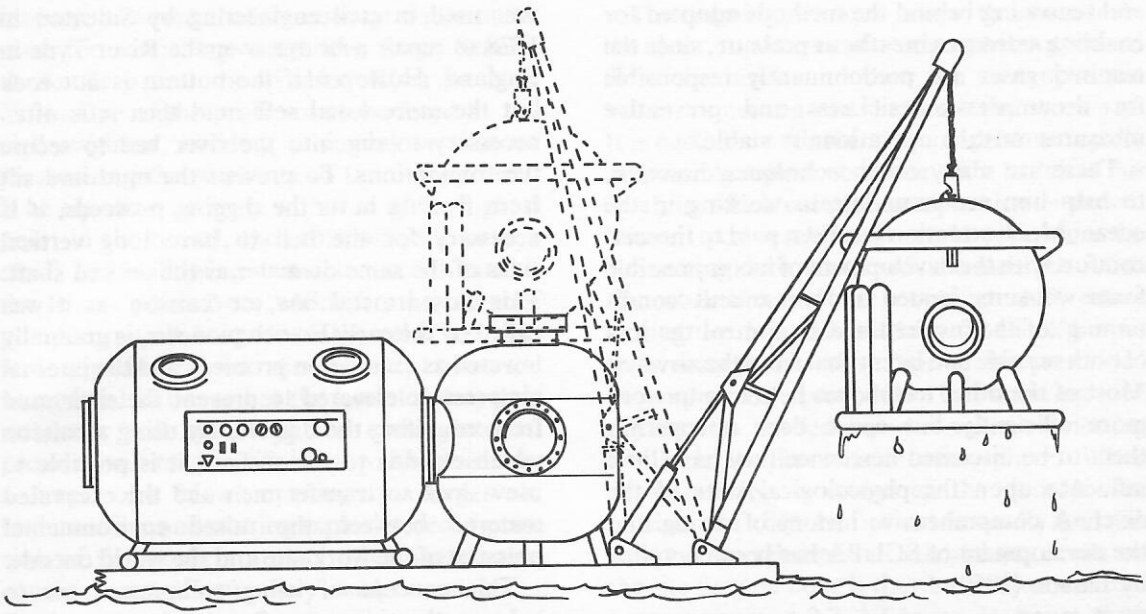

Fig. 5 A diving bell shown 'mating to the transfer sphere of a deck decompression chamber (DDC) to which divers can be transferred under pressure. There is also a lock to provide access for an attendant or physician needed to reach the divers while holding them at pressure. Quite complex systems of interconnecting chambers can be assembled in this way

bell, or similar undersea habitat, he can then breathe the gas mixture within it; some chambers are fitted with 'built-in breathing systems' (BIBS) to enable the diver to breathe one of several different mixtures or to alternate between the chamber mix and any one of the others as instructed. Generally it is not practicable to provide more than one chamber mix and three others. However, if the submerged unit to which the diver has returned can be sealed and is capable of withstanding internal pressure, then it is safer to use it to convey him to the surface at his 'bottom pressure' and then worry about decompression divorced from the natural hazards which the ocean can pose.

Surface decompression

Surface decompression is a decision forced upon divers as a result of cold water and strong tides which render decompression in the open sea impracticable. These days the diver can be returned to the surface in a pressurized transfer capsule (PTC) or bell so that, once he has sealed the hatch at the bottom, his decompression can proceed quite independently of his location. On returning to the surface in this way he can follow a normal decompression table in the pressurized transfer vehicle or, if the schedule is a long one, the PTC can be mated to a deck decompression chamber (DDC) to which he can be transferred under pressure. He can then continue his decompression in warm, dry surroundings with toilet facilities and when suitable locks are provided the bell can then be freed for use by other divers. The decompression schedule used is the same as that in water with the exception that the diver can alternate between breathing mixes, inspiring either chamber air or the mixture supplied by mask connected to the BIBS provided in most deck decompression chambers. The transfer from bell to DDC is often arranged to coincide with the switch from heliox to air as the breathing mix, so that only the much smaller bell needs to be filled with helium while the DDC can be brought to the mating pressure with air. A typical 'saturation system' suitable for a long decompression on deck is shown in fig. 5.

Other aspects of diver welfare

The foregoing summary has outlined the history

and reasoning behind the methods adopted for enabling a diver to breathe at pressure, since the respired gases are predominantly responsible for decompression sickness and preventive measures must be operationally viable.

There are many other techniques, however, to help him accommodate to working in the ocean. Much attention has been paid to thermal comfort with the development of incompressible foam wet-suits, heated underwear and 'conditioning' of the inspired mix to control the loss of both sensible and latent heat from the airways. Most of the other techniques help him to work more efficiently but space does not permit them to be discussed here since they have little influence upon the physiological state of the diver. A comprehensive history of diving and the development of SCUBA has been compiled by Larson (1959).

Caisson and Tunnel Work

Civil engineering

If underwater foundations are needed for a span of a bridge over a river and they cannot be installed from the surface, then it is a relatively simple operation to lower a diving bell until its open bottom settles onto the proposed construction site. This technique was probably first used in civil engineering by Smeaton in 1778 to repair a bridge over the River Tyne in England. However, if the bottom is not rock but the more usual soft mud then it is often necessary to dig into the river bed to secure the foundations. To prevent the mud and silt from flowing in as the digging proceeds, it is necessary for the bell to have long vertical sides of the same diameter as the desired shaft. This closed metal box, or 'caisson' as it was called by the early French pioneers, is gradually lowered as excavation proceeds and the internal air pressure elevated to prevent the river mud from engulfing the diggers. By using a caisson which extends to the surface, it is possible to use a lock to transfer men and the excavated material between the raised environmental pressure of the work-site and the world outside.

This concept of using compressed air to balance the pressure of water in the subsoil can be extended to the construction of tunnels, the technique being first patented by Sir Thomas Cochrane in 1830. It became feasible with the development of compressors with sufficient capacity to deliver the large volumes of air needed. Triger is often quoted as the first to use a caisson in the construction of a bridge across the River Loire at Zhalonnes in France in 1841.

It was not until the end of the nineteenth

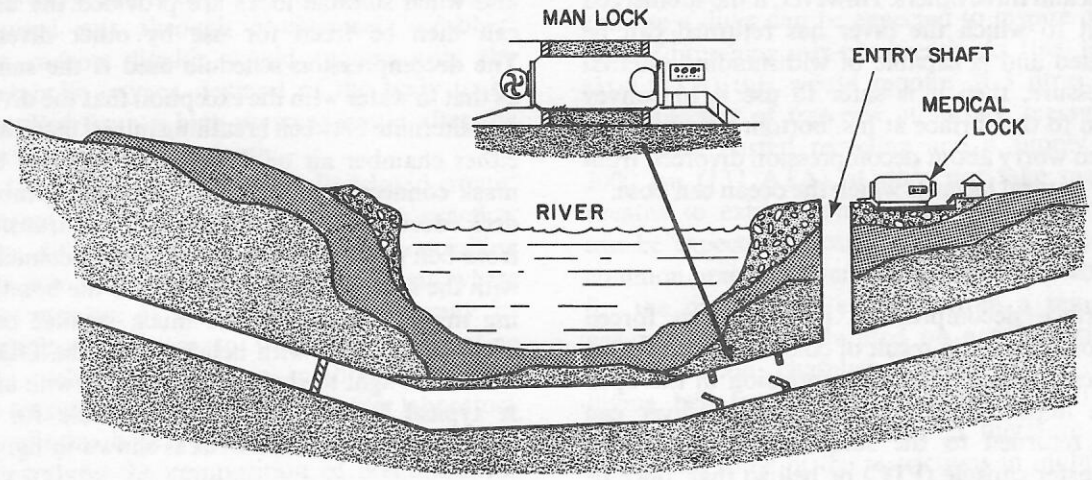

Fig. 6 Demonstrating the system of locks required for containing the compressed air needed for tunnelling under a porous river bed

century, however, that the concept was actually used for tunnelling under the River Scheldt at Antwerp and the Hudson River in New York. One of the problems to be faced by the civil engineer building a tunnel is that of pressurizing the work-site to the correct level. If he equalizes pressure with that of the highest point in the tunnel, then this will still leave a small head allowing water to accumulate at the lowest point from which it must then be pumped out. If he goes to the other extreme and equilibrates the air pressure with the water head in the soil at the lowest point, then no water will enter but the excess internal pressure will tend to lift the top. There is then a danger of a 'blow', opening up a large void to the surface and causing explosive decompression of the workers among other undesirable consequences. Fortunately such occurrences are very rare.

Air supply

The workers respire freely in the air in the tunnel, so that it needs to be clean, dry and relieved of most of the heat of compression. Performing heavy manual labour they exhale significant quantities of carbon dioxide, while this and other noxious gases can also be emitted from the ground into which they are boring. The British regulations for work in compressed air (Special Regulations, 1958) specifies a minimum ventilation rate of 10 cubic feet of fresh air per minute per person. When considering this demand and the leak rates when the tunnel reaches a porous region, vast quantities of low-pressure air must be available, Haxton and Whyte (1969) quoting a capacity of 29,000 cubic feet of free air per minute for the construction of the Clyde tunnels.

The locks

Air-locks must be provided to enable both men and materials to be passed through the bulkhead sealing off the workings from the atmosphere beyond. On the smaller projects one lock might serve both purposes but often there are three—two for materials and one for men.

The ingoing workers enter the man-lock, the door to the outside atmosphere is closed from the inside and then the men open the valve connecting the lock to the work-site. It is customary for them to compress as rapidly as possible unless someone fails to 'clear his ears', in which case the compression is slowed down. Upon reaching the working pressure the connecting door is opened, the men get out at the work-site and the outgoing shift enters closing the door behind them. The lock-keeper then ensures that they receive the prescribed decompression procedure by reducing the pressure as needed using a valve connecting the lock to the outside atmosphere. When decompression is complete, the door to the outside can then be opened inwardly and the workers are released but advised to remain on the site for one hour if they have returned from a pressure over 2·2 ATA; or 1½ hours from over 3·5 ATA.

Smaller locks are often available to enable engineers, foremen and maintenance men to make short visits to the work-site.

Decanting

Because the shaft to a tunnel or a caisson is vertical, the locks tend to have the same orientation. If the vertical man-lock is too narrow for the comfort of a shift during a decompression (which may last two hours), then they may be rapidly decompressed to normal atmospheric pressure and transferred to a 'horizontal lock', recompressed to their previous working pressure and then undergo the gradual decompression prescribed for their exposure. Under present British regulations the transfer time may not exceed five minutes. This method of rapid transit through the vertical lock followed by recompression in a horizontal lock is termed 'decanting' and corresponds to surface decompression as originally practised in diving (p. 162). It is also used where there is just one main lock which is horizontal and needs to be cleared quickly for excavated material produced by the next shift, the men then being transferred to a 'decanting lock'.

The 'bends'

Inadequate decompression can lead to a number of undesirable effects which are given the general term decompression sickness or compressed-air illness, the symptoms being discussed in detail in Chapter 2. The principal discomfort is pain which is worsened if the victim stands erect. During the construction of the Brooklyn Bridge in 1894, when large numbers of caisson workers were afflicted in this way, they would often assume a stoop resembling the posture adopted by the fashionable ladies of New York at that time—termed the Grecian Bend. Hence these poor victims were described by their fellow workers as having 'the bends' and the term has remained in use ever since.

The medical lock

The first use of the caisson by Triger in 1841 also produced the first symptoms of compressed-air illness (Triger, 1845; Pol and Watelle, 1854). It was not until the construction of the Hudson River Tunnel in 1889, however, that Sir Ernest Moir used the first 'medical lock' to treat 'the bends' by recompression. This is a pressure chamber divided into two parts to enable an attendant or a physician to be 'locked-in' to attend to the man undergoing treatment. These medical locks must be provided on the site of all tunnels where the working pressure exceeds 2 ATA according to British regulations—which tend to be used as a basis for other sets of regulations, since the problem is rather more acute in Britain where the climatic conditions and consistency of the subsoil necessitate the use of compressed air in tunnelling. Some 1,700–1,800 men are now registered with the Central Registry of Compressed-air Workers in Newcastle-upon-Tyne. Policy has been guided by a nation-wide interdisciplinary Decompression Panel of the Medical Research Council which enjoys the confidence of the civil engineering contractors in setting up standards to protect compressed-air workers and so minimizing private litigation.

Hyperbaric Therapy

There are two aspects to the clinical use of pressure: the effectiveness of the treatment to the patient; and the exposure to be tolerated by the medical personnel who may be required to accompany that patient to the same pressure but often breathing a different mix.

Hyperbaric personnel

Occasionally an entire hospital operating-theatre team may be taken to pressures of 2–3 ATA for a surgical procedure such as amputation of a limb affected by gas gangrene. Most oxygen treatments, however, involve exposures seldom exceeding 3 ATA for periods of the order of 1–2 hours, depending upon the disease, and may be repeated 3–4 times in the same day. The therapy can be given in a small chamber, such as the portable version manufactured by Vickers, which is just large enough to take a stretcher. More often it is desirable for a nurse to be present, or for various technicians to perform laboratory tests such as blood-gas analyses—in which case a larger chamber must be used similar in construction to the 'medical locks' described earlier. These hyperbaric personnel are exposed to an atmosphere which is predominantly air compressed to the treatment pressure. In this way some of these people are receiving cumulative exposures not unlike those of caisson workers and it is not surprising to find some of them requiring recompression for 'the bends', while a few have shown other similar manifestations of compressed air such as radiographic evidence of bone lesions (p. 195).

Safety aspects

The larger chambers are fitted with man-locks which permit nurses or technicians to take turns on duty and allow for a physician to visit the patient or for maintenance men to inspect the equipment without interrupting the therapy. Substitution of personnel by use of the lock is one means of reducing the exposure of any one individual and often avoids anyone accumulating decompression time.

In all but the smaller chambers 'tailored' to patient dimensions, a patient for oxygen

therapy is given pure oxygen to breathe within a head-tent or, possibly, by mask or mouthpiece. Any wound, burn or skin infection to be treated is often contained within a fire-resistant plastic bag vented with oxygen. The head-tent atmosphere can be sucked through a carbon dioxide scrubber simply using the Venturi effect of the make-up oxygen, injected from a high-pressure orifice, as the recirculating force.

The patient is often sedated and therefore less prone to convulse with hyperbaric oxygen but, if he should, then removal of the mask by the nurse, or by his own movements in the seizure, returns him to air breathing and hence rapid restoration of his previous state.

Confinement of the pure oxygen to the patient avoids similar occurrences in the attendants who are not sedated—and may even be active—and hence more prone to oxygen toxicity (see p. 220). In many chamber facilities the purge from the oxygen system is vented outside the chamber. Where it is vented into the chamber, the atmosphere is monitored and the oxygen content not allowed to rise above about 25%; but there must be good mixing to avoid pockets of 'dumped' oxygen, especially in heliox environments in which layering tends to occur.

Dilution of dumped oxygen reduces the risk of fire and explosion, since the inert gas present exerts a quenching action by absorbing the heat from any flame. This can overcome the enhanced ignition potential of increased oxygen partial pressure as can be demonstrated by a lighted candle which can be extinguished by compression in air.

A further advantage of oxygen confinement is the reduced cost of operation by supplying oxygen only to the immediate environment of the patient and not using the gas to compress the whole chamber.

The term 'patient' can, in its broadest sense, include the diver or caisson worker receiving treatment for the bends or those receiving elevated oxygen partial pressures as a preventive measure during decompression. There are many detailed descriptions of hyperbaric facilities, their maintenance and safety aspects but a succinct coverage has been compiled by the Committee on Hyperbaric Oxygenation (1966).

Approaches to hyperbaric therapy

Medical interest in hyperbaric oxygen has fluctuated widely, from the first clinical use of hyperbaric air by Henshaw in 1662 (recorded by Simpson, 1857), to the construction of the six-storey, 72-room 'hyperbaric hotel' by Cunningham in the 1920s. An entertaining account of this 'maverick of medical treatment' has been prepared by Trimble (1974) who describes the early rush to use hyperbaric oxygen clinically but the really scientific assessment of its value was probably pioneered by Borema in Holland and Illingworth in Scotland.

Hyperbaria can be used clinically in several distinct ways; it can be used purely as a physical agent to reduce gas volume; or for its chemical potentiation of oxygen *in vivo*. When used chemically, it can be employed either to displace a chemical equilibrium in a desired direction and so minimize the effect of an undesirable competitor with oxygen (such as carbon monoxide) or it can be invoked to help relieve oxygen insufficiency in the tissues (anoxia).

There is no question of the benefits to be gained in using pressure *per se* as the mechanical agent in treating gas embolism and this is discussed in Chapter 8. This applies whether air embolism was induced unintentionally by a surgical procedure, an illegal attempt at abortion, or by decompression. The last of these includes gas embolism due to rupture of the pulmonary membrane or to cavitation (as shall be reviewed in greater detail later).

'Burst lung' and 'the squeeze'

These accidents can occur very easily in the untrained individual attempting to dive or in the trained diver overcome by fear or an oxygen convulsion during decompression. If one of these individuals instinctively closes his glottis, his thoracic cavity becomes a closed gas chamber whose walls then offer the only restraint to the free expansion of that trapped gas which would otherwise take place during decompression.

This leads to a positive pressure difference between lung gas and the environment, i.e. a pressure differential across the pulmonary membrane separating air from blood—a barrier with the equivalent surface-area of a tennis court yet tissue-paper thin (1–3 μm). When this differential increases to about 60–100 mm Hg (Moses, 1964), structural failure starts to occur. It leads to a condition known as 'burst lung' resulting in injection of air into pulmonary venous blood and on into the arterial circulation where it can cause most damage in occluding blood flow to those organs where the emboli happen to lodge. This is the usual cause of death in submarine escape or in the inexperienced pearl fisherman who dives simply by holding a conventional helmet over his head but then panics on meeting an octopus or a shark. In his haste to swim to the surface, he has been known to abandon his helmet and close his glottis, only to pass into a coma within a short time of reaching the surface—often with massive pulmonary haemorrhage. Needless to say, a large part of diver and submarine-escape training is aimed at overcoming this instinctive urge to close the glottis in fear. This example also emphasizes the inherent danger in continuing the decompression of a man in an oxygen convulsion.

Before bursting, some support in maintaining the integrity of the lung structure is derived from the chest wall. If the chest muscles are partially relaxed, however, then this support is diminished. This explanation has been offered for the many cases of gas embolism occurring with over-inflation of the lungs of patients under surgical anaesthesia in the early days of assisted ventilation.

It also raised the very difficult question of whether to recommend the mouth-to-mouth technique of artificial respiration to resuscitate a victim of 'burst lung' undergoing recompression therapy. Although more efficient in effecting passive lung inflation, any appreciable increase in the air-to-blood pressure differential increases the potential pressure-head tending to inject air into the pulmonary circulation.

The pulmonary membrane can also be ruptured by an excess pressure in the other direction. This applies to the breath-hold diver or anyone holding their breath for too long during compression. The closed thoracic cavity is then subjected to 'the squeeze', with the airways of the lung tending to implode. While this may cause massive pulmonary haemorrhage as rupture occurs, subsequent inflation of the lung can cause air to pass into the pulmonary circulation, again resulting in air embolism. Once again it is a matter of training to keep the glottis open and prevent closure of the thoracic cavity. This applies to the rapid compression phase of submarine-escape and to the emergency device being developed by the author for the rescue of divers in the event of mechanical failure of the novel normobaric diving suits currently under development for particularly deep diving (1000–3000 feet).

In all but military combat situations, a pressure chamber should be available, since rapid recompression is the only effective treatment. It is Naval practice to have a chamber open at the top of the escape training tank with a well drilled team ready to receive a suspected victim within seconds of his breaking surface.

Hyperbaric oxygenation

There is little doubt that compression to 3 ATA with pure oxygen greatly increases the rate of recovery from carbon monoxide poisoning—and the chances of recovery if the case is discovered soon enough (End and Long, 1942; Sluyter, 1963). This success has a simple physico-chemical interpretation based upon the law of mass action.

The greatly elevated partial pressure of oxygen enables that gas to recapture more of the sites on the haemoglobin (Hb) molecules in competition with carbon monoxide for which these blood pigments have a much greater chemical affinity. For instance, a heavy smoker with 7% saturation of haemoglobin with carbon monoxide, has a carbon monoxide partial pressure/tension (P_{CO}) of only about 0·00005 ATA. This very low figure provides a word of warning to divers to prevent any motor exhaust from reaching the compressor intake when

refilling gas bottles. In direct surface supply, the P_{CO} of a gas inspired at depth is increased above that on the surface in proportion to the compression ratio.

The use of hyperbaric oxygen to relieve anoxia is more controversial since, at some time or another, someone has tried this 'uncertain miracle' as a means to cure almost every disease (Trimble, 1974) but many of the early claims have not been substantiated. Now that a clearer picture is starting to emerge, it is currently recommended for a number of disorders which include burns, vertigo, crush injuries to the head and body, gas gangrene, intestinal obstruction, drowning and asphyxia, stroke, skin grafts and ulcers, osteomyelitis, gastric ulcer, pulmonary insufficiency, electrocution, myocardial infarction, actinomycosis, cyanide poisoning, overdoses of digitalis, some forms of infection giving Meleney ulcer and the acute episode of sickle cell anaemia. A comprehensive handbook for the treatment of these diseases with hyperbaric oxygen (HBO) has been compiled by Kindwall (1973).

Much of the controversy surrounding the therapeutic use of HBO stems from the difficulty in using controls to evaluate a clinical procedure as are used with animals to test a physiological hypothesis. The question now seems more one of deciding whether HBO at two or three ATA is significantly better than pure oxygen at normal pressure and whether any improvement is too marginal to warrant the heavy investment in equipment and personnel needed for a hospital to 'go hyperbaric'.

Physiological considerations

The physiological aspects and apparent advantages of HBO have been succinctly expressed by Lambertsen (1966) and Lanphier and Brown (1966). The vital question seems to be whether the driving force for oxygenating the anoxic cell relevant to a particular disorder is the arterial oxygen tension (P_{aO_2}) or the venous value (P_{vO_2}) or something in between. Only a few workers have faced this fundamental question (Evans and Naylor, 1963) which is discussed in detail with respect to decompression sickness in Chapter 7. Where the oxygen consumption is high relative to the blood supply, such as in tumours, there is little difference in P_{vO_2} when breathing pure oxygen whether at pressure or not—see fig. 10. Hence the concept of the venous driving force has been offered (Hills, 1969a) as the reason for the comparative failure of hyperbaric radiotherapy in treating cancer (Atkins *et al.*, 1965), a disappointment which seems to have adversely and unjustifiably affected opinion upon the use of HBO to treat other disorders.

Altitude Ascent

For many centuries mountaineers have been experiencing a number of the physiological restraints encountered when the ambient atmospheric pressure falls significantly below that at sea level (hypobaric conditions) superimposed upon the many other discomforts which this hardy minority of the community seem willing to accept. These limitations are mostly related to hypoxia whose effects are felt long before the summit of Mount Everest (29, 141 feet); although many mountain tribes show remarkable physiological adaptation to life at high altitude (Sorensen and Severinghaus, 1968). Mountain climbing, however, usually represents such a low rate of pressure change that decompression *per se* offers no problem.

This is not the case with direct aerial ascent which really started in 1783 with the hydrogen balloon of Professor Charles and the hot-air balloon of the Montgolfier brothers. Extravagant claims of the altitude reached in such escapades were the order of the day as 'balloonomania' became an obsession of the times. In 1803 Zambeccari and Grassati both became unconscious while ascending in their hot-air balloon, an incident to be followed by reports of similar disability occurring during many more ascents performed during the nineteenth century.

In the meantime, in France, Junod had constructed what was probably the first hypobaric chamber to be used for experiments on man. Using a more sophisticated two-compartment model in 1875, Paul Bert found that he

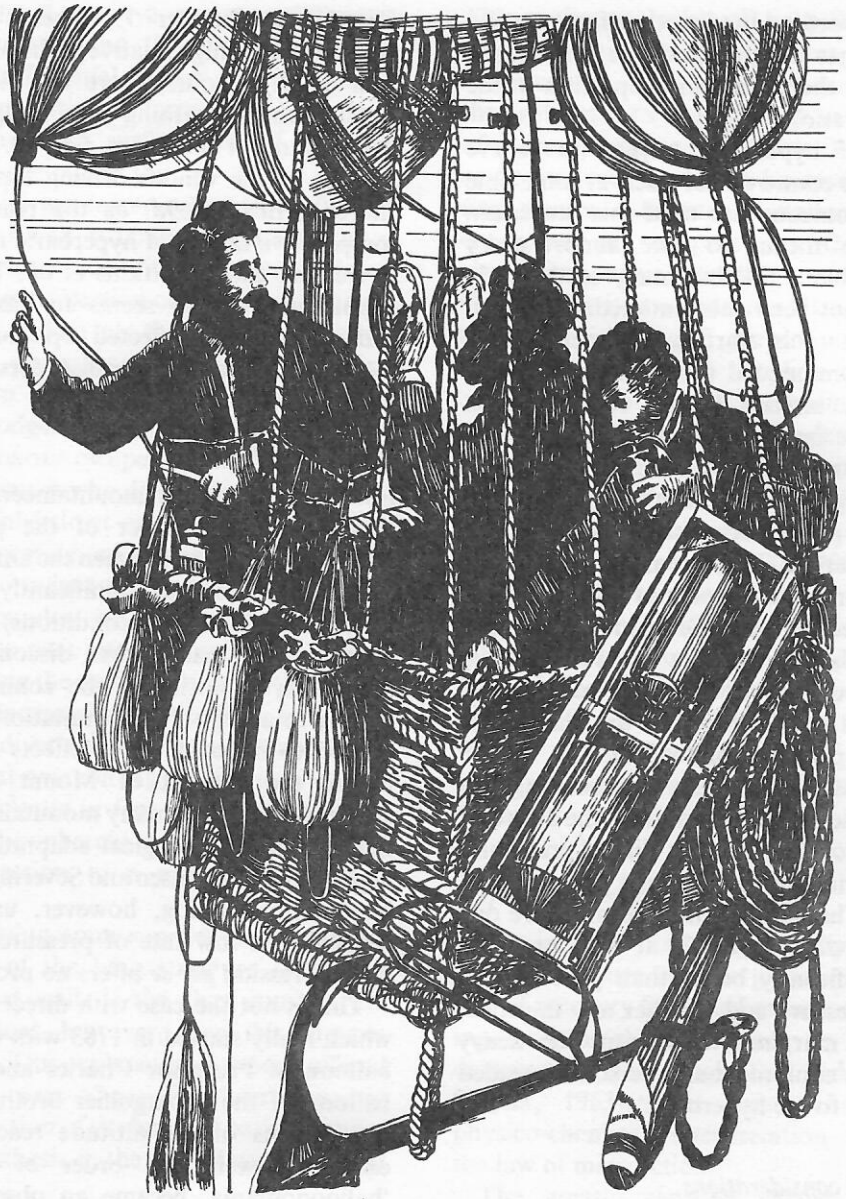

Fig. 7 An artist's impression of the flight of the early balloonists Tissandier, Sivel and Crocé-Spinelli in 1875. Redrawn from Randel (1971)

did not experience the symptoms of hypoxia if he breathed oxygen at a simulated altitude of 28,000 feet. Although, from his work, Bert was the first to implicate bubble formation in the 'mal des caissons' associated with divers and caisson workers, it was von Schrotter from Vienna who first commented on an altitude response inexplicable in terms of hypoxia. The publication of his book in 1906 gives the first clear description of aerial decompression sickness and attributes the phenomenon to the bubbles described by Paul Bert. This early history has been traced in great detail by Fryer (1969).

Aviators

The early aviators did not reach sufficient altitude for physiological limitations to be troublesome. During the First World War and for some time after, the emphasis was upon hypoxia which becomes apparent at 10,000 to 12,000 feet (see Chapter 8). The provision of oxygen breathing equipment was believed to take care of the needs of the pilots and there was little interest aroused when Beyne (1923) reported that a fit pilot had collapsed suddenly at 36,750 feet to recover upon descent to 24,500 despite receiving an adequate oxygen supply during the whole flight. We now realize that it is impossible to maintain normoxic conditions above about 34,000 feet (187 mm Hg), since pure oxygen inspired at this pressure gives a normal alveolar oxygen partial pressure after dilution by water vapour.

During this period there was not the commercial incentive to fly higher since the piston engine has a better performance at lower altitudes. Interest in greater altitude was largely restricted to a few record-breaking attempts—38,180 feet by Schroder and 40,800 feet by Macready in the U.S.A. in 1921.

Positive-pressure suits

Attempts to protect the pilot against the effects of low absolute pressure were not popular with these pioneers on account of the weight penalty which any mechanical casing would have imposed upon their light, single-seater aircraft. However, their efforts did help to establish that the limiting altitude for normal oxygen equipment is about 45,000 feet.

Haldane (1920) was probably the first to advocate the use of a pressure suit, although this concept did not become a reality until 1933 when Sir Robert Davis (1947) modified a standard Siebe-Gorman diving suit to provide a positive internal pressure of 150 mm Hg over external. The history of the development of positive-pressure suits has been well documented by Ernsting (1965).

Pressurized cabins

The first attempt at maintaining a positive pressure within the whole cabin took place in Britain in 1921 using a de Havilland biplane but lack of adequate pressure control led to its abandonment. The idea was taken up in France where Cogno reached 30,000 feet in 1935 before crashing to his death, while a serious programme, started in Germany in 1928, led to a Junkers JU 49 fitted with a two-seater pressure cabin attaining 41,000 feet in 1936.

By the Second World War, however, there were only a few aircraft with pressure-adjusted cabins; a few German high-altitude reconnaissance planes, some British fighters with the altitude capability of intercepting them and a few others. The vast armadas of bombers which used to fly across the English Channel in both directions in the early 1940s were non-pressurized and because they tended to keep above 30,000 feet over hostile territory to take advantage of any inaccuracy in the anti-aircraft fire, half of the crew were often incapacitated by the time they reached their target—by decompression sickness if not already overcome by hypoxia. This led to a large research programme into these problems by the U.S.A.F. during the Second World War which provided a unique opportunity to amass a wealth of experience unobtainable in normal times. Data from the training of very large numbers of cadets during the war have enabled many of the less obvious trends in individual susceptibility to decompression sickness to be established statistically and many references to this work are made later.

The jet engine

Aerial interest in decompression sickness has changed since the late 1940s with the introduction of the jet engine which operates more efficiently at higher altitudes. This factor, and the availability of more power, has forced the use of cabins with pressures adjusted to simulated altitudes of 6,000–10,000 feet, i.e. to just below the level for the effects of hypoxia to

be apparent to passengers. Incidentally, it also happens to fall just below the height at which there is evidence for the onset of cavitation in body tissues (see p. 239). However, the jet engine has also greatly reduced the time taken to reach the altitude set as the ceiling for cabin pressure, thus greatly increasing potential rates of decompression.

The history of the pressure cabin has been well documented by Brown (1965). Its reduction in weight in such developments as '*Concorde*', the Anglo-French supersonic passenger plane, has led to decompression studies into the consequence of a window 'blow-out' at the 50,000–70,000 feet altitude at which it cruises (Brierley and Nicholson, 1969a,b).

Current Air Force interests in the bends are limited to decompression occurring as a result of enemy action, equipment failure and the welfare of the pilot who bales out.

Astronauts

The desire to probe beyond the earth's atmosphere has stimulated the technology to develop the ultimate in positive-pressure protection—the space capsule and the space suit. The American lunar modules tend to operate at 5 psi with the astronauts breathing 60% oxygen, while the Russians prefer a higher pressure (15 psi) and the joint U.S.–U.S.S.R. 'Apollo–Soyuz' space-docking venture employed a compromise pressure of 10 psi. The American space suits are now designed for 3·5 psi and tested to 15 psi. The chances of decompression sickness occurring in the module are small if nitrogen wash-out is adequate before blast-off but the risk does increase at the lower pressures of a space walk or in transfer between capsules.

Only one case of orbital bends has ever been reported—and that unofficially. Unlike diving, the time taken for nitrogen wash-out is no problem; a few more hours of pre-flight nitrogen wash-out than necessary (three to four hours in practice) are most unlikely to make any significant dents in the space budgets of the U.S.A. and U.S.S.R. and avoid jeopardizing such costly space flights by incurring a case of decompression sickness.

General

The significance of the aerial aspects should not be minimized on the basis of the small pressure changes involved compared to diving or caisson work. In fact, at low pressures, Boyle's Law would predict the volume change of any gas formed in tissue to be much greater and to amount to a decrease of over 40% in making the apparently small (1·5 psi) adjustment from a space suit to the U.S. lunar module.

Before entering into detail about decompression and the involvement of gases already implied, it will be as well to clarify some of the basic physical laws of gases and their solutions and to give some of the definitions more familiar to those disciplined in the physical sciences. Equally desirable, perhaps, is an outline of the processes involved in transporting gases *in vivo* and the physiological function for which those processes evolved. This is taken first for the benefit of the physical scientists or offshore engineers with no previous conception of biological order. The reader well versed in both physical and biomedical fundamentals might well proceed to Chapter 2.

Elements of Physiological Transport

From a thermodynamic viewpoint the animal body can be regarded as an engine powered by chemical energy in the form of food. This local conversion of nutrients into useful work needed for an organ to perform its function is termed metabolism—a complex series of chemical reactions which are usually oxidative in nature.

Metabolism is confined to the cells or, in mammals at least, to the parenchymal cells as opposed to blood cells. These parenchymal cells are grouped, according to their useful function, into organs. Cancer essentially kills its host by introducing cells which do not perform a useful function and yet consume chemical energy in competition with those that do.

Cell environment

Each organ system and the body as a whole is organized to try to provide the ideal environment for each parenchymal cell to perform its useful function. The 'services' to be provided for each cell include the supply of nutrients and oxygen together with the removal of heat and the waste products of reaction, requiring a transport system geared to the complexity of the organ and to the size of the animal as a whole. It is essential to grasp the fundamentals of this overall system because many of its component processes are non-selective in what they transport and therefore provide the vehicle for unwanted substances accumulating in the tissues—such as nitrogen during an exposure to compressed air. Particular attention needs to be focused upon the supply of oxygen because it is the concentration of this substance in the extracellular environment which is first likely to be depleted with malfunction of the transport system and to cause irreversible damage to the parenchymal cell. As Lanphier (1969) so aptly states for the whole body that, whereas the 'fuel' for oxidative metabolism can be stored in large quantities, the oxygen uptake or carbon dioxide elimination must be matched to the level of activity on an almost moment-to-moment basis.

In order to acquire a better appreciation of the complex chain of processes whereby an oxygen molecule is transferred from the atmosphere to its site of chemical assimilation in the cell, it might be better to approach the problem phylogenetically.

Evolution of transport processes

In a unicellular organism, the metabolic consumption of oxygen decreases its local concentration below that in the external medium, so providing a gradient for oxygen diffusion into the cell. The simultaneous release of carbon dioxide establishes a gradient for this gas in the opposite direction, so that respiration in the single cell depends upon simple diffusion only. However, as the size of the organism increases beyond about one millimetre (Harvey, 1928), then the distances for simple molecular diffusion have increased to the extent that this process needs to be supplemented by convective transfer. The gross macro-distribution of oxygen throughout larger creatures, therefore, is effected by a circulation with subsequent micro-distribution of oxygen from this system into the cells by diffusion, as before.

The aqueous external medium providing the 'ideal environment' for the cells, i.e. the extracellular space, is pervaded by a series of somewhat porous vessels, the systemic capillaries, through which the convection medium, blood, is pumped by the heart or other mechanism. The chemical constitution of blood has also evolved to facilitate transport—particularly of the respiratory gases on a regenerative basis necessary for its continuous cycling between the capillaries and the sources of oxygen and nutrients.

This 'source' for oxygen, and 'sink' for carbon dioxide and waste metabolic heat, is still the external environment against which the creature needs some physical protection in the form of a skin. The skin itself, however, presents a diffusion barrier and, moreover, its area for gas exchange is only increasing with body size as roughly the two-thirds power of the volume of the tissue which is demanding metabolic oxygen and producing carbon dioxide. In the larger animals, therefore, the need for increased gas exchange with the environment is satisfied by additional mass transfer units in the form of gills or lungs—which have been appropriately termed 'external gas exchangers' by Rahn (1967). However, their evolution represents not only a larger area for gas transfer but a transition of the zone of the external environment in immediate contact with the animal from a static phase to a forced convective system, i.e. introducing ventilation. By virtue of the mechanical protection afforded the fragile blood vessels of the lungs by situating them within the body, it is feasible for the thickness of the blood–air diffusion barrier to be reduced to a thin membrane—the pulmonary membrane. In man this has a total surface area about equal to that of a tennis court yet

the thickness of thin tissue paper. Anatomically, this large gas-exchange surface is obtained by multiple branching of both the airways bringing fresh air from the mouth and the vessels conveying blood from the right-hand side of the heart to the lungs. On the air side, some 23 generations of branching have been traced in man (Weibel, 1964) between the mouth and the terminal units whose overall ensemble of alveolar capillaries resembles a honeycomb.

Oxygenation in the lungs

Functionally, the mammalian lung has evolved with two forced convective systems—one for the continuous flow of blood and the other for the reciprocating flow of air. The closest proximity of these systems occurs at the level of greatest subdivision of each so that, with such a large area of gas–blood contact across such a thin membrane, the system would

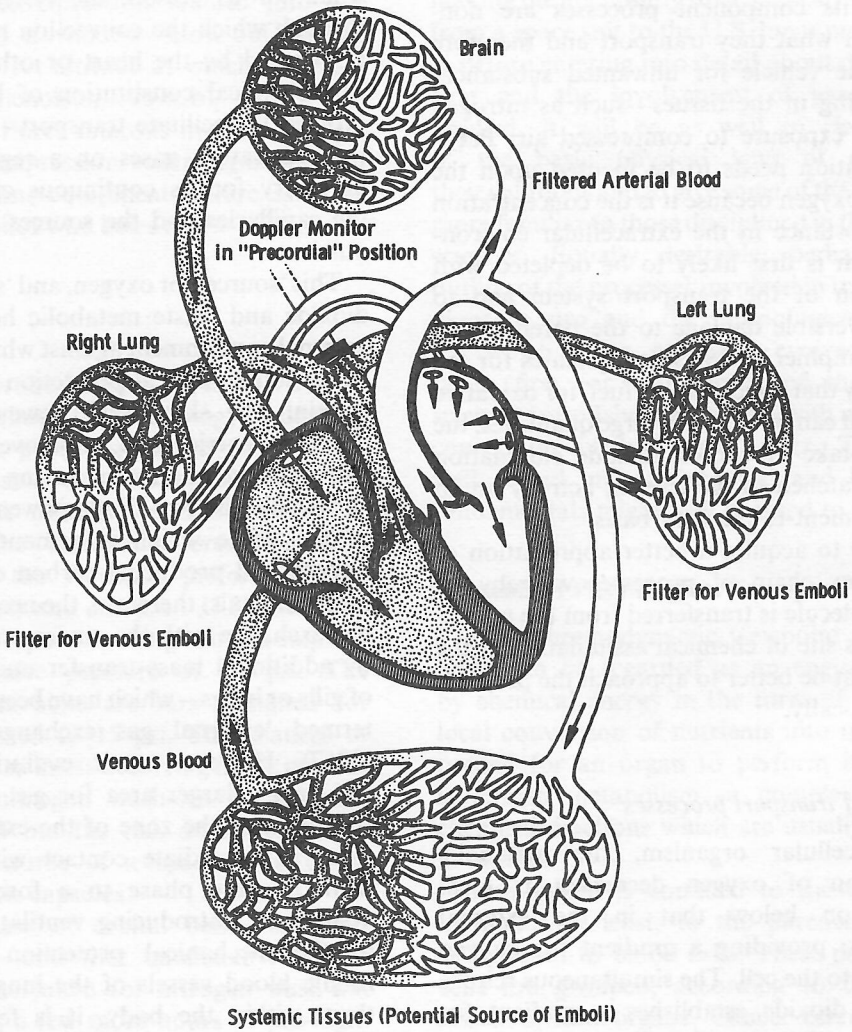

Fig. 8 The cardio-respiratory system showing the various chambers of the heart and depicting the peripheral tissues as a potential source of bubbles with the lungs as a filter. Also shown is the alignment of a Doppler ultrasonic bubble detector for monitoring in the recommended precordial position

appear ideal. There would therefore seem to be no problem in fully equilibrating with air the oxygen-deficient blood returned to the heart from the other tissues via the veins (venous blood).

However, this ideal oxygenation of the blood to be returned from the lungs to the left-hand side of the heart (fig. 8) for subsequent despatch to the peripheral tissues at a higher pressure (arterial blood) is not quite realized in practice—for several reasons. Firstly, the 2·5 litres of air in the lung is not replaced with each breath; under resting conditions, at least, only the 0·5 litre farthest from the blood is tidal. The oxygen, therefore, must diffuse across the non-tidal gas in the terminal airways in order to reach the pulmonary membrane. This does not appear to offer an appreciable barrier unless its density is increased by compression (Saltzman *et al.*, 1971; Chouteau, 1969) or it is replaced by liquid (Kylstra *et al.*, 1966).

Secondly, the gas must diffuse across the pulmonary membrane; although this should present a negligible barrier in view of its large area (90 m^2) and 1 μm. thickness. Thirdly, oxygen molecules then need to diffuse or to be transferred by convection to the red blood cells in which they can be stored by reversible chemical reaction for subsequent release in the peripheral tissues. Fourthly, the kinetics of chemical assimilation may not be sufficiently rapid to enable the reaction to go to completion during the limited (0·75 sec) sojourn of blood in the pulmonary capillary.

Fifthly, the ideal situation described earlier can fail to achieve full oxygen equilibration if part of the venous blood bypasses the lung (shunt) or there is a local mismatch of the oxygen carrying capacities of the two convective systems. To give an extreme example, there would be no oxygenation if all of the blood perfused one lung and all of the air ventilated the other. Needless to say, there are an infinite number of ways of matching the spatial distributions of the two convective systems, ranging from this worst possible occurrence to the ideal case described previously. This is known as the ventilation-perfusion ($\dot{V}_A/\dot{Q}$) inequality

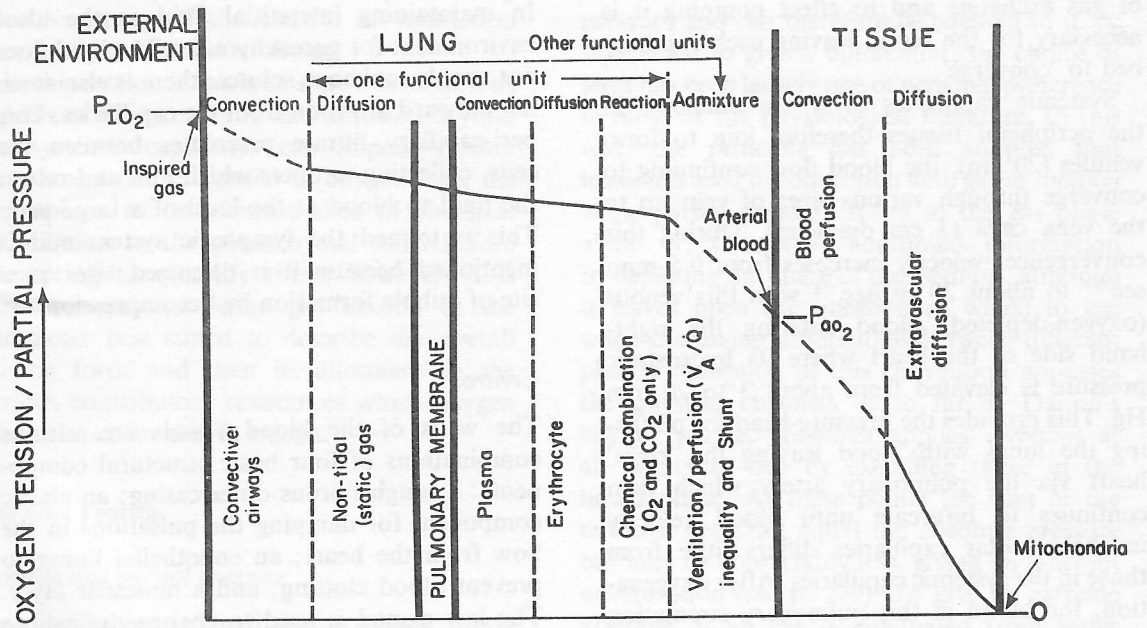

Fig. 9 Illustrating the 'oxygen conduction line' (Holmgren, 1966) as the continuous fall in the oxygen partial pressure/tension in passing from atmospheric air to the sites of metabolic assimilation of oxygen in the peripheral tissues. The fall in arterial P_{O_2} due to local inequalities in matching the ventilation to the perfusion of the lungs is represented by other units in parallel to the one depicted in detail

and is the major cause of hypoxia in respiratory patients. This phenomenon, and its clinical aspects, has been particularly well described by West (1965).

Each of the above processes can be regarded as offering a resistance to the oxygenation of venous blood (fig. 9) and all except the fourth (chemical reaction) would also apply to the transient uptake of inert gases. However, before attempting to quantify their contributions to the disequilibrium between the external environment and arterial blood, it might be as well to complete the qualitative description of both the forced convective systems as they have evolved.

Circulation

The simple concept of a circulation cycling the convection medium between the alveolar capillaries of the 'honeycomb' of the lungs and the systemic capillaries pervading the extracellular spaces of the peripheral tissues needs more elaboration. In order to reduce frictional forces in transporting blood between these two regions of gas exchange and to effect pumping it is necessary for the blood leaving each capillary bed to 'converge'.

Systemic capillaries of 8 μm diameter in the peripheral tissues therefore join to form venules (20 μm), the blood flow continuing to converge through various sizes of vein up to the vena cava (3 cm diameter). During this convergence, velocity increases from 0.5 mm/sec^{-1} to about 20 cm/sec^{-1} with this venous (oxygen-depleted) blood entering the right-hand side of the heart where its hydrostatic pressure is elevated from about 3 to 20 mm Hg. This provides the pressure-head for perfusing the lungs with blood leaving the 'right' heart via the pulmonary artery which then continues to bifurcate until blood velocity in the alveolar capillaries differs little from those in the systemic capillaries. After oxygenation, the blood in this pulmonary circulation starts to converge until it enters the left-hand side of the heart via the pulmonary vein. The hydrostatic pressure of this oxygenated blood is then raised from almost zero to a hydrostatic pressure alternating between a peak (systolic) value around 120 mm Hg and a low (diastolic) value around 80 mm Hg.

Arterial blood then leaves the 'left' heart via the aorta (2·5 cm diameter) with successive branching of arteries until it reaches arterioles (30 μm diameter) and ultimately returns to the capillaries of the systemic circulation. These are separated from the parenchymal cells which they supply by an interstitial space amounting to 10–60% of the total tissue volume, the exact value depending upon the organ and its physiological state.

The manner in which the two parts of the human circulation, systemic and pulmonary, lie in series is shown in fig. 8 together with other basic elements of the cardio-respiratory system as they apply to gas transport.

This outline uses general values for man given by Burton (1968) whose text is recommended for a concise description of the circulatory system.

It should also be mentioned that fig. 8 does not show a secondary fluid circulation amounting to less than one per cent of that outlined. In maintaining interstitial fluid as the ideal environment for parenchymal cells, blood does not simply exchange solutes; there is also some net outward filtration from the capillaries. This peri-capillary filtrate percolates between the cells, collecting in ducts which join and return the fluid to blood at the level of a large vein. This is termed the lymphatic system and is mentioned because it is discussed later as a site of bubble formation by decompression.

Control

The walls of the blood vessels are various combinations of four basic structural components: a tough fibrous outer casing; an elastic component for damping the pulsations in the flow from the heart; an endothelial lining to prevent blood clotting; and a muscular layer. The last named is used to change the calibre of the vessel, particularly arteries, and thus limit or direct flow to the organs or more localized tissue regions with the greatest oxygen demand. This is sensed by chemoreceptors—

some sensitive to oxygen but dominated by those sensitive to carbon dioxide accumulation. Overall, such sensors act not only to control local blood perfusion by diversion of flow from other areas but also to regulate overall cardiac output and hence heart rate, respiratory frequency and tidal volume.

The fact that the chemoreceptors sensitive to carbon dioxide tend to dominate others does not usually matter, since oxygen depletion tends to go hand-in-hand with carbon dioxide accumulation. However, this system can be fooled—but not without risk. A case in point is the breath-hold diver who voluntarily hyperventilates, i.e. consciously breathes more deeply and more rapidly to drop his blood carbon dioxide to an artificially low level before diving. Underwater, his carbon dioxide rises but not to a level sufficient to urge him to surface before his oxygen falls to a point at which he becomes unconscious and drowns.

Most textbooks of general mammalian physiology give good introductions to the neurologic control of blood flow and distribution, while Lanphier (1969) gives a particularly good summary of the control of ventilation specifically orientated to diving.

In this section it has been shown how various aspects of the circulation and diffusion beyond the systemic capillaries can impose further impedances to the transfer of oxygen from the atmosphere to its ultimate sites of chemical assimilation in the parenchymal cells. Before attempting to quantify these, however, it is first necessary to define gas tension as the parameter best suited to describe the overall driving force and then its allotment to the various contributory resistances which oxygen molecules encounter in transit.

The Gas Tension

Tension and partial pressure

Gases will move in the direction of descending concentration in any medium which is otherwise homogeneous. This applies whether the medium is macroscopically static, when concentration gradients tend to be dissipated by diffusion, or it is in motion, when there is also convection.

However, this no longer applies where molecules can move across a boundary into a medium in which the gas has a different solubility. This is particularly relevant *in vivo* where the body has at least two solvents for gas—one predominantly aqueous and the other hydrophobic (lipid) having a solubility ratio (partition coefficient) of about five for nitrogen. That is: the concentration of nitrogen in fat is five times that in water equilibrated with the fat.

If the aqueous and lipid solutions are in nitrogen-equilibrium with each other, then there must be a gaseous phase with which both are also in nitrogen-equilibration. If the partial pressure of nitrogen in this gaseous phase is P_{N_2}, then both solutions are said to have a nitrogen *tension* of P_{N_2}. Tension is thus related to concentration (c_{N_2}) for simple solutions by Henry's law as

$$c_{N_2} = S_{N_2}.P_{N_2} \qquad (1)$$

where S_{N_2} is the solubility.

Tension has the same dimensions as partial pressure and can therefore be equated to it, or subtracted to give a differential; the choice of term has been largely one of personal preference in most of the physiological literature. In this text, the principle has been adopted that tension is used in connection with gas *in solution* while partial pressure refers to the gas phase alone. This conveys additional information by depicting the phase of the medium; although it leaves open the question of which to use when discussing differentials between different phases. Adoption of this convention appeases the physical chemists in so far as Dalton's law of partial pressures applies *verbatim* at all points *in vivo* by excluding those in the liquid phase. At these points the sum of the tensions need not equal the absolute pressure but may be appreciably less, giving an inherent unsaturation (see p. 239). To give an extreme example, if all gas is eliminated from water by boiling and it is then cooled without exposure to the air, its total gas tension will be only the water vapour pressure—appreciably less than the absolute hydrostatic pressure.

Driving force

If any two nitrogen solutions, one aqueous and the other lipid, are now placed in contact, the nitrogen will tend to traverse the boundary between them in the direction of descending nitrogen tension. This means that if the *tension* in the aqueous solution is greater than that in the lipid, nitrogen will tend to shift from aqueous to lipid even though the lipid may have a higher nitrogen concentration. Thus the driving force for the transfer of any gas by any passive process is the tension gradient—whatever the phases involved, e.g. liquid-to-liquid or gas-to-liquid. Moreover, this is not limited to media with different physical affinities for a gas, as expressed by their solubilities, but it also applies where various constituents of the medium have a reversible chemical affinity for that gas. A case of particular importance in this connection is oxygen in blood.

Blood

For the 'convection medium' used in the circulation to be able to maintain that 'ideal environment' for the parenchymal cell, it needs to convey appreciable quantities of oxygen from the lungs to the tissues. Oxygen, however, is sparingly soluble in most aqueous fluids—0·003 ml of oxygen at standard pressure dissolving in 1 ml of water at body temperature (37 °C) and 100 mm Hg tension compared with a metabolic demand of about 240 ml oxygen per minute needed by the average man at rest. The circulation must therefore either be very rapid at the expense of using much energy, or the capacity of the convection medium for oxygen must be greatly increased. The second of these is adopted by the body by incorporating oxygen-absorbing pigments into the blood, while the first is used as a secondary means of augmenting oxygen transport largely to satisfy fluctuations in demand and thus effect control of oxygen supply as already outlined.

The blood 'pigments', so-called for the colour they impart, consist of large molecules composed of various proteinaceous units such as four of haemoglobin (Hb). Each of these has the capability of reacting with an oxygen molecule to form a fairly stable complex—oxyhaemoglobin (HbO_2). Moreover, as each of the four oxygen molecules is taken up, there is a successively higher equilibrium constant for the others to combine with the remaining sites on the overall haemoglobin molecule, so that there is, in effect, a graded chemical affinity for oxygen. The kinetics and thermodynamics of the four sequential reactions are particularly complex and for further details reference should be made to the classical work of Roughton (1964) and co-workers.

However, it is most significant that the driving force for chemical assimilation is still the oxygen tension (P_{O_2}), so that the blood equilibrated with oxygen at a given P_{O_2} value will have a single oxygen content (C_{O_2})—other factors remaining constant. The relationship between C_{O_2} and P_{O_2} is therefore particularly important since it determines the oxygen loading capacity of the blood. Furthermore, since the affinity of oxygen for haemoglobin is rapidly reversible, it also enables one to estimate the quantity of oxygen which the blood can deliver at the lower tensions of the systemic capillaries supplying the parenchymal cells.

A typical oxyhaemoglobin dissociation curve for human blood is shown in fig. 10 where it can be seen that 100 ml of arterial blood at a P_{aO_2} of 100 mm Hg contains about 20 ml of available gaseous oxygen in chemical combination and only 0·3 ml in true physical solution, in accordance with Henry's law, to give a total arterial content (C_{aO_2}) of 20·3 ml. Different tissues have different oxygen demands and different blood supplies but the body average is 4·8 ml to give a residual 15·5 ml of oxygen per 100 ml left in mixed venous blood. This is apportioned as 15·4 ml of oxygen in chemical combination at a P_{vO_2} of 40 mm Hg for which Henry's law gives the remainder in physical solution as 0·12 ml of oxygen per 100 ml of blood. This example uses typical values of blood contents and tensions for healthy resting young men taken from standard textbooks (e.g. Comroe, 1969) which

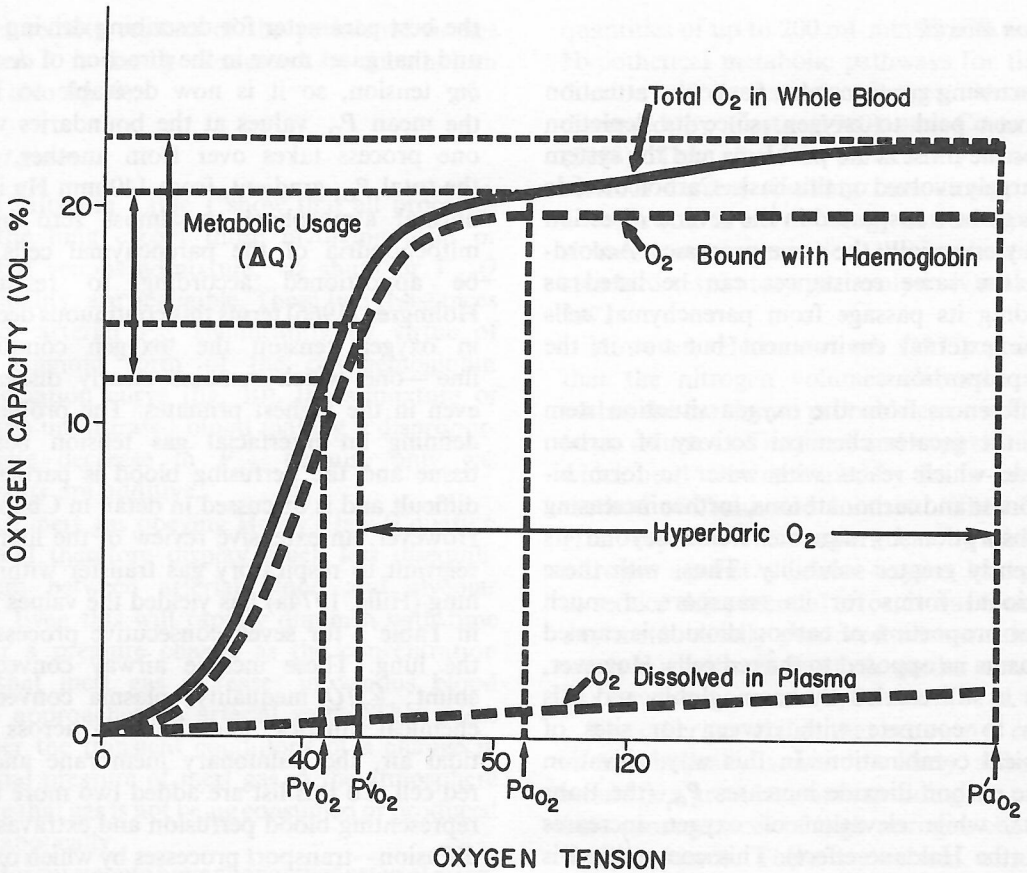

Fig. 10 The relationship between the total oxygen content of blood and its tension. This plot also shows how a large increase in arterial oxygen tension ($P_{aO_2} \rightarrow P'_{aO_2}$) results in a much smaller rise at the venous level ($P_{vO_2} \rightarrow P'_{vO_2}$) for the same metabolic consumption of oxygen by tissues (ΔQ)

should be consulted for a broader introduction to the subject.

On the basis that local blood flow is controlled to enable the cells to take the oxygen required, it can be seen in fig. 10 that large increases in arterial P_{O_2} result in much smaller increases in venous P_{O_2}. These are almost negligible unless P_{aO_2} is so high that the haemoglobin remains saturated in venous blood and all metabolic usage is derived from oxygen in physical solution only.

Before discussing gases other than oxygen, it must be emphasized that blood has many other functions. While the pigments for oxygen transport are contained within membranes to form erythrocytes, or red cells, there are also white cells to combat infection of the body, nutrients for the parenchymal cells, ions to maintain the necessary electrical properties and various plasma colloids. These exert an osmotic influence upon capillary filtration to help maintain fluid balance while, as platelets, they have a key role in healing—a complex process which can be initiated by exposing blood to the gaseous phase. This is relevant to decompression since, as shall be seen later, this can produce a gaseous phase other than the air at a wound to which the system is intended to respond.

Needless to say, the study of blood is a complex subject which is outlined in most textbooks of physiology but one of the most comprehensive treatments of haematology is that compiled by Wintrobe (1968).

Carbon dioxide

In discussing gas transport, particular attention has been paid to oxygen, since its depletion causes the most acute problems and the system has largely evolved on this basis. Carbon dioxide needs to be transported in the reverse direction and by essentially the same processes. Accordingly the same resistances can be listed as impeding its passage from parenchymal cells to the external environment but not in the same proportions.

Differences from the oxygen situation stem from the greater chemical activity of carbon dioxide which reacts with water to form bicarbonate and carbonate ions, further increasing its absorption by aqueous fluids beyond its inherently greater solubility. Thus, with these additional forms for its transport, a much higher proportion of carbon dioxide is carried in plasma as opposed to the red cells. However, some is still carried by haemoglobin and this tends to compete with oxygen for sites of chemical combination. In this way, elevation of the carbon dioxide increases P_{O_2} (the Bohr effect), while elevation of oxygen increases P_{CO_2} (the Haldane effect). This competition is best summarized by the blood–gas diagrams of Rahn and Fenn (1955) who plot C_{O_2} versus C_{CO_2} for contours of P_{O_2} and P_{CO_2}, so that once any two of these are fixed for a given blood the other two can be estimated from the chart.

Resistances to gas transfer

Having summarized some of the unique properties of blood which render it such an ideal convection medium for respiratory gases, it is now feasible to try to quantify the individual resistances to gas transfer. Resistance can be defined as simply (driving force)/(gas flux), when the distribution of the overall driving force between the various transfer processes will represent their relative resistances. At least, this holds true for oxygen under the quasi-steady-state conditions of normal respiration where the transfer processes lie in series and therefore have the same oxygen flux.

It has already been shown that tension is the best parameter for describing driving force and that gases move in the direction of *descending* tension, so it is now desirable to know the mean P_{O_2} values at the boundaries where one process takes over from another. Thus the total P_{O_2} gradient, from 140 mm Hg in the normal atmosphere to almost zero in the mitochondria of the parenchymal cells, can be apportioned according to resistance. Holmgren (1966) terms this continuous decrease in oxygen tension the 'oxygen conduction line'—one which remains clearly discernible even in the highest primates. The problem of defining an interfacial gas tension between tissue and the perfusing blood is particularly difficult and is discussed in detail in Chapter 7. However, an extensive review of the literature relevant to respiratory gas transfer within the lung (Hills, 1974a) has yielded the values given in Table 1 for seven consecutive processes in the lung. These include airway convection; shunt; $\dot{V}_A/\dot{Q}$ inequality; plasma convection; chemical kinetics; and diffusion across non-tidal air, the pulmonary membrane and the red cell. To this list are added two more terms representing blood perfusion and extravascular diffusion—transport processes by which oxygen is transmitted from arterial blood even to the

Table 1 The oxygen conduction line in man: estimated differences in P_{O_2} contributed by the various processes involved in oxygen transport (fig. 9)

Transport process (or resistance)	Location	Estimated* ΔP_{O_2} (in mm Hg)
Ventilation	convecting airways	37·9
Diffusion	terminal airways	< 1·0
Diffusion	pulmonary membrane	0·4
Convection	within plasma	< 1·0
Diffusion	into red cell	< 1·8
Chemical reaction	red cell	< 0·1
Venous admixture	shunt	5·0
$\dot{V}_A/\dot{Q}$ inequality	parallel units	3·6
Blood perfusion Bulk diffusion	peripheral tissues extravascular tissue	> 97·2†
Total	(P_{IO_2})	148

† For diffusion/perfusion distribution see Chapter 7.
* Estimates taken from a review by Hills (1974a).

most remote regions of the peripheral tissues where it is finally consumed by metabolism (see also fig. 9).

Inert gases

The values in Table 1 show that all processes in the lung except those involving total or partial venous admixture, viz shunt or $\dot{V}_A/\dot{Q}$ inequality, are negligible. These two resistances lower arterial P_{O_2} significantly by virtue of the sigmoid form of the oxyhaemoglobin dissociation curve (fig. 10), the admixture of a little unsaturated blood making a disproportionate decrease in P_{aO_2} because only gas *contents* are additive.

An inert gas obeying Henry's law (Equation 1) will therefore display much less disequilibrium between arterial blood and alveolar gas. Even this will rapidly diminish with time after a pressure change as the concentration of that inert gas increases in venous blood and approaches an arterial value. This arises under the transient conditions of a change in partial pressure of inert gas in the atmosphere since that gas is not being consumed or produced metabolically.

Measurements have shown that arterial nitrogen tensions asymptote to within 1% of the alveolar value (P_{AN_2}) within one minute of a change in P_{AN_2} (Ferris and Engel, 1951). Hence any delay in inert gas uptake or elimination imposed by the lungs is generally considered negligible for all except dives of very short duration.

Alveolar P_{N_2} is related to absolute pressure (P) and the fraction of nitrogen (F_{IN_2}) in dry inspired air by

$$P_{AN_2} = F_{IN_2}(P - P_w) \qquad (2)$$

where P_w is the vapour pressure of water at body temperature.

Metabolic nitrogen

The assumption that nitrogen is metabolically inert has been challenged recently by Muysers (1970), Dudka *et al.*, (1971) and Cissik and Johnson (1972) who claim that it can be produced in its elemental form by man in quantities of up to 200 ml min^{-1} with exercise. Hypothetical metabolic pathways for the production of molecular nitrogen have been discussed by Costa (1960) and Costa *et al.* (1968). This claim is particularly serious in view of current thinking that nitrogen plays a major role in the aetiology of decompression sickness, not to mention the implications to standard respiratory gas analysis (Cissik *et al.*, 1972).

However, Herron *et al.* (1973) point out that the nitrogen volumes claimed are still within the maximum probable error in the very large volumes of inspired and expired nitrogen which need to be measured by the air-breathing method of Cissik and Johnson. When Herron *et al.* repeated their experiment by measuring nitrogen against a helium-oxygen background to reduce this potential error, it was found that any metabolically produced nitrogen does not reach a significant level. A similar conclusion has now been reached by Muysers *et al.* (1974).

The other possibility that nitrogen is *consumed* metabolically is even less likely, although it would be a great benefit in avoiding the undesirable consequences of high nitrogen concentrations in tissue. There are certain cultures of azobacters (Nicholas, 1963a,b) which will assimilate elemental nitrogen but, unfortunately, none of these organisms seems at all compatible with the normal physiological state of mammalian tissues.

Active transport

In this text transport has been used in its most general sense but, in most of the physiological literature, the term tends to take on a particular connotation related to the active transfer of various substances—particularly the cations. These charged particles can be secreted by certain membranes in a direction contrary to the concentration gradient, either to impart particular electrical properties to a cell, or as a consequence of those properties. Studies of these phenomena form a large part of the complex subject of neurobiology; active transport is also involved in many other organ systems such as the kidney.

Secretion versus diffusion

So far, in this text, it has been assumed that gas transfer is purely passive, i.e. gases follow paths of decreasing tension. However, it was Haldane (1895, 1920) who believed that the pulmonary membrane can actively transport, or secrete oxygen from the alveoli into blood in the alveolar capillaries—a concept contrary to the beliefs of Barcroft (1914, 1925) and Krogh (1907, 1941) who advocated that diffusion was passive. This controversy raged for many years and it was not until the 1940s that the Haldane concept was finally laid to rest. Its influence upon respiratory physiology has been reviewed by Bartels *et al.* (1955a,b), Mochizuki and Bartels (1955) and Comroe (1950).

What is more interesting in this context is not so much the outcome but the reason for Haldane adopting his position, since it is fundamental to his approach to decompression—a very minor interest of this eminent physiologist by comparison with his work in respiration. His reason for postulating secretion arose from his measurements which indicated that arterial blood had a higher oxygen tension than the partial pressure of alveolar air, i.e. $P_{aO_2} > P_{AO_2}$ indicating the movement of oxygen against the tension gradient.

The measurement of alveolar partial pressures is still controversial and 'Haldane samples' from forced end-expired air provide the lowest estimates. Even so, the real controversy hinged around Haldane's method of measuring P_{aO_2} by analysing a bubble of gas which had been 'equilibrated' with his sample of arterial blood.

However, there is no way in which a gas phase can equilibrate with a liquid at the same hydrostatic pressure if the sum of the tensions in that liquid does not equal that absolute pressure (P)—at least, not without dissolving all the gas and then having none left to analyse. Haldane realized this but incorrectly assumed that nitrogen would take up the difference in the liquid phase as it must do in the gaseous phase in accordance with Dalton's law.

Since it is now known that arterial blood is unsaturated (fig. 45), true equilibration with the bubble would not occur, but each gas would have a higher partial pressure in the bubble than in the 'equilibrated' blood. Haldane's bubbles therefore gave P_{O_2} values higher than the true P_{aO_2} and which even exceeded his values for P_{AO_2}—hence his invalid secretion hypothesis.

Blood saturation

What emerges of fundamental importance to the subsequent discussion of his approach to decompression is the belief that true saturation is achievable in the body after attaining steady-state conditions. Haldane and Meacham (1898) measured P_{O_2}, P_{CO_2}, P_w and then quoted values for P_{N_2} in blood estimated as the difference between their total and the absolute hydrostatic pressure (P),

$$P_{N_2} = P - P_{O_2} - P_{CO_2} - P_w \qquad (3)$$

Accordingly, after implying that true 'saturation' of tissues can occur at a particular pressure, it is then necessary to postulate 'supersaturation' on decompression in order to provide a driving force for eliminating that gas. Haldane later corrected his stance that Equation 3 must hold in blood (Haldane and Priestley, 1935) but not until many years after publication of his diving tables. However, unlike the implications of his negative $(P_{AO_2} - P_{aO_2})$ difference to respiratory physiology, the saturation assumption and his supersaturation concept in decompression has not been seriously challenged until recently. Before tracing the dominance of this line of thinking in hyperbaric physiology (Chapter 5), it is first necessary to outline the symptoms of inadequate decompression and the factors which influence their occurrence.