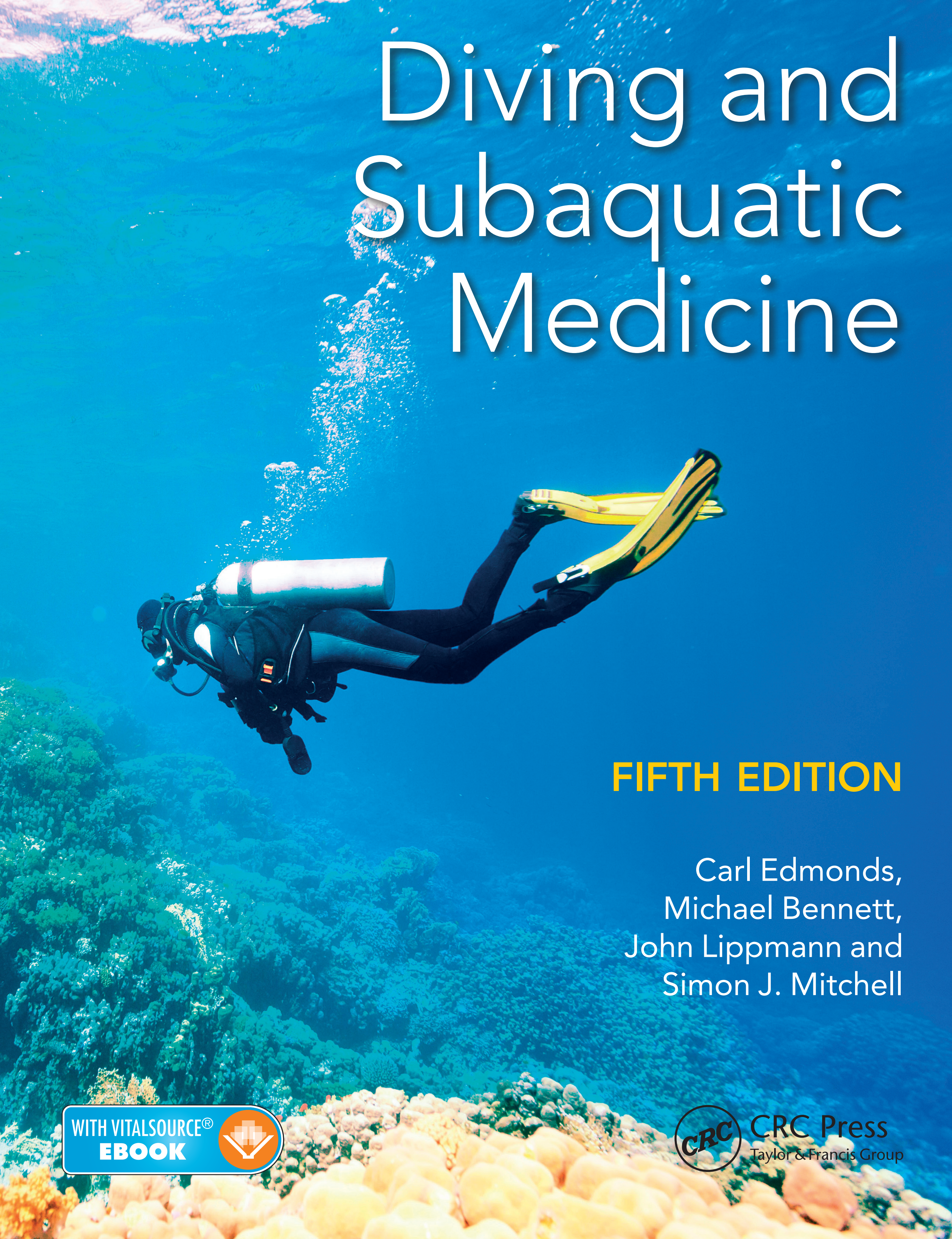

Diving and Subaquatic Medicine

FIFTH EDITION

Carl Edmonds,
Michael Bennett,
John Lippmann and
Simon J. Mitchell

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CRC Press
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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Version Date: 20150608

International Standard Book Number-13: 978-1-4822-6013-7 (eBook - PDF)

Visit the Taylor & Francis Web site at
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Contents

List of abbreviations

ADS	atmospheric diving suit
ADV	automatic diluent valve
AGE	arterial gas embolism
ALS	advanced life support
ARDS	acute respiratory distress syndrome
ATA	atmosphere absolute
ATG	atmosphere gauge
BCD	buoyancy compensator device
BLS	basic life support
BOV	bail-out valve
BSAC	British Sub-Aqua Club
CAD	coronary artery disease
CAGE	cerebral arterial gas embolism
CCR	closed-circuit rebreather
CMF	constant mass flow
CPAP	continuous positive airway pressure
CPR	cardiopulmonary resuscitation
CSF	cerebrospinal fluid
CSL	Commonwealth Serum Laboratories
DAN	Divers Alert Network
dB	decibel
DCI	decompression illness
DCIEM	(Canadian) Defence and Civil Institute of Environmental Medicine
DCS	decompression sickness
DDC	deck decompression chamber
DPV	diver propulsion vehicle
EAD	equivalent air depth
ECC	external cardiac compression
ECG	electrocardiogram
ECMO	extracorporeal membrane oxygenation
ECoG	electrocochleography
EEG	electroencephalogram
ENG	electronystagmography
EPIRB	electronic position-indicating radio beacon
FEV_1	forced expiratory volume in 1 second
FIO_2	fraction of inspired oxygen
FVC	forced vital capacity
HBOT	hyperbaric oxygen therapy
HPNA	high-pressure neurological syndrome
IBCD	isobaric counterdiffusion
ICP	intracranial pressure
IDDM	insulin-dependent diabetes mellitus
ILCOR	International Liaison Committee on Resuscitation
IPE	immersion pulmonary oedema
IPPV	intermittent positive pressure ventilation
ISO	International Organization for Standardization
lpm	litres per minute
MOD	maximum operating depth
msw	metres of sea water
NEDU	Navy Experimental Diving Unit
NOAA	National Oceanic and Atmospheric Administration
NUADC	National Underwater Accident Data Centre
OPV	over-pressure valve
$PaCO_2$	alveolar pressure of carbon dioxide
$PaCO_2$	arterial pressure of carbon dioxide
PADI	Professional Association of Diving Instructors
PaO_2	alveolar partial pressure of oxygen
PaO_2	arterial partial pressure of oxygen
PCO_2	partial pressure of carbon dioxide
PEEP	positive end-expiratory pressure
PEF	peak expiratory flow
PFO	patent foramen ovale
$PICO_2$	inspired partial pressure of carbon dioxide

PIO_2	inspired partial pressure of oxygen
PMCT	post-mortem computed tomography
PMDA	post-mortem decompression artefact
PMV	pressure maintaining valve
PN_2	partial pressure of nitrogen
PO_2	partial pressure of oxygen
PPV	positive pressure ventilation
RAN	Royal Australian Navy
RCC	recompression chamber
RGBM	reduced gradient bubble model
RMV	residual minute volume (also respiratory minute volume)
SCR	semi-closed-circuit rebreather
scuba	self-contained underwater breathing apparatus
SDPE	scuba divers' pulmonary oedema
SMB	surface marker buoy
SPUM	South Pacific Underwater Medicine Society
SSBA	surface-supply breathing apparatus
SWAS	salt water aspiration syndrome
UHMS	Undersea and Hyperbaric Medical Society
UPTD	unit of pulmonary toxic dose
USN	United States Navy
VC	vital capacity
VER	visual evoked response
VGE	venous gas emboli
VPM	varying permeability model
V/Q	ventilation-perfusion

Preface and excerpts from earlier editions

This book is written for doctors and paramedics who are called on to minister to the medical needs of those divers who venture on or under the sea. It was based on our experience in dealing with a vast number of diving accidents and with trouble-shooting many diving problems, and it is also an attempt to integrate the experience and more erudite research of others.

The very generous praise bestowed by reviewers on the first edition of *Diving and Subaquatic Medicine,* and its surprising acceptance outside the Australasian region, inspired us to prepare further editions of this text.

In the later editions, we attempted to be less insular. Instead of an Australian book about Australian experiences, we sought the advice and guidance of respected friends and colleagues from other countries, and from other disciplines, especially in the United Kingdom, the United States, Canada, Japan and mainland Europe. This has not prevented us from being judgemental and selective when we deemed it fit. This is still a very specialized field where evidence-based medicine is in its infancy. Truth is not always achieved by voting, and consensus is often a transitory state. We have documented what we believe to be current best practice. The future will judge this.

The extension of diving as a recreational and commercial activity has led to the bewildered medical practitioner's being confronted with diving problems about which he or she has received little or no formal training. Doctors interested in diving had previously found themselves without a comprehensive clinical text. We tried to remedy this. Our primary focus remains on the diving clinician, the physician responsible for scuba divers, the diving paramedic and the exceptional diving instructor who needs some guidance from a practical reference text.

Diving accidents are much better defined, investigated and treated than when we commenced writing on this subject, many years ago. It was our intent to present, as completely as possible, an advanced and informative book on clinical diving medicine. We have avoided the temptation to write either a simplistic text or a research-oriented tome.

This text encompasses the range of diving disorders experienced by divers. It presents all aspects of diving medicine from ancient history to the latest trends, in a concise and informative manner. Each disorder is dealt with from a historical, aetiological, clinical, pathological, preventive and therapeutic perspective. Summaries, case histories and revision aids are interspersed throughout. For the doctor who is not familiar with the world of diving, introductory chapters on physics and physiology, equipment and the diving environments have been included.

The inclusion of anecdotes and occasional humour may lessen the load on the reader, as it does on the authors. As in previous editions, each chapter is edited by one of the authors, with overview and peer review available from the others. This means that not always will there be exact agreement among authors, and there may be some variation among chapters. This is inevitable when evidence and consensus are not always complete. It is also healthy for the future.

Three of the four previous authors have departed from this scene, and the fourth is about to leave. The baton needs to be passed. Our legacy and intent are that our younger colleagues will experience as much excitement, fascination, achievement, camaraderie and fun from diving as we have.

Carl Edmonds, 2015
on behalf of all previous
and new authors of this text.

Dedication

This book is dedicated to the memory of Pluto, who died, even though he never left dry land.

I have often been asked who Pluto was. He was a much loved basset hound who strolled into our study when the original three authors were postulating about an appropriate dedicatee for their text. We could not decide between Paul Bert, Al Behnke, Jr., and J.B.S. Haldane. Pluto solved our dilemma.

Acknowledgements

Carl Edmonds, John Lippmann, Michael Bennett and Simon Mitchell would like to thank Christopher Lowry, John Pennefather and Robyn Walker for their invaluable contributions to previous editions, upon which material in this latest fifth edition is based.

We wish to acknowledge the assistance given by the Royal Australian Navy, the Royal Navy and the United States Navy for permission to reproduce excerpts from their diving manuals, and to the many pioneers on whose work we have so heavily drawn, our families who have suffered unfairly, and our clinical tutors – the divers.

Numerous experts have been consulted to review and advise on specific chapters of this or previous editions. Our gratitude is extended to these valued colleagues, but they are not to blame for the final text. They include the following:

Peter Bennett
Ralph Brauer
Greg Briggs
Ian Calder
Jim Caruso
Richard Chole
David Dennison
Chris Edge
Glen Egstrom
David Elliott
Des Gorman
John Hayman
Eric Kindwall
Clarrie Lawler
Christopher Lawrence
Dale Mole
Owen O'Neill
John Pearn
Peter Sullivan
Ed Thalmann
John Tonkin
John Williamson
David Yount

Originally published in 1976 by the Diving Medical Centre (Australia) ISBN 09597191-0-5.

PART 1

Diving

1

History of diving

BREATH-HOLD DIVING

The origins of breath-hold diving are lost in time. Archaeologists claim that the Neanderthal human, an extinct primitive human, dived for food, likely in the first instance gathering shellfish by wading at low tide before diving from canoes. By 4500 BC, underwater exploration had advanced from the first timid dive to an industry that supplied the community with shells, food and pearls.

From the ancient Greek civilization until today, fishers have dived for sponges, which, in earlier days, were used by soldiers as water canteens and wound dressings, as well as for washing.

Breath-hold diving for sponges continued until the nineteenth century when helmet diving equipment was introduced, allowing the intrepid to gamble their lives in order to reach the deeper sponge beds. Greek divers still search the waters of the Mediterranean Sea as far afield as northern Africa for sponges.

The ancient Greeks laid down the first rules on the legal rights of divers in relation to salvaged goods. The diver's share of the cargo was increased with depth. Many divers would prefer this arrangement to that offered by modern governments and diving companies.

In other parts of the world, industries involving breath-hold diving persist, to some extent, to this time. Notable examples include the Ama, or diving women of Japan and Korea, and the pearl divers of the Tuamoto Archipelago.

The Ama has existed as a group for more than 2000 years. Originally the male divers were fishermen, and the women collected shells and plants. The shells and seaweed are a prized part of Korean and Japanese cuisine. In more recent times, diving has been restricted to the women, with the men serving as tenders. Some attribute the change in pattern to better endurance of the women in cold water. Others pay homage to the folklore that diving reduces the virility of men, a point many divers seem keen to disprove.

There is a long history of the use of divers for strategic purposes. Divers were involved in operations during the Trojan Wars from 1194 to 1184 BC. They sabotaged enemy ships by boring holes in the hull or cutting the anchor ropes. Divers were also used to construct underwater defences designed to protect ports from the attacking fleets. The attackers in their turn used divers to remove the obstructions.

By Roman times, precautions were being taken against divers. Anchor cables were made of iron chain to make them difficult to cut, and special guards with diving experience were used to protect the fleet against underwater attackers.

An interesting early report indicated that some Roman divers were also involved in Mark Anthony's attempt to capture the heart of Cleopatra. Mark Antony participated in a fishing contest held in Cleopatra's presence and attempted to improve his standing by having his divers ensure a constant supply of fish on his line. The Queen showed her displeasure by having one of her divers fasten a salted fish to his hook.

Marco Polo and other travellers to India and Sri Lanka observed pearl diving on the Coromandel Coast. They reported that the most diving was to depths of 10 to 15 metres, but that the divers could reach 27 metres by using a weight on a rope to assist descent. They carried a net to put the oysters in and, when they wished to surface, were assisted by an attendant who hauled on a rope attached to the net. The divers were noted to hold their nose during descent.

The most skilled of the American native divers came from Margarita Island. Travellers who observed them during the sixteenth, seventeenth and eighteenth centuries reported that these divers could descend to 30 metres and remain submerged for 15 minutes. They could dive from sunrise to sunset, 7 days a week and attributed their endurance to tobacco! They also claimed to possess a secret chemical that they rubbed over their bodies to repel sharks. The Spaniards exploited these native divers for pearling, salvage and smuggling goods past customs. The demand for divers was indicated by their value on the slave market, fetching prices up to 150 gold pieces.

Free diving appears to have evolved as a modern sport in the mid-1940s, initially as a competition among Italian spearfishers. Currently the sport, which is steadily gaining popularity, encompasses a variety of disciplines. These include the following:

In 'no limits', a diver can use any means to travel down and up the line, as long as the line is used to measure the distance. Most divers descend down a line using a weighted sled and return to the surface aided by an inflatable balloon. Officially recorded depths in excess of 210 metres have been achieved using this method.

'Constant weight apnoea' diving is where descent and ascent occur along a line, although the diver is not permitted to pull on this line to assist movement. No weights can be removed during the dive. Monofins or bi-fins can be used.

'Constant weight without fins' is the same as constant weight apnoea but without the use of fins.

With 'variable weights', the diver again descends with the aid of a weighted sled, but this weight is limited. Ascent is achieved by finning or pulling up the cable, or both.

'Free immersion', which emerged in places where equipment was difficult to obtain, involves a finless diver (with optional suit, mask or weights) who pulls himself or herself down and then up a weighted line.

'Static apnoea' involves resting breath-holding (usually lying in a pool) with the face submerged. Officially recorded times in excess of 11 minutes have been achieved using this method.

'Dynamic apnoea' measures the distance covered in a pool during a single breath-hold.

EARLY EQUIPMENT

The history of diving with equipment is long and complex, and in the early stages it is mixed with legend. The exploits of Jonah are described with conviction in one text, but there is a shortage of supporting evidence. Further reference is made to him later, on the technicality that he was more a submariner than a diver. Because his descent was involuntary, Jonah was at best a reluctant pioneer diver. The history of submarine escape, when the submariner may become a diver, is discussed in Chapter 64.

Some claim that Alexander the Great descended in a diving bell during the third century BC. Details of the event are vague, and some of the fish stories attributed to him were spectacular. One fish was said to have taken 3 days to swim past him! It is most unlikely that the artisans of the time could make glass as depicted in most of the illustrations of the 'event'. This may have been a product of artistic licence or evidence that the incident is based more in fable than in fact.

Snorkels, breathing tubes made from reeds and bamboo (now plastic, rubber or silicone), were developed in many parts of the world. They allow a diver to breathe with the head underwater. Aristotle inferred that the Greeks used them. Columbus reported that the North American Indians would swim toward wild fowl while breathing through a reed and keeping their bodies submerged. They were able to capture the birds with nets, spears or even their bare hands. The Australian aborigines used a similar approach to hunt wild duck. Various people have 'invented' long hose snorkels. The one designed by Vegetius, dated 1511, blocked the diver's vision and imposed impossible loads on the breathing muscles.

Some have interpreted an Assyrian drawing dated 900 BC as an early diving set. The drawing shows a man with a tube in his mouth. The tube is connected to some sort of bladder or bag. It is more likely a float or life jacket. The tube length was a metre or more and so impossible to breathe through.

Leonardo da Vinci sketched diving sets and fins. One set was really a snorkel that had the disadvantage of a large dead space. Another of his ideas was for the diver to have a 'wine skin to contain the breath'. This was probably the first recorded design of a self-contained breathing apparatus. His drawings appear tentative, so it is probably safe to assume that there was no practical diving equipment in Europe at that time.

Another Italian, Borelli, in 1680, realized that Leonardo was in error and that the diver's air would have to be purified before he breathed it again. Borelli suggested that the air could be purified and breathed again by passing it through a copper tube cooled by sea water. With this concept, he had the basic idea of a rebreathing set. It could also be claimed that he had the basis of the experimental cryogenic diving set in which gas is carried in liquid form and purified by freezing out carbon dioxide.

Diving bells were the first successful method of increasing endurance underwater, apart from snorkels. These consist of a weighted chamber, open at the bottom, in which one or more people could be lowered under water. The early use of bells was limited to short periods in shallow water. Later, a method of supplying fresh air was developed. The first fully documented use of diving bells dates from the sixteenth century.

In 1691, Edmond Halley, the English astronomer who predicted the orbit of the comet that bears his name, patented a diving bell that was supplied with air in barrels (Figure 1.1). With this development diving bells became more widespread. They were used for salvage, treasure recovery and general construction work. Halley's bell was supplied with air from weighted barrels, which were hauled from the surface. Dives to 20 metres for up to 1 1/2 hours were recorded. Halley also devised a method of supplying air to a diver from a hose connected to the bell. The length of hose restricted the diver to the area close to the bell. It is not known whether this was successful. Halley was one of the earliest recorded sufferers of middle ear barotrauma.

Swedish divers had devised a small bell, occupied by one person and with no air supply to it. Between 1659 and 1665, 50 bronze cannons, each weighing more than 1000 kg, were salvaged from the *Vasa*. This Swedish warship had sunk in 30 metres of water in Stockholm harbour.

Figure 1.1 Edmond Halley's diving bell, 1691. The weighted barrels of air that were used to replenish the air can be clearly seen.

The guns were recovered by divers working from a bell, assisted by ropes from the surface. This task would not be easy for divers, even with the best of modern equipment.

MODERN DIVING EQUIPMENT

The first people to be exposed to a pressure change in a vessel on the surface were patients exposed to higher or lower pressure as a therapy for various conditions – the start of hyperbaric medicine. The origins of diving medical research can also be traced to these experiments.

During the second half of the nineteenth century, reliable air pumps were developed. These were able to supply air against the pressures experienced by divers. Several people had the idea of using these pumps for diving and developed what are now called open helmets, which cover the head and shoulders. Air was pumped down to the diver, and the excess air escaped from the bottom of the helmet. The diver could breathe because the head and neck were in air, or at least they were until the diver bent over or fell. If this happened, or if the hose or pump leaked, the helmet flooded and the diver was likely to drown. The Deane brothers were the inventors and among the major users of this equipment, and John Deane continued to use it up to the time of the Crimean War.

Standard rig, or **standard diving dress,** was first produced in 1840 by Augustus Siebe (a Russian immigrant engineer who later became a naturalized British citizen). This equipment consisted of a rigid helmet sealed to a flexible waterproof suit (Figure 1.2). Air was pumped down from the surface into the helmet, and excess air bled off through an outlet valve. The diver could control buoyancy by adjusting the flow through the outlet valve and thus the volume of air in the suit. This type of equipment, with a few refinements, is still in use.

Siebe's firm came to be the major manufacturer, but his role in the design may have been overstated, possibly for the marketing advantages gained by his firm, which marketed the first acceptable equipment of this type. The origins and evolution from open helmet and standard dress were the subject of a study by Bevan, who discussed several designs that were developed at the same time, with borrowing and stealing of ideas from each other.

Figure 1.2 Augustus Siebe's first helmet.

By the mid-nineteenth century, several types of diving suits and a bell were used by the Royal Engineers on dives on the wreck of the *Royal George,* which obstructed the anchorage at Spithead. The Siebe suit was found to be greatly superior to the other designs. Siebe's apparatus allowed the diver to bend over or even lie down without the risk of flooding the helmet. Also, the diver could control his depth easily. A diver in an open helmet had to climb a ladder or rely on his tenders to do this.

In more modern versions, the helmet is fitted with communications to allow the diver to confer with another diver or the surface. One of the developments from the Siebe closed helmet was the US Navy Mark 5 helmet. It probably set a record by being in service for 75 years.

The Royal Engineers were taught to dive by civilian divers in 1939–40 while on the *Royal George*. They then established a training facility at Gillingham in 1844 where they reintroduced diving to the Royal Navy, which set up their first diving school on HMS *Excellent* later that year.

Decompression sickness was noted, albeit not recognized in divers, following the development of these diving suits. Divers were given fresh dry undergarments because the 'rheumatic' pains they suffered were attributed to damp and cold. Other divers suffered paralysis that was attributed to fatigue from zeal and overexertion. Most of these men would have been suffering from decompression sickness because they were diving for up to three times the accepted limits for dives without decompression stops.

Decompression sickness was also observed in workers employed in pressurized caissons and tunnels. In these operations, the working area is pressurized to keep the water out. The history of decompression sickness is discussed in Chapter 10.

Paul Bert and J. S. Haldane are the fathers of diving medicine. Paul Bert published a text book *La pression barométrique* based on his studies of the physiological effect of changes in pressure. His book is still used as a reference text even though it was first published in 1878. Bert showed that decompression sickness was caused by the formation of gas bubbles in the body and suggested that it could be prevented by gradual ascent. He also showed that pain could be relieved by a return to higher pressures. Such cases were initially managed by the diver's returning to the pressure of the caisson. However, specially designed recompression chambers were introduced and utilized at some job sites within a few years.

J.S. Haldane, a Scottish scientist, was appointed to a Royal Navy committee to investigate the problem of decompression sickness in divers. At that time the Royal Navy had a diving depth limit of 30 metres, but deeper dives had been recorded. Greek and Swedish divers had reached 58 metres in 1904, and Alexander Lambert had recovered gold bullion from a wreck in 50 metres of water in 1885, but he had developed partial paralysis from decompression sickness.

Haldane concluded from Paul Bert's results that a diver could be hauled safely to the surface from 10 metres with no evidence of decompression sickness. He deduced from this that a diver could be surfaced from greater than 10 metres in stages, provided that time was spent at each stage to allow absorbed nitrogen to pass out of the body in a controlled manner. This theory was tested on goats and then on men in chambers. Haldane's work culminated in an open water dive to 64 metres in 1906 and the publication of the first acceptable set of decompression tables. Haldane also developed several improvements to the diving equipment used.

In 1914, US Navy divers reached 84 metres. The next year they raised a submarine near Hawaii from a depth of 93 metres. This was a remarkable feat considering that the salvage techniques had to be evolved by trial and error. The divers used air, so they were exposed to a dangerous degree of nitrogen narcosis, as well as decompression sickness.

SELF-CONTAINED EQUIPMENT

Self-contained underwater breathing apparatus (scuba) is used to describe any diving set that allows the diver to carry the breathing gas supply with him or her. There are several claims to its invention, based on old drawings. The first workable form probably dates from the early nineteenth century. There is a brief report of an American engineer, Charles Condert, who made a scuba in which the compressed air was stored in a copper pipe worn around his body. The gas was released into a hood that covered the upper half of his body. Accumulation of carbon dioxide was controlled by allowing the respired gas to escape through a small hole. It was then replaced by fresh gas from the storage pipe. Condert died while diving with his equipment in the East River in New York in 1831.

In 1838, Dr Manuel Guillaumet filed a patent in France for a back-mounted, twin-hose demand regulator that was supplied with air from hoses to the surface. A patent for a similar device was also filed in England earlier that year by William Newton, but it seems likely that this was done on behalf of Guillaumet.

Another early development was the Rouquayrol and Denayrouze device of 1865 (Figure 1.3). This set was supplied with air from the surface that was breathed on demand via a mouthpiece. It was fitted with a compressed air reservoir so that the diver could detach himself or herself from the air hose for a few minutes. The endurance, as a scuba, was limited by the amount of air in the reservoir.

The first successful scuba with an air supply appears to have been developed and patented in 1918 by Ohgushi, who was Japanese. His system could be operated with a supply of air from the surface or as a scuba with an air supply cylinder carried on the back. The diver controlled the air

Figure 1.3 The aerophore, devised by Rouquayrol and Denayrouze, 1865. This device was widely used and was an important milestone in the development of the modern scuba.

supply by triggering air flow into the mask with the diver's teeth. Another scuba was devised by Le Prieur in 1933. In this set, the diver carried a compressed air bottle on the chest and released air into the face mask by opening a tap.

In 1943, Cousteau and Gagnan developed the first popular scuba as we know it today. It was an adaptation of a reducing valve that Gagnan had evaluated for use in gas-powered cars and was far smaller than the Rouquayrol-Denayrouze device.

Closed-circuit oxygen sets were developed during the same period as the modern scuba. In these rebreathing sets, the diver is supplied with oxygen and the carbon dioxide is removed by absorbent. These sets are often called scuba, but they may be considered separately because of the difference in principles involved. The patent for the first known prototype of an oxygen rebreather was given to Pierre Sicard, who was French, in 1849. The first known successful rebreathing set was designed by English engineer H. A. Fleuss in 1878. This was an oxygen set in which carbon dioxide was absorbed by rope soaked in caustic potash.

Because of the absence of lines and hoses from the diver to the surface, the set was used in flooded mines and tunnels where the extra mobility, compared with the standard rig, was needed. Great risks were taken with this set and its successors when used underwater because the work of Paul Bert on oxygen toxicity was not widely known. This equipment was the precursor of oxygen sets used in clandestine operations in both world wars and of other sets used in submarine escape, firefighting and mine rescue.

MODERN MILITARY DIVING

The military use of divers in warfare was, until 1918, largely restricted to the salvage of damaged ships, clearing of channels blocked by wrecks, and assorted ships' husbandry duties. One significant clandestine operation conducted during the First World War was the recovery of code books and minefield charts from a sunken German submarine. This was of more significance as an intelligence operation, although the diving activity was also kept secret.

During the First World War, Italy developed a human torpedo or chariot that was used in 1918 to attack an Austrian battleship in Pola Harbour in what is now Croatia. The attack was a success in that the ship was sunk, but, unfortunately, it coincided with the fall of the Austro-Hungarian Empire, and the ship was already in friendly hands! The potential of this method of attack was noted by the Italian Navy. They put it to use in the Second World War with divers wearing oxygen rebreathing sets as underwater pilots. In passing, it is interesting to note that the idea of the chariot was suggested to the British Admiralty in 1909, and Davis took out patents on a small submarine and human torpedo controlled by divers in 1914. This was pre-dated by a one-person submarine designed by J.P. Holland in 1875.

Diving played a greater part in offensive operations during the Second World War. Exploits of note include those of the Italian Navy. They used divers riding modified torpedoes to attack ships in Gibraltar and Alexandria. After a series of unsuccessful attempts with loss of life, they succeeded in sinking several ships in Gibraltar harbour in mid-1941. Later that year, three teams managed to enter Alexandria harbour and damage two battleships and a tanker. Even Sir Winston Churchill, who did not often praise his enemies, said they showed 'extraordinary courage and ingenuity'. Churchill had previously been responsible for rejecting suggestions that the Royal Navy use similar weapons.

In Gibraltar, a special type of underwater war evolved. The Italians had a secret base in neutral Spain, only 10 kilometres away, and launched several attacks that were opposed by British divers who tried to remove the Italian mines before they exploded.

Divers from the allied nations made several successful attacks on enemy ships, but their most important offensive roles were in the field of reconnaissance and beach clearance. In most operations, the divers worked from submarines or small boats. They first surveyed the approaches to several potential landing sites. After a choice had been made, they cleared the obstructions that could impede the landing craft. One of the more famous exploits of an American diving group was to land unofficially and leave a 'Welcome' sign on the beach to greet the US Marines, spearheading the invasion of Guam. The British Clearance Divers and the US Navy Sea, Air, Land Teams (SEALs) evolved from these groups. The Clearance Divers get their name from their work in clearing mines and other obstructions, a role they repeated during and after the Gulf War.

The research back-up to these exploits was largely devoted to improvement of equipment and the investigation of the nature and onset of oxygen toxicity (Chapter 17). This work was important because most of these offensive operations were conducted by divers wearing oxygen breathing apparatus. The subjects were the unsung heroes of the work. This group of scientists, sailors and conscientious objectors deliberately and repeatedly suffered oxygen toxicity in attempts to understand the condition.

Oxygen-nitrogen mixtures were first used for diving by the Royal Navy in conjunction with a standard diving rig. This approach was based on an idea proposed by Sir Leonard Hill and developed by Siebe Gorman and Co. Ltd. The advantage of this equipment is that, by increasing the ratio of oxygen to nitrogen in the breathing gas, one can reduce or eliminate decompression requirements. It is normally used with equipment in which most of the gas is breathed again after the carbon dioxide has been removed. This allows reduction of the total gas volume required by the diver.

During the Second World War, this idea was adapted to a self-contained semi-closed rebreathing apparatus that was first used extensively by divers clearing mines. This development was conducted by the British Admiralty Experimental Diving Unit in conjunction with Siebe Gorman and Co. Ltd. The change to a self-contained set was needed to reduce the number of people at risk from accidental explosions in mine-clearing operations. The reduction, or elimination, of decompression time was desirable in increasing the diver's chances of survival if something went wrong. The equipment was constructed from non-magnetic materials to reduce the likelihood of activating magnetic mines and was silent during operation for work on acoustically triggered mines.

DEEP DIVING

The search for means to allow humans to descend deeper has been a continuing process. By the early twentieth century, deep diving research had enabled divers to reach depths in excess of 90 metres; at which depth the narcosis induced by nitrogen incapacitated most humans.

After the First World War, the Royal Navy diving research tried to extend its depth capability beyond 60 metres. Equipment was improved, the submersible decompression chamber was introduced and new decompression schedules were developed that used periods of oxygen breathing to reduce decompression time. Dives were made to 107 metres, but nitrogen narcosis at these depths made such dives both unrewarding and dangerous.

Helium diving resulted from a series of American developments. In 1919, a scientist, Professor Elihu Thompson, suggested that nitrogen narcosis could be avoided by replacing the nitrogen in the diver's gas supply with helium. At that stage, the idea was not practical because helium cost more than US $2000 per cubic foot. Later, following the exploitation of natural gas supplies that contained helium, the price dropped to about 3 cents per cubic foot.

Research into the use of helium was conducted during the 1920s and 1930s. By the end of the 1930s, divers in a compression chamber had reached a pressure equal to a depth of 150 metres, and a dive to 128 metres was made in Lake Michigan. Between the two world wars, the United States had a virtual monopoly on the supply of helium and thus dominated research into deep diving.

For **hydrogen diving,** the use of hydrogen in gas mixtures for deep diving was first tried by Arne Zetterstrom, a Swedish engineer. He demonstrated that hypoxia and risks of explosion could be avoided if the diver used air from the surface to 30 metres, changed to 4 per cent oxygen in nitrogen and then changed to 4 per cent or less oxygen in hydrogen. In this manner, the diver received adequate oxygen, and the formation of an explosive mixture of oxygen and hydrogen was prevented.

In 1945, Zetterstrom dived to 160 metres in open water. Unfortunately, an error was made by the operators controlling his ascent, and they hauled him up too fast, omitting his planned gas transition and decompression stops. He died of hypoxia and decompression sickness shortly after reaching the surface.

Hydrogen has been used successfully both for decreasing the density of the breathing gas mixture and ameliorating the signs and symptoms of high-pressure neurological syndrome. The cheapness of hydrogen compared with helium, and the probability of a helium shortage in the future, may mean that hydrogen will be more widely used in deep dives.

Other European workers followed Zetterstrom with radical approaches to deep diving. The Swiss worker Keller performed an incredible 305-metre dive in the open sea in December 1962 (Figure 1.4). He was assisted by Bühlmann, who developed and tested several sets of decompression tables and whose decompression algorithm has been adapted and used in many of the early and current generations of diving computers.

Modern gas mixture sets have evolved as the result of several forces. The price of helium has become a significant cost. This, combined with a desire to increase the diver's mobility, has encouraged the development of more sophisticated mixed gas sets. The most complex of these have separate cylinders of oxygen and diluting gas. The composition of the diver's inspired gas is maintained by the action of electronic control systems that regulate the release of gas from each cylinder. The first of these sets was developed in the 1950s, but they have been continually refined and improved.

Figure 1.4 Prof Bühlmann (rear) and Hannes Keller prepare for the first simulated dive to 3000 m (1000 ft) on 25 April 1961.

Modern air or gas mixture helmets have several advantages compared with the older equipment. A demand system reduces the amount of gas used, compared with the standard rig. The gas-tight sealing system reduces the chance of a diver's drowning by preventing water inhalation. The primary gas supply normally comes to the diver from the surface or a diving bell and may be combined with heating and communications. A second gas supply is available from a cylinder on the diver's back. Americans Bob Kirby and Bev Morgan led the way with a series of helmet systems. A model, used for both compressed air and

Figure 1.5 A Kirby-Morgan 97 helmet.

gas mixtures, is shown in Figure 1.5. These helmets have been used to depths of around 400 metres.

Saturation diving is probably the most important development in commercial diving since the Second World War. Behnke, an American diving researcher, suggested that caisson workers could be kept under pressure for long periods and decompressed slowly at the end of their job, rather than undertake a series of compressions and risk decompression sickness after each.

A US Navy Medical Officer, George Bond, among others, adopted this idea for diving. The first of these dives involved tests on animals and men in chambers. In 1962, Robert Stenuit spent 24 hours at 60 metres in the Mediterranean Sea off the coast of France.

Despite the credit given to Behnke and Bond, it could be noted that the first people to spend long periods in an elevated pressure environment were patients treated in a hyperbaric chamber. Between 1921 and 1934 an American, Dr Orval Cunningham, pressurized people to 3 ATA for up to 5 days and decompressed them in 2 days.

Progress in saturation diving was rapid, with the French-inspired Conshelf experiments and the American Sealab experiments seeking greater depths and durations of exposure. In 1965, the former astronaut Scott Carpenter spent a month at 60 metres, and two divers spent 2 days at a depth equivalent to almost 200 metres. Unfortunately, people paid for this progress. Lives were lost, and there has been a significant incidence of bone necrosis induced by these experiments.

In saturation diving systems, the divers live either in an underwater habitat or in a chamber on the surface. In the second case, another chamber is used to transfer the divers under pressure to and from their work sites. Operations can also be conducted from small submarines or submersibles with the divers operating from a compartment that can be opened to the sea. They can either transfer to a separate chamber on the submarine's surface support vessel or remain in the submarine for their period of decompression. The use of this equipment offers several advantages. The submarine speeds the diver's movement around the work site, provides better lighting and carries extra equipment. Additionally, a technical expert who is not a diver can observe and control the operation from within the submarine.

Operations involving saturation dives have become routine for work in deep water. The stimulus for this work is partly military and partly commercial. Divers work on the rigs and pipelines needed to exploit oil and natural gas fields. The needs of the oil companies have resulted in strenuous efforts to extend the depth and efficiency of the associated diving activities.

Atmospheric diving suits (ADSs) are small, one-person, articulated submersibles resembling a suit of armour (Figure 1.6). These suits are fitted with pressure joints to enable articulation, and they maintain an internal pressure of 1 ATA, so avoiding the hazards of increased and changing pressures. In effect, the diver becomes a small submarine.

The mobility and dexterity of divers wearing early armoured suits were limited, and these suits were not widely used. The well-known British 'JIM' suit, first used in 1972, enabled divers to spend long periods at substantial depths. However, these were never fitted with propulsion units and were replaced by the Canadian 'Newtsuit' and the WASP, which have propellers to aid movement and can be fitted with claws for manipulating equipment.

In 1997, the ADS 2000 was developed in conjunction with the US Navy. This evolution of the Newtsuit was designed to meet the Navy's needs.

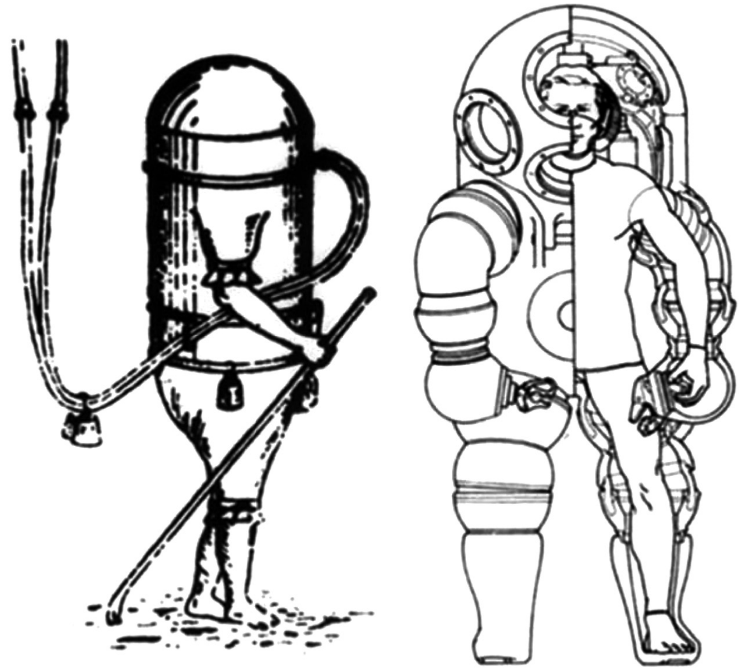

Figure 1.6 Armoured diving suits, past and present (JIM).

It was designed to enable a diver to descend to 610 metres (2000 ft) and had an integrated dual-thruster system to allow the pilot to navigate easily underwater. The ADS 2000 became fully operational and certified by the US Navy in 2006 when it was used successfully on a dive to 610 metres.

Liquid breathing trials, in which the lungs are flooded with a perfluorocarbon emulsion and the body is supplied with oxygen in solution, have been reported to have been conducted in laboratories. The potential advantages of breathing liquids are the elimination of decompression sickness as a problem, freedom to descend to virtually any depth and the possibility of the diver's extracting the oxygen dissolved in the water.

RECREATIONAL DIVING

Amateur diving started with breath-hold diving, mainly by enthusiasts in Italy and the south coast of France who were keen spearfishers. This was also the area where compressed air scuba diving developed as a result of the work of Hass, Cousteau and others. As a sport, diving rapidly spread to Britain and the United States and the rest of the world.

From this beginning, diving has become a recreational activity that is often combined with tourism and photography. Others explore caves and wrecks and seek the excitement that deeper and further penetrations provide. Special interest groups such as cave and technical divers have developed and in some areas are the modern pathfinders. These groups and their problems are discussed in greater detail in later chapters.

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This chapter was reviewed for this fifth edition by John Lippmann.

2

Physics and physiology

INTRODUCTION

A basic knowledge of the physics and physiology of diving is essential to understand most of the medical problems encountered. Aspects of physics and physiology that have a wide application to diving are discussed in this chapter.

Some of the basic physiological implications are also mentioned, but most aspects of diving physiology and pathophysiology are relegated to the relevant chapters on specific diving disorders.

PRESSURE, GASES AND DIVING

On the surface of the Earth, we are exposed to the pressure exerted by the atmosphere. This is called the atmospheric or barometric pressure. Most people regard this pressure as caused by the mass of the atmosphere pressing down on them. A flaw in this argument is that the pressure remains in a bottle after it is sealed, although its contents are contained and are no longer exposed to the column of air above. The physically correct explanation is that atmospheric pressure is generated by collisions of the molecules of gas in accordance with the kinetic theory of gases. Either explanation is acceptable for the following discussion.

The pressure decreases as we move upward through the atmosphere and increases as we move down into a mine or into the sea. At the top of Mount Everest the atmospheric pressure is about 40 per cent of that at sea level. Because water is much heavier than air, the pressure changes experienced by divers over a particular depth change are much greater than those encountered by climbers or aviators as they change altitude.

Pressure is measured in a variety of units from either of two reference points. It can be expressed with respect to a vacuum, i.e. zero pressure. This reading is called an **absolute pressure.** The second method measures pressures above or below local pressure. These readings are called **gauge pressures.** At sea level, the absolute pressure is 1 atmosphere (1 ATA) and the gauge pressure is 0. These units are commonly abbreviated to ATA and ATG.

Common examples are the barometric pressure used by weather forecasters, which is an absolute pressure, and the blood pressure, which is a gauge pressure reading.

With descent in water, pressure increases. For each 10 metres of depth in sea water, the pressure increases by 1 atmosphere, starting from 1 ATA or 0 ATG at the surface. The gauge pressure remains 1 atmosphere less than the absolute pressure. For example, at 10 metres, the pressure is 2 ATA and 1 ATG. At 90 metres, the pressure is 10 ATA and 9 ATG.

Table 2.1 Pressure conversion factors (commonly used approximations shown in brackets)

1 atmosphere	= 10.08 (10) metres sea water
	= 33.07 (33) feet sea water
	= 33.90 (34) feet fresh water
	= 101.3 kilopascals (kPa)
	= 0.1013 megapascals (MPa)
	= 1.033 kg/cm^2
	= 14.696 (14.7) lbs/in^2
	= 1.013 bars
	= 760 millimetres mercury (mm Hg)
	= 760 torr
	= 1 ATA

Note: Actual conversions from sea water depth to ATA depend on salinity and temperature. A complete conversion matrix is provided in Table 2.2.

Pressure units

Because diving involves facets of engineering and science, it is plagued with many units of pressure. These include absolute and gauge atmospheres, pascals and multiples such as the kilopascal, metres or feet of sea water, bars, pounds per square inch, torr and several other rarer units. Table 2.1 lists conversions for the more commonly used units.

Pressure and the diver's body

Many people have difficulty in understanding why the pressure of the water does not crush the diver. The answer to this problem may be considered in two parts:

The solid and liquid parts of the body are virtually incompressible, so a pressure applied to them does not cause any change in volume and is transmitted through them. After immersion, the increased pressure pushes on the skin, which in turn pushes on the tissues underneath, and so the pressure is transferred through the body until the skin on the other side is pushed back against the water pressure. Therefore, the system remains in balance. This is in accordance with **Pascal's Principle,** which states: *'A pressure exerted anywhere in a confined incompressible fluid is transmitted equally in all directions throughout the fluid such that the pressure ratio remains the same'.*

Table 2.2 Pressure conversions

	atm	n/m^2 or Pa	bars	mb	kg/cm^2	gm/cm^2 (cm H_2O)	mm Hg	lb/in^2 (psi)
1 atmosphere	1	1.013 x 10^5	1.013	1013	1.033	1033	760	14.70
1 Newton (N)/m^2 or Pascal (Pa)	0.9869 x 10^{-5}	1	10^{-5}	0.01	1.02 x 10^{-5}	0.0102	0.0075	0.1451 x 10^{-3}
1 bar	0.987	10^5	1	1000	1.02	1020	750.2	14.51
1 millibar (mb)	0.9869 x 10^{-3}	100	0.001	1	0.00102	1.02	0.7502	0.01451
1 kg/cm^2	0.9681	0.9806 x 10^5	0.9806	980.6	1	1000	736	14.22
1 gm/cm^2 (1 cm H_2O)	968.1	98.06	0.9806 x 10^{-3}	0.9806	0.001	1	0.736	0.01422
1 mmHg	0.001316	133.3	0.001333	1.333	0.00136	1.36	1	0.01934
1 lb/in^2 (psi)	0.06804	6895	0.06895	68.95	0.0703	70.3	51.70	1

However, the effect of pressure on the gas spaces in the diver's body is more complex. The applied pressure does not cause any problems if the pressure in the gas space is close to that of the surrounding water. There is, for example, no physical damage to a diver's lungs if the air space was exposed to an internal pressure of 100 metres of water, provided that this pressure is balanced by the pressure exerted by surrounding water acting on the walls of the lung to balance any tendency of the lungs to expand. If the lungs were exposed to an internal pressure sufficiently more than the surrounding atmospheric tissue, they would overexpand and burst.

Water pressure and lung inflation

Immersion up to the neck in water reduces vital capacity by about 10 per cent (Figure 2.1 shows lung volumes). This is caused in part by the hydrostatic pressure of the water compressing the thorax. With immersion, there is also a loss of gravitational effects. This reduces the volume of blood in lower, mainly leg, veins and increases thoracic blood volume. This change in turn reduces the compliance of the lungs.

When a diver is using breathing equipment, pressure at the point from which the gas is inhaled can be different from the pressure at the chest. If upright in the water, a scuba diver is inhaling air released at the pressure at the level of the mouth. A snorkel diver is inhaling air from the surface, and this is at surface pressure. In both these cases, the air is at a lower pressure than the diver's lungs. This reduces the amount of air the diver can inhale because part of the inhalation force is used in overcoming this pressure difference.

Conversely, when descending, face-down, a diver whose air is released at mouth pressure can inhale to greater than normal vital capacity but could not exhale to the normal residual volume. This is because in this orientation, the water pressure is helping to inflate the lungs.

Pressure and volume changes

When a diver descends, the increased pressure of the surrounding water compresses gas in the gas spaces within the diver's body. These spaces include the lungs, middle ears, sinuses and intestines.

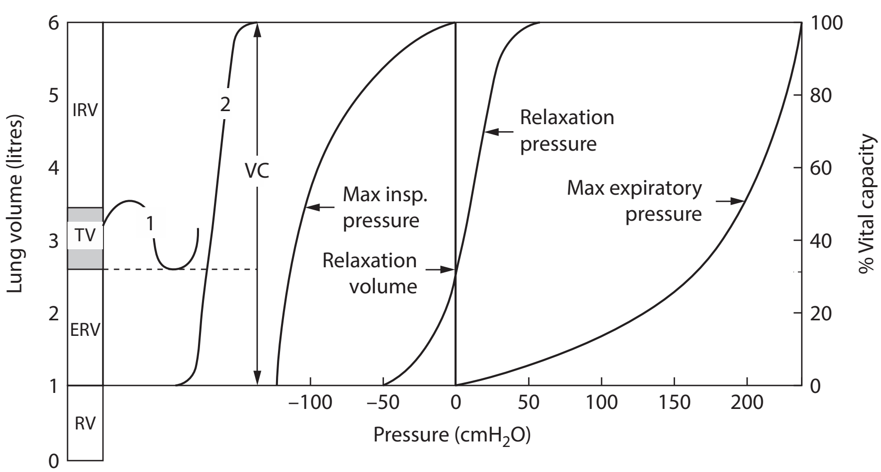

Figure 2.1 Lung volumes and intrapulmonary pressure. The various components of lung volumes are labelled on the left. On the right, the relationships among lung volume, airway pressure and the maximum effort that can be made for inhalation and exhalation of air are plotted. Curve 1 is the volume change during quiet breathing, and curve 2 is the volume change during a maximum inhalation starting at the residual volume. ERV, expiratory reserve volume; insp., inspiratory; IRV, inspiratory reserve volume; RV, residual volume; TV, tidal volume; VC, vital capacity. (Redrawn from Lamphier EH, Camporesi EM. Respiration and exertion. In: Bennett PB, Elliott DH. The phyisology & medicine of diving, 4th edn. London:WB Saunders Co Ltd; 1993, with permission).

This is one of the many aspects of diving medicine that is concerned with the relationship between pressure change and change of gas volume. The relationship between changes in volume of a gas and the pressure applied to it is described by **Boyle's Law.** This states: *'if the temperature remains constant, the volume of a given mass of gas is inversely proportional to the absolute pressure'.* This means that the absolute pressure multiplied by volume has a constant value, and this constant changes with the mass of gas considered. To a mathematician, this means that $P \times V = K$ or $P_1 \times V_1 = P_2 \times V_2$, where P and V are pressure and volume. For example, 10 litres of gas at sea level pressure (1 ATA) will be compressed to:

5 litres at 2 ATA (10 metres).
2 litres at 5 ATA (40 metres).
1 litre at 10 ATA (90 metres).

During ascent into the atmosphere, the reverse happens and the gas expands. This means that the 10 litres of air would expand to 20 litres at 0.5 ATA (an altitude of about 5000 metres or 18 000 feet) and to 40 litres at 0.25 ATA (an altitude of about 10 300 metres or 33 400 feet).

Gas volumes expand when pressure decreases and contract when pressure increases.

The volume of a mass of gas in a flexible container decreases with pressure or depth increase and expands during ascent or pressure reduction (Figure 2.2). It should be noted that volume changes are greatest near the surface. Conversely, gas has to be added if the volume of a container or gas space is to remain constant as the pressure is increased. The effects of this law are important in many aspects of diving medicine.

During descent, the increasing pressure in the water is transmitted through the body fluids to the tissue surrounding the gas spaces and to the gas spaces themselves. The pressure in any gas space in the body should increase to equal the surrounding pressure. In the lungs, during descent on breath-hold dives, this is accompanied by a decrease in lung volume. Air should enter cavities with rigid walls,

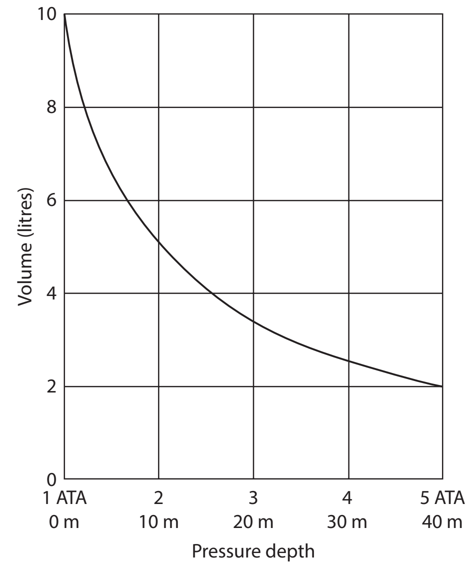

Figure 2.2 Effect of Boyle's Law: While breathing underwater, the diver's respiratory volume is about the same as it would be if he or she worked at the same rate on the surface. Because of the increase in density of this breathing gas under increased pressure, the diver must move a greater mass of gas with each breath. In some situations, this physical effect can limit the diver's capacity to do work.

such as the sinuses or the middle ear. If air entry does not take place to equalize pressures, then a pressure difference between the space and the surrounding tissue will develop, with the pressure in the gas space being less than in the surrounding tissue. The results are tissue distortion and damage, such as congestion, oedema or haemorrhage.

During ascent, as the pressure decreases, gas within body spaces will expand. Unless gas is vented from the space, the expanding gas will exert pressure on the surrounding tissue and will eventually damage it. Pressure changes in the middle ear can also result in rupture of the tympanic membrane.

The same volume changes with pressure occur in bubbles in tissue or blood. Again, the volume changes are greatest close to the surface. An injury caused by pressure change is called barotrauma.

Barotrauma is the general name for an injury caused by pressure change.

Respiration in water and under pressure

While breathing air underwater, the diver's respiratory volume is about the same as it would be if he or she worked at the same rate on the surface. A consequence of this is that a cylinder that contains enough air for 100 minutes at 1 ATA would last about 50 minutes at 2 ATA (10 metres) or 20 minutes at 5 ATA (40 metres) for dives with the same energy expenditure. This is because the gas in the cylinder expands to a smaller volume when it is released against the ambient pressure at depth than it would if used at the surface. A cylinder that contains 5000 litres of gas if it is released at the sea surface would yield only 1000 litres of gas if it is released at 5 ATA, or 40 metres. A diving physician needs to keep this in mind when estimating the amount of gas needed for any task or therapy.

With depth, gas is compressed and there is an increase in density of the gas because there are more molecules in a given space. So, at depth, a diver must move a greater mass of gas with each breath. This requires greater effort and involves an increase in the work of breathing. In some situations, this can limit the capacity to do work.

The density of the breathing gas can be reduced by replacing nitrogen with a lighter gas such as helium. For example, the density of air at 1 ATA is about 1.3 kg/cubic metre. At 10 ATA, the density of air would be about 13 kg/cubic metre. The use of lighter gas helps to reduce density. For example, at 40 ATA, the density of a 1 per cent oxygen and helium mixture is 6.7 kg/cubic metre.

As the density of a gas increases, there is an increased tendency for the flow to become turbulent. This causes a further increase in the energy used in breathing. These factors can lead to fatigue of the inspiratory muscles and reduce maximum breathing capacity and the work output. To minimize this load, the body responds by using less gas for a given workload. This can result in the development of hypercapnia. Continued exposure to dense gas, as is encountered in deep dives, may cause an adaptive response.

Temperature and volume changes

Charles' Law states: *'If the pressure is constant, the volume of a mass of gas is proportional to the absolute temperature'.*

The absolute temperature (A°) is always 273° more than the centigrade temperature. A more useful expression of the law is as follows:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \text{ or } \frac{V}{T} = K$$

Where V_1 is the volume of a mass of gas at temperatures T_1°A and V_2 is its volume after the temperature has changed to T_2°A.

This law has much less relevance to diving medicine than Boyle's Law. However, it should be remembered when considering gas volumes and how they may change.

Boyle's and Charles' Laws may be combined and used if temperature and pressure both change – from P_1 and T_1 to P_2 and T_2 with a volume change from V_1 to V_2. The combined laws can be expressed as the **universal gas equation:**

$$\frac{P_1 \times V_1}{T_1} = \frac{P_2 \times V_2}{T_2}$$

A temperature-pressure problem that often causes discord can be used to illustrate the use of this equation. This is the effect of temperature on the pressure in a gas cylinder.

A diver may ask to have the compressed air cylinder filled to 200 ATA. The gas compressor heats the gas so the cylinder may be charged with gas at 47°C. When the diver gets in the water at 7°C, the diver may find that he or she has only 175 ATA in the cylinder. In this case $V_1 = V_2$ because the cylinder is rigid and the pressure falls as the gas cools.

$$47°\text{C} = 320°\text{A},\ 7°\text{C} = 280°\text{A},\ V_1 = V_2$$

$$\frac{200 \times V_1}{320} = \frac{P_2 \times V_2}{280}$$

$$P_2 = 175 \text{ ATA.}$$

So the reduced pressure is a result of temperature change, not a leaking valve or fraud by the air supplier.

Partial pressures in gas mixtures

Dalton's Law states: *'the total pressure exerted by a mixture of gases is the sum of the pressures that would be exerted by each of the gases if it alone occupied the total volume'.* The pressure of each constituent in a mixture is called the partial pressure (Figure 2.3). In air, which is approximately 80 per cent nitrogen and 20 per cent oxygen, the total pressure at sea level (1 ATA) is the sum of the partial pressures of nitrogen, 0.8 ATA, and oxygen, 0.2 ATA. At 2 ATA (10 metres) these partial pressures will rise to 1.6 and 0.4 ATA, respectively.

The partial pressures of breathing gases can be manipulated to the diver's advantage. For example, the composition of the gas breathed may be modified to reduce the chance of decompression sickness (DCS) by decreasing the percentage of inert gas in the mixture.

Undesirable effects can also occur. Air from an industrial area may contain more than 0.3 per cent carbon dioxide and 0.002 per cent carbon monoxide. If incorporated in compressed breathing gas and delivered at high partial pressures, both constituents could be toxic unless measures were taken to remove these contaminants before use.

It may be necessary to combine Boyle's and Dalton's Laws in calculations. For example, it may be decided that a diver should be given a mixture with a partial pressure of 0.8 ATA oxygen and 1.2 ATA nitrogen in a recompression chamber pressurized to 2 ATA. If oxygen and air are the only gases available, the gas laws can be used to calculate how to prepare a cylinder charged with the right gas mixture.

The mixture will need to be 40 per cent oxygen and 60 per cent nitrogen (Dalton's Law). If the gas is to be prepared in a cylinder charged to 200 ATA, it should contain 120 ATA of nitrogen (60 per cent of 200). If this is to be obtained from compressed air (assumed to be 80 per cent nitrogen in this exercise), it will be necessary to put 150 ATA of compressed air into the cylinder (30 ATA of oxygen and 120 ATA of nitrogen) with 50 ATA of oxygen.

This simple mixing process cannot be used as successfully with helium mixtures. At high pressures, helium does not follow the predictions of Boyle's Law accurately. It is less compressible than the ideal gas described by Boyle's Law. Mixing can be conducted with allowance for this or by putting a calculated weight of each gas in the cylinder.

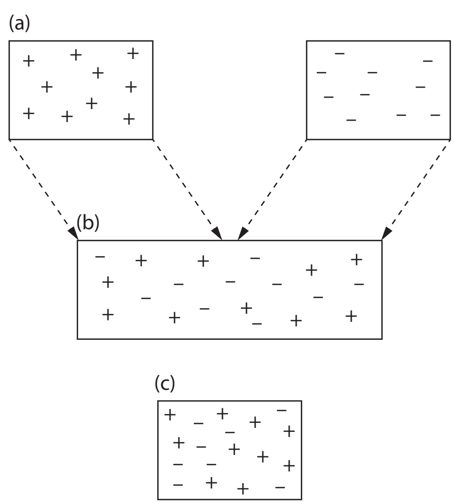

Figure 2.3 Dalton's Law: **(a)** two spaces each at 1 ATA; **(b)** total pressure 1 ATA, 0.5 ATA each component of the mixture; **(c)** total pressure 2 ATA, 1 ATA of each component of the mixture.

Solution of gases in liquids

Henry's Law states: *'at a constant temperature, the amount of a gas that will dissolve in a liquid is proportional to the partial pressure of the gas over the liquid'.* This law implies that an equilibrium is established with each gas passing into and out of any solution in contact with it (Figure 2.4). At sea level (1 ATA), an individual's body tissues contain about 1 litre of gaseous nitrogen in solution. If the diver dived to 10 metres and breathed

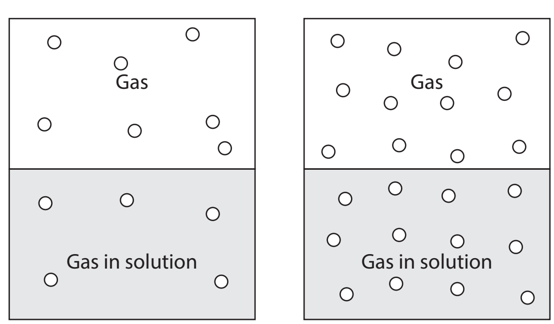

Figure 2.4 Henry's Law.

air at 2 ATA, more gas would dissolve and he or she would eventually reach equilibrium again and have twice as much nitrogen in solution in the body. The time taken for any inert gas to reach a new equilibrium depends on the solubility of the gas in the tissues and the rate of gas supplied to each tissue.

When the total pressure, or the partial pressure of a particular gas, is reduced, gas must pass out of solution. If a rapid total pressure drop occurs, a tissue may contain more gas than it can hold in solution. In this situation, bubbles may form and may cause DCS.

The physiological effects of the solubility of gases are also relevant in nitrogen narcosis and oxygen toxicity.

It should be noted that each gas has a different solubility and the amount of any gas that will dissolve in a liquid depends on the liquid. For example, carbon dioxide is very soluble in water compared with other common gases. Beer aerated with compressed air instead of carbon dioxide would have far fewer bubbles. Nitrogen is more soluble in fats and oils than in aqueous solutions.

Henry's Law is also time dependent. It takes time for gases to enter and leave solution or form bubbles. If this was not so, champagne would go flat as soon as the cork was popped.

At depth, a diver breathing air absorbs nitrogen in accord with Henry's Law. The amount depends on depth and time of exposure. When the diver surfaces, the excess nitrogen must pass from the body. If it is eliminated from solution through the lungs, there will not be any complications. In some cases, the nitrogen comes out of solution in the blood or tissues, thus forming bubbles that may lead to DCS.

Gas movement in body tissues

Gas transfer from the lungs to the tissues is dependent on the cardiovascular circulation, and the gas supplied to a portion of tissue depends on the blood perfusing it. In a permeable substance such as body tissues, gas molecules can migrate by diffusion. That is, gas molecules dissolve in the tissue fluids and tend to move from areas of high to low partial pressure until the partial pressure of the dissolved gas is uniform. This can take hours. It is the dissolved gas pressures that tend to equilibrate, not the number of gas molecules. If a gas is twice as soluble in one tissue compared with another, then twice as many molecules will be in the first tissue to produce the same partial pressure in the tissue. This information can be estimated from the solubility coefficients of the gas in the components of the tissue.

The rate of gas movement between two points depends on several factors. The difference in partial pressure and the distance between the two points may be combined into a concentration gradient. The other major factor is the permeability of the tissue, an expression of the ease of gas movement. A large partial pressure between two points that are close together (a steep gradient) and a greater permeability both increase the rate of gas transfer.

Metabolic gas exchange

In divers, gas exchange mechanisms are basically the same as at normal pressure. Oxygen diffuses down a concentration gradient from the lungs to the tissues. The carbon dioxide gradient is normally in the opposite direction. The exchange of inert gases becomes important and there are changes in the finer details of metabolic gas exchange.

With increasing depth, there is an increase in the partial pressures of the constituents of the breathing mixture in accordance with Dalton's Law. This causes higher alveolar pressures and arterial pressures of the inhaled gases.

Elevated pressures of oxygen facilitate oxygen transport, but they may interfere with the elimination of carbon dioxide in two ways: first, by the depression of respiration induced by high arterial oxygen tensions; and second, by direct interference with the transport of carbon dioxide. When the inspired oxygen partial pressure is elevated, there is an increase in oxygen transport in solution in the plasma (Henry's Law). When one is inhaling oxygen at a partial pressure above 3 ATA, the total oxygen requirement may be carried in solution. If this happens, the haemoglobin may be still saturated with oxygen in the venous blood, and this can prevent the transport of carbon dioxide in the form of carbaminohaemoglobin.

The result is an increased tissue carbon dioxide level. In some situations, there may also be an increase in the inspired carbon dioxide pressure. Causes include contamination of the breathing gas supply, the external dead space of the equipment, inadequate ventilation or failure of the absorbent system.

There is a tendency for experienced divers to be less sensitive to elevated carbon dioxide partial pressures. This reduces the total ventilation requirement during working dives. Elevated arterial carbon dioxide levels increase susceptibility to oxygen toxicity, DCS and inert gas narcosis. For these reasons, it is desirable to control the factors that cause carbon dioxide retention.

> Diving is associated with a tendency to retain carbon dioxide.

Inert gas exchange

The topic if inert gas exchange is considered in the chapters on DCS. Therefore, to avoid duplication, the topic is not considered in detail here. As indicated earlier, increased total pressure is usually accompanied by an increase in nitrogen (and/or other inert gas) pressure (Dalton's Law). This causes gas transfer to the body tissues. When pressure is reduced at the end of the dive, the transfer is reversed. If there is an excess of gas, then it can come out of solution as bubbles. These bubbles are the cause of DCS. If bubbles do occur, they are also subject to the same physical laws. Their size decreases if the pressure is increased, and gas enters or leaves them depending on the concentration gradients of gases.

BUOYANCY

Archimedes' Principle states: *'any object, wholly or partially immersed in liquid, is buoyed up by a force equal to the weight of liquid displaced'*. A diver is an object immersed in water and is therefore affected by this principle. It determines the effort the diver must make to dive. If a diver weighs less than the weight of water he or she displaces, the diver will tend to float to the surface – i.e. he or she has positive buoyancy, which makes descent difficult. If the diver weighs more than the weight of water he or she displaces, the diver has negative buoyancy, which will assist descent and make ascent more difficult.

A diver can change buoyancy in several ways. If the diver wears a weight belt, he or she increases weight by a significant amount and displaces only a little more water and, as a result, will decrease buoyancy. If the diver displaces more water, he or she will increase buoyancy. This can be achieved by retaining more air in the lungs. It can also be achieved by inflating the diver's buoyancy compensator device (BCD) – a device used to control buoyancy. It has an air space that the diver can inflate or deflate to make him positively, negatively or neutrally buoyant, as needed.

An interesting combination of the effects of Boyle's Law and Archimedes' Principle is shown by the changes in buoyancy experienced by a diver wearing BCD or a compressible suit. If slightly positively buoyant at the surface with air in the BCD, the diver will experience some difficulty in descending. As the diver descends he or she will pass through a zone where he or she is neutrally buoyant and, if the diver descends further, he or she will become negatively buoyant. The increased pressure reduces the volume of gas in the BCD or suit, the volume of fluid displaced and, consequently, the diver's buoyancy.

The weight of a scuba cylinder decreases as gas is consumed from it, and this will lead to an increase in buoyancy. An empty cylinder can weigh 1 to 2 kg less than a full one, depending on the initial pressure and the size and type of the cylinder (e.g. steel, alloy).

Immersion creates a condition resembling the gravity-free state experienced by astronauts. In air, a standing person has a pressure gradient in the circulation where the hydrostatic pressure is greatest at the feet and least at the head. For an immersed diver, the hydrostatic gradients in the circulatory system are almost exactly counterbalanced by the ambient water pressure. This reduces the volume of pooled blood in the leg veins. In addition, peripheral vasoconstriction will occur in response to any cold stress. These changes result in an increase in central blood volume, leading to diuresis and subsequent haemoconcentration and decreased plasma volume.

The effect of haemoconcentration on normal dives is not major except that it gives divers a physiological excuse for well-developed thirst and sometimes the need to urinate. Urine production rates of more than 300 mL/hour cause problems for divers trying to keep their dry suit dry, unless it is fitted with a relief outlet.

The other effect of increased central blood volume is on cardiac performance. There is an increase in cardiac output as a result of increased stroke volume. Immersion alone, or in combination with various other factors associated with the diving environment, can precipitate cardiovascular dysfunction in susceptible individuals. This is discussed in Chapter 39.

ENERGY EXPENDITURE

Measurements of energy expenditure, while swimming on the surface and underwater, have been made using indirect calorimetry and by prediction from heart rate. These results show that oxygen consumption underwater of more than 3 litres/minute (lpm) is possible, and values greater than 2 lpm are quite common. The diver's energy expenditure when inactive may be lower than found on land, presumably because the absence of gravitational effects reduces the energy required to maintain posture underwater.

Typical gas consumption and energy expenditure levels are as follows:

For a slow swim, 0.5 knots, the diver would have an air consumption of 20 lpm and an oxygen consumption of 0.8 lpm. A swim of 0.8 knots would cause an air consumption of almost 40 lpm and an oxygen consumption of 1.4 lpm. A fast swim of 1.2 knots would cause an oxygen consumption of about 2.5 lpm and an air consumption of 60 lpm (air consumption measured at the depth the diver was swimming and oxygen consumption at 1 ATA).

Increased gas density increases the work of breathing. This increases the resistance to gas flow through the diver's airways and breathing apparatus, increases the work of breathing and reduces ventilatory capacity. A maximum breathing gas density (helium) of around 8 g/litre appears to be realistic for practical purposes, thus limiting diving to around 400 to 500 metres for useful work.

> Gas density may prove to be the limiting factor for deep diving.

It may be expected that the higher oxygen partial pressures in hyperbaric environments could improve physical performance. However, chamber experiments, in which the subjects exercised while breathing oxygen at 3 ATA, showed that the maximum aerobic work performance was not significantly increased.

ALTITUDE AND SATURATION DIVING

Our normal idea of diving is that a diver descends from sea level, 1 ATA, and returns when the dive has finished. There is a series of variations from this situation. A diver may have to dive in a mountain lake where the pressure on the surface is less than 1 ATA. Another variation occurs when a diver starts from an environment where the pressure is greater than 1 ATA. This happens when divers operate from a pressurized compartment or underwater habitat. These conditions introduce complexities that require understanding of the physics involved.

A diver operating in a high mountain lake is returning to a lower surface pressure than a diver at sea level. This decreases the pressure at which the diver is while releasing inert gas after a dive and so increases the tendency to form bubbles. Therefore, the diver may need to modify the decompression plan. Another minor correction will be required if it is a fresh water lake. Fresh water is less dense than salt water, so the diver is exposed to a slightly lower pressure change per unit depth.

In addition, this diver will have to exhale faster during ascent. A diver who ascends from 10 metres (2 ATA) to the surface (1 ATA) without exhaling would find that the volume of gas in the lungs has doubled. Most divers realize this and exhale at an adequate rate during ascent. However, they may not realize that a similar doubling in gas volume occurs during the last 5 metres of ascent to the surface, if the pressure at the surface was 0.5 ATA.

High-altitude diving may require that the depth or duration of dive and the rate of ascent be reduced to allow for the lower than normal surface pressure at the end of the dive. Tables are available for diving at higher altitudes, and many dive computers are programmed to compensate for this.

A diver living in a human-made environment where the pressure is high can operate to deeper than normal depths. This system is used in saturation diving, where the diver operates from a base at increased pressure and becomes equilibrated with it. The eventual return to the surface can take many days. The use of such environments has proved to be invaluable where deep or long dives are required (see Chapter 67).

Another pressure-related problem can occur when a diver dives and then flies or ascends into mountains. Some dives and ascents will require the diver to ensure that adequate time is spent at the surface before ascending to high altitude, to avoid DCS. This problem is encountered by a diver tourist who wants to fly home after diving or one who needs to pass over hills or mountains when returning from a dive. It is also encountered when it is necessary to transport a diver with DCS. There may be an increase in manifestations of DCS when the pressure is decreased, even by a relatively small amount.

PHYSICAL ASPECTS OF THE MARINE ENVIRONMENT

Heat

Diving and exposure to high pressures change the heat transfer from a diver's body. In air, there is some insulation from the air trapped near the body, either by the clothes or the hair and the boundary layer. In water this is lost. The water adjacent to the skin is heated, expands slightly, and causes a convection current that tends to remove the layer of warmed water. This process is accelerated by movement of the diver or the water. The net result is that a diver cools or heats up much more quickly than he or she would in air of the same temperature.

Heat loss is also increased in warming the cooler inhaled air or gas. For a diver breathing air, most of this heat is used to humidify the dry air used for diving and is not sufficient to cause concern in most circumstances. However, the heat lost in a helium dive is more significant. Helium has a greater specific heat than nitrogen. The problem is compounded because at depth, the mass of gas inhaled is increased.

The heat transfer by conduction is also increased in a helium environment. The result is that a helium diver may need external heating to maintain body warmth at a water, or gas, temperature where external warming would not be required if the diver was in an air environment.

In warm environments, it is possible for a diver to suffer heat stress. A diver who is wearing a protective suit cannot lose heat by sweating because the sweat cannot evaporate. In a pressure chamber, the atmosphere can become saturated with water, and evaporative cooling is prevented. The heat stress for a given temperature is also increased if there is helium in the mixture.

Despite wearing thermal insulation in warm tropical waters, divers can continue to lose heat over several days of repetitive diving, and 'silent' hypothermia can develop, somewhat insidiously.

> A diver in water or a helium-rich environment can cool or heat up at a temperature that would be comfortable in an air environment.

Light

Even in the cleanest ocean water, only about 20 per cent of the incident light reaches a depth of 10 metres and only 1 per cent reaches 85 metres. Clean water has a maximum transparency to light with a wave length of 480 millimicrometres (blue). This variation of absorption with wave length causes distortion of colours and is responsible for the blue-green hues seen at depth. Red and orange light is absorbed most. Because of the absorption of light, the deep ocean appears black, and lights are needed for observation or photography. Because of the greater absorption of reds by water, some illumination is needed to see the true colours, even at shallow depths. Part of the appeal of diving at night is that objects that have a blue-green colour in natural light have a new brightness when they are illuminated with a torch.

Coastal water, with more suspended material, has a maximum transparency in the yellow-green band, about 530 millimicrometres. Absorption and scattering of light by suspended particles restrict vision and can tend to even out illumination.

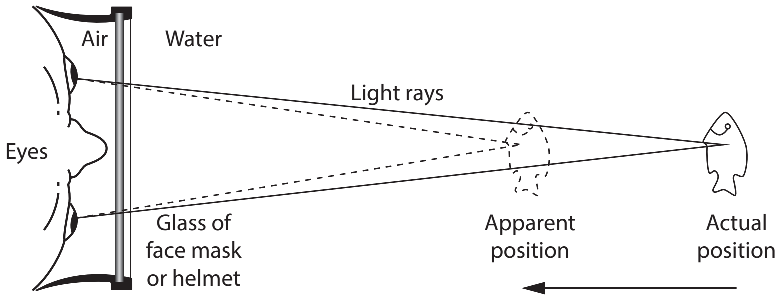

Figure 2.5 Displacement of image in water.

This can make the light intensity the same in all directions and is an important factor in causing loss of orientation.

When the eye focusses on an object in air, most of the refraction of light rays occurs at the air–cornea interface. In water, this refractive power is lost and the eye is incapable of focussing. A face mask provides an air-cornea boundary, which restores refraction at the cornea surface to normal. Refraction also occurs at the face mask surface, mainly at the glass–air boundary. This results in an apparent size increase of about 30 per cent and this makes objects appear closer than they are. Practice and adaption of the hand–eye co-ordination system allow the diver to compensate for this distortion, except when describing the size of fish (Figure 2.5).

Masks also restrict vision by narrowing the peripheral fields, and they distort objects that subtend large visual angles. Both absorption of light by water, which reduces apparent contrast, and scattering by suspended particles reduce visual acuity. Attempts have been made to improve the diver's vision by modification of the face mask, the use of coloured filters, ground mask lenses and contact lenses. These can be relatively successful but can also impose their own problems.

Sound

Sound in water is transmitted as waves with a longitudinal mode of vibration. The speed of sound is about 1530 metres/second in sea water and 1470 metres/second in fresh water at 15°C. Water is a better transmitter of sound than air, so sounds travel greater distances under water. Low-pitched sounds travel farther than higher-pitched sounds. Transmission of sound is enhanced by reflection from the surface. This reflection also enhances the transmission of sound in air over water but reduces the transmission of sounds from air to water and from water to air.

Both high-pressure air and helium-oxygen mixtures cause speech distortion. This is greater when breathing helium mixtures and can render speech unintelligible. Distortion in air causes the voice to become more nasal and crisp as the pressure increases.

It is often thought that divers cannot talk underwater. This is not so if the diver has an air space to speak into. Helmet divers can communicate easily by touching their helmets together and using the air-metal-air pathway. Some scuba divers have mastered the art of talking by taking their demand valve from their mouth and speaking into an air space created by cupping their hands.

DIVING GASES

Most diving is based on the use of compressed air and other oxygen–nitrogen mixtures as a breathing gas. Commercial, military, technical and experimental diving may involve the use of other gas mixtures. For this reason, it is desirable to give the reader some salient points on the gases mentioned in this text and related literature.

Oxygen (atomic weight 16, molecular weight 32) is the essential constituent of all breathing mixtures. At high altitude people survive with less than 0.1 ATA in their inspired air. However, for diving, oxygen should be present at a partial pressure of at least 0.2 ATA to avoid hypoxia. At higher partial pressures oxygen causes oxygen toxicity. Prolonged exposure to more than 0.55 ATA causes pulmonary oxygen toxicity, and shorter exposure to more than about 1.5 ATA results in central nervous system effects. The risk of these problems may be acceptable in a recompression chamber, where oxygen may be used at partial pressures of up to 2.8 ATA. Oxygen toxicity is discussed in Chapter 17.

In the range 0.2 to 2.8 ATA, oxygen has little effect on the respiratory centre and minute volume will remain close to normal. Oxygen is vasoactive; high oxygen tensions cause vasoconstriction.

Nitrogen (atomic weight 14, molecular weight 28) is the major component of air – about 79 per cent. Nitrogen is often considered to be physiologically inert. Bubbles, composed mainly of nitrogen, can cause DCS if a diver who has been breathing air or an oxygen–nitrogen mixture ascends too rapidly. In solution, it may cause nitrogen narcosis at depth (see Chapter 15). At partial pressures of nitrogen greater than about 3 ATA, there is a demonstrable decrement in the diver's performance. At higher partial pressures, the effect is likely to cause the diver to make mistakes. The other problem that restricts the use of nitrogen is that its density at increased pressure increases the work of breathing.

Despite these disadvantages, nitrogen is of major importance in diving, at depths less than 50 metres and as a part of more complex mixtures at greater depths.

Helium (atomic weight 4) is a light, inert gas. It is found in natural gas wells in several countries. Helium is used to dilute oxygen for dives to depths greater than 50 metres, where nitrogen should not be used alone. The two major advantages of helium are that it does not cause narcosis and, because of its lightness, helium-oxygen mixtures are easier to breathe than most alternatives. Helium-oxygen mixtures can allow a shorter decompression time (albeit often with a different profile) than an equivalent saturation dive with the diver breathing air because helium diffuses more rapidly than nitrogen.

The use of helium can cause several problems. The speech of a diver at depth may need electronic processing to make it understandable because of the distortion. A diver in a helium atmosphere is more susceptible to heat and cold because the high thermal conductivity speeds the transfer of heat to and from the diver. The other problem with the use of helium is that it is associated with a disorder called the high-pressure neurological syndrome (HPNS) (see Chapter 20).

Hydrogen (atomic weight 1, molecular weight 2) has the advantage of being readily available at low cost. Because of its lightness it is the easiest gas to breathe. These factors may lead to its use as a replacement for helium. The reluctance to use stems from fears of explosion. Explosions can be prevented if the oxygen level does not exceed 4 per cent, and such a mixture is breathable at depths in excess of 30 metres. Hypoxia can be prevented by changing to another gas near the surface. Hydrogen causes thermal and speech distortion problems similar to those encountered with helium.

FURTHER READING

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This chapter was reviewed for this fifth edition by John Lippmann.

3

Free diving

INTRODUCTION

Free diving refers to dives made from surface to surface during voluntary apnoea on a single breath. No underwater breathing apparatus is used. Free diving (also often referred to as 'breath-hold diving' or 'snorkel diving') is regarded as the purest and most natural form of diving. Unencumbered by bulky equipment, the diver is free to move weightlessly and silently in the underwater world. Practised in some societies for thousands of years, free diving in its simplest form requires no equipment at all. The introduction of various performance-enhancing apparatus such as face masks, fins, weight belts, buoyancy vests and thermal protection suits may present new problems. For example, the addition of goggles or face masks allows for clear vision but introduces a gas space that must be 'equalized' to prevent barotrauma. Near the surface, wetsuits generate positive buoyancy that decreases as they are compressed during descent. If a weight belt is used to offset the initial positive buoyancy of the wetsuit, this will render the diver negatively buoyant as he or she begins the ascent. Nevertheless, recreational free divers and spearfishers often wear a mask, snorkel, fins, wetsuit and weights and carry a spear gun, knife and bag. Competitive free divers may also employ specialized devices such as weighted sleds for descent and inflatable lift bags for ascent to achieve remarkable depths. Even with such modern specialized equipment, human diving capabilities are paltry in comparison with those of marine mammals and other sea animals (Table 3.1).

HUMANS AS FREE DIVERS

> You're running on reserve tank and there's no warning before you hit empty!
>
> *Record-holding free diver*

There are two principal (and somewhat interrelated) challenges in free diving:

1. The challenge of increasing depth, with its attendant risk of pressure-related injury to gas-containing spaces.
2. The challenge of increasing duration, with its attendant risk of exhaustion of oxygen (O_2) stores.

Table 3.1 Depth penetrations of human divers and marine animals

Comparative depth penetrations	Depth (m)
Human free (breath-hold) diver	
• 'Constant ballast no fins'	101
• 'No limits'	214
Human diver using underwater breathing apparatus	
• Bounce dive (surface to surface)	318
• Saturation diving lockout from bell	>400
Sperm whale	1150
Northern elephant seal	1500
Wreck of *Titanic*	3810
Octopus species	5639
Deepest known fish	7703
Amphipod crab	9789
Deepest manned submersible dive	10 911
Deepest part of ocean	~11 000

A third challenge that is most relevant to the more extreme exponents of free diving is the related exposure to markedly elevated gas partial pressures with related risks such gas toxicities and decompression sickness.

The challenge of increasing depth

Any anatomical or equipment gas spaces are subject to compression during descent, and their volumes may need to be compensated if barotrauma is to be avoided. Obvious examples, which are discussed elsewhere in this text, include the middle ear (see Chapter 7), sinuses (see Chapter 8) and mask. The lung is of particular relevance to free divers because, unlike divers using underwater breathing apparatus who compensate intrapulmonary pressure and volume with each breath of compressed gas, the lung volume of a free diver is progressively compressed as depth increases.

It was long believed that the limiting factor on depth in free diving would be the point at which lung volume was compressed to residual volume because compression to smaller volumes could, logically, result in trauma to the chest wall or lung itself. Thus, a diver with a total lung capacity of 6 litres and a residual volume of 1.5 litres should theoretically be able to breath-hold dive to 30 metres (4 ATA) where the total lung volume would be compressed to the residual volume (1.5 litres), a simple application of Boyle's Law. A corollary was that divers with a larger total lung capacity and/or a smaller residual volume would be capable of greater depths before injury occurred.

The fallacy of the 'residual volume limit' is immediately clear when it is considered that a human has descended to 214 metres (22.4 atmospheres absolute [ATA]) without suffering obvious lung barotrauma and that free divers regularly descend to depths greater than a theoretical maximum calculated in this way. The factors that were missing from these early attempts to predict maximum depth were the distensibility of the pulmonary vasculature and the concomitant potential for intrapulmonary blood pooling to compensate for compression of lung volume, effectively allowing for compressions below predicted residual volume. The beginnings of such compensation can be seen with simple head-out immersion in an upright subject. The negative transthoracic pressure generated by having the airway open to a pressure of 1 ATA while the thorax is exposed to greater pressure (because of the surrounding water pressure) results in a shift of about 0.7 litre of blood into the thorax. A greater engorgement of the pulmonary circulation is likely if the transthoracic pressure increases further.

Notwithstanding this remarkable and fortunate mechanism for compensation, there will nevertheless come a point where pulmonary vascular capacitance is maximized and further descent will cause the lung's remaining gas volume to develop an increasingly negative pressure relative to the environment and surrounding tissue. If this becomes excessive, then both fluid extravasation from capillaries to the alveolar space and frank haemorrhage are possible, and there is evidence from competitive free diving that both occur. This problem is referred to as pulmonary barotrauma of descent or 'lung squeeze'. Although it is interesting and potentially of increasing importance as free diving depths are extended, this is currently a minor contributor to free diving accidents in comparison with the challenges of increasing duration underwater.

The challenge of increasing duration

It is self-evident that oxygenation is maintained from steadily dwindling O_2 stores during a free dive. In contrast to marine mammals, a human's stores are relatively small. The total O_2 stores in a 70-kilogram man at resting lung volume (functional residual capacity) have been calculated to be approximately 1.5 litres. This store would be increased at total lung capacity whose value is variable among individuals. If nearly all this O_2 can be extracted, one could predict that a resting man who has an O_2 consumption of 300 mL per minute would completely deplete his O_2 stores in 5 minutes. In reality, most untrained humans can only breath-hold for approximately 1 minute because the drive to breathe is dependent largely on rising pressures of carbon dioxide (CO_2) rather than falling levels of O_2 (although the two are synergistic). This inherent inability to breath-hold voluntarily to the point of critical hypoxia (an arterial partial pressure of O_2 [Po_2] above approximately 25 mm Hg must be maintained to avoid loss of consciousness) is clearly protective in free diving. However, it can be confounded in two important ways: by the use of hyperventilation before breath-holding and through the effects of changing ambient pressure during descent and ascent from a free dive.

Hyperventilation refers to taking a series of rapid deep breaths before breath-holding. This is often done in the mistaken belief that it significantly enhances O_2 stores. Although hyperventilation does increase the alveolar O_2 content to a small extent, the volume of O_2 involved is effectively inconsequential. What hyperventilation can achieve is a marked lowering of arterial CO_2 levels. Competitive breath-hold divers have had end-tidal CO_2 pressures as low as 20 mm Hg measured at the end of their typical pre-apnoea routine. This has the effect of prolonging the breath-hold duration before the onset of a strong urge to breathe.

The obvious danger associated with hyperventilation is that it will extend the breath-hold duration closer to the point where the arterial Po_2 falls below that required to maintain consciousness. There is little doubt that hyperventilation has been a contributory factor in many free diving deaths. There is also some evidence that well-practised free divers can induce a decrease in sensitivity of the medullary respiratory control centre to CO_2, or they can learn to resist the uncomfortable urges to breathe that CO_2 generates as its arterial pressure rises, or both. Interestingly, however, although competitors in static apnoea events (effectively breath-holding competitions without pressure change) aggressively employ hyperventilation and are highly motivated not to breathe for as long as possible, symptomatic hypoxia is not frequent as would be expected. This brings the discussion to changing ambient pressure during a free dive as an added and significant risk factor for critical hypoxia.

Arterial gas tensions during breath-hold dives change with the partial pressure of the gases in the lungs. When the breath-hold diver descends, the partial pressures of the gases in the lungs increase as their volume is decreased and gas inside is compressed. The reverse takes place during ascent back toward the surface. This leads to concomitant rises and falls in alveolar and arterial Po_2.

Figure 3.1 shows alveolar pressures of the metabolic gases during (a) a breath-hold period without ambient pressure change, (b) a breath-hold dive to 10 metres and (c) a breath-hold dive to 10 metres with prior hyperventilation. In Figure 3.1 (b) and 3.1 (c), ambient and thus alveolar gas partial pressures rise during descent according to Boyle's Law. The rise in O_2 is somewhat reduced because of continued consumption. Because of the high alveolar

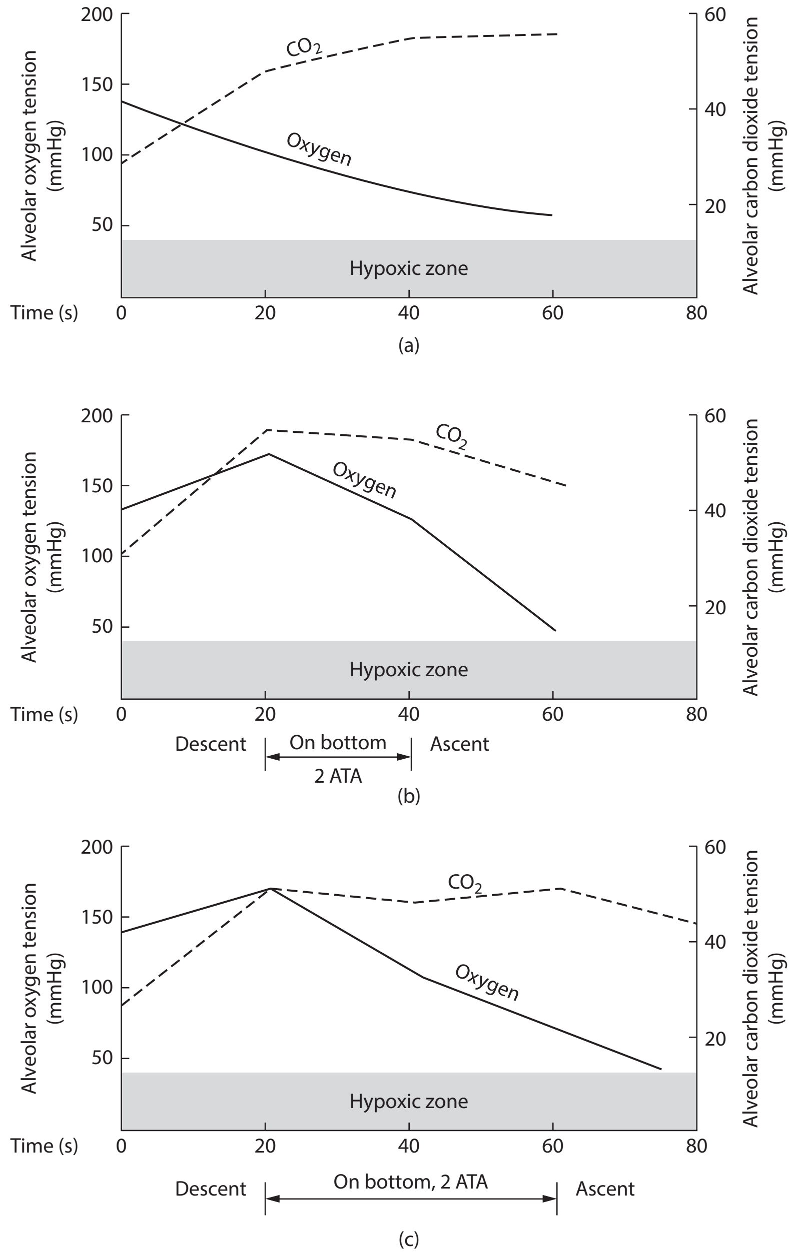

Figure 3.1 Alveolar pressures of the metabolic gases during **(a)** a breath-hold period without ambient pressure change, **(b)** a breath-hold dive to 10 metres and **(c)** a breath-hold dive to 10 metres with prior hyperventilation.

Po_2 at depth, there is a sufficient alveolar-arterial gradient to allow continuing O_2 uptake for a considerable time.

In contrast, during ascent there is a rapid fall in alveolar Po_2 as the lung re-expands and the volume of the alveolar gas increases. This is greater than expected from gas laws alone, thus reflecting ongoing oxygen metabolism. The dive with prior hyperventilation depicted in Figure 3.1 (c) had a longer bottom time as would be expected when prior lowering of the arterial CO_2 makes the diver more comfortable remaining at depth for longer. It can be seen that a lower alveolar partial pressure of O_2 develops by the time the diver reaches the surface, and such falls in alveolar and arterial Po_2 during ascent would be even more dramatic on deeper dives. The obvious risk is that the diver could experience critical arterial hypoxaemia as the alveolar Po_2 is rapidly falling in the latter stages of the ascent. Indeed, loss of consciousness during either the final phase of ascent or on arrival at the surface is a recurring event at free diving competitions. The dangers of breath-hold diving and hyperventilation are discussed further in Chapter 16.

In addition to hyperventilation, there are two other strategies, both controversial, that elite free divers use or manipulate in order to extend their duration underwater.

The first of these is an attempt to expedite the so-called diving reflex that can be observed in all air breathing vertebrates but that is highly developed in marine mammals (see later). This reflex is initiated by apnoea and also by facial cooling. Its principal effector arm is a marked sympathetically mediated increase in peripheral vascular resistance that increases blood pressure and in turn elicits a vagally mediated bradycardia. At the same time, there is some evidence that the sympathetic activation induces splenic contraction, increasing circulating red blood cells. Peripheral vasoconstriction has the effect of reducing the circulation of blood to the peripheries, and the bradycardia reduces O_2 consumption by the heart. Central redistribution of blood makes more O_2 available to vital organs. A concurrent and unwanted side effect of these processes is a predisposition to arrhythmias. This probably arises from vagal inhibition of nodal conduction combined with sympathetic sensitization of ectopic pacemakers. Not surprisingly, ventricular ectopic beats are common.

Although these are autonomically mediated phenomena, there is a strong belief among free divers that they can manipulate the process through conditioning, relaxation techniques and practice. Given that there is considerable inter-subject variability in the potency of the diving reflex, and that it tends to wane with age, it does seem plausible that it is 'open' to manipulation by skilled divers. In a 2014 interview William Trubridge, holder of the constant ballast no fins world depth record of 101 metres, articulated it thus:

> The training I do is targeted at creating a physiology that conserves oxygen as much as possible. Whereas someone who is extremely fit would be able to supply a high amount of oxygen to their muscles very quickly, I need to shut down that oxygen flow to the muscles so that they can work anaerobically and that conserves the oxygen for the heart and the brain. Physiology for freediving is such a different set of effects to what is found in any other sport that we're still discovering exactly what they consist of.
>
> *New Zealand Listener Magazine,* 4 January 2014

Similarly, on his website Francesco "Pippin" Ferreras, a previous world record holder, described his approach in more detail:

> My heart, under direct control of the Central Nervous System, begins a rapid slowdown. This diminution of my cardiac output is a result of the body's decreasing needs for oxygen and energy consumption. This efficiency in energy conservation is of vital importance for survival in the undersea environment while in a state of apnea. As an example, when I begin my pre-immersion preparations my resting heart rate is 75 bpm, 10 minutes after entering a stare of deep relaxation it drops, to 55 bpm. As I begin my descent, in a matter of seconds it has slowed to 30 bpm. My cardiovascular performance is influenced by other factors, foremost being my physical conditioning, and mental preparation.... Once I have reached a depth of 110 m., I institute one last command to my heart to slow down. At this point my heart is down to a mere 10 to 14 bpm. On several immersions when all of the above mentioned factors are

ideal I have obtained readings of an incredible 7 bpm! Obviously these findings are augmented by the power of mind over body that I have developed over the years, through the study and practice of Yoga.

The second controversial strategy used by elite free divers to extend both depth and duration underwater is so-called 'lung packing', more correctly referred to as glossopharyngeal insufflation. This technique involves using the glossopharyngeal muscles to pump air into the lungs, thus enabling an increase in the total lung capacity by up to 20 per cent. This extra volume potentially increases the depth at which lung compression becomes hazardous (as described earlier) and also represents an increase in the O_2 stores. Adept exponents of lung packing can increase the volume of air carried by several litres, although this does not translate directly into an increase in lung volume because the gas is held in the lungs under positive pressure and is therefore compressed. Therein lies the potential problem with this strategy. There are sporadic reports of excessive packing leading to pulmonary barotrauma because of the high positive transpulmonary pressures that can reach 60 mm Hg or even more. There are also reports of hypotensive loss of consciousness resulting from profound reduction in venous return associated with high intrathoracic pressure during the act of packing. In view of these potential hazards the technique cannot be recommended. Nevertheless, it is unlikely that packing will be abandoned by extreme free divers looking for any possible edge.

Largely for completeness (and for curious interest value), there are some extreme free divers who have developed the technique of glossopharyngeal exsufflation, that is, packing in the opposite direction. This is used in those situations near terminal depth when the lungs are compressed at or below residual volume, and it is therefore impossible to generate a Valsalva manoeuvre to clear the ears or sinuses. An alternative approach to avoiding barotrauma under these conditions, and one that has been proven radiologically, is to let the sinuses (and to some extent the middle ears) flood with water!

The challenge of avoiding gas toxicities and decompression sickness

The combination of increasing depth and duration (particularly the former) during free diving opens up the possibility that extreme exponents will suffer gas toxicities and decompression sickness, complications usually associated with compressed gas diving. Neurological decompression sickness in breath-hold divers has been reported. Although some cases may be caused by arterial gas embolism following pulmonary barotrauma, predictions of inert gas tensions following repeated and closely spaced deep breath-hold dives do suggest that pathological bubble formation from dissolved inert gas is certainly possible (see Chapter 10).

Despite the extreme depths reached by free divers, overt effects of nitrogen narcosis are only rarely reported, although there may be a strong reporting bias operant here. It may also be that narcosis is not as likely as predicted on the basis of depth alone simply because the partial pressure of nitrogen in the relevant tissues takes time to equilibrate with the partial pressure of nitrogen in the lungs, and the short duration of the dives therefore limits any effect. Nevertheless, as extreme free divers are pushing deeper, there are increasing numbers of stories of strange sensations and 'funny turns' during these dives. It is impossible to know their exact cause, but potential explanations include nitrogen narcosis (see Chapter 15), high-pressure neurological syndrome (see Chapter 20) and cerebral O_2 toxicity (see Chapter 17). Cerebral O_2 toxicity seems an unlikely explanation given the very short exposures, the starting fraction of inspired O_2 of 0.21 and the fact that O_2 is being consumed from the moment apnoea begins. However, some reported events (e.g. facial or diaphragmatic twitching) are very typical of O_2 toxicity. These sorts of problems are likely to become more common as record depths are pushed further.

Record diving

Trained free divers have been able to achieve remarkable underwater feats, and in certain societies these divers are accorded celebrity status.

Records are attempted for various categories of diving involving depth, duration and underwater distance. Because of the potential risks involved, dedicated competitions sanctioned by an umbrella society are run according to strict protocols. Physiologists and physicians need to be aware of these remarkable achievements. The records cited here are valid for January 2015 but may have been superseded at the time of reading. A complete list of current records is available at: http://www.aidainternational.org/competitive/worlds-records.

The purest form of depth record is referred to as *constant weight apnoea without fins* and involves return to the surface with the same weights carried down (if any) and, as the name implies, no use of fins. The record is currently 101 metres for male divers and 69 metres for female divers.

At the opposite end of the spectrum is so-called *no limits* free diving. This is the most extreme category in respect of depth and requires no swimming at all. Divers hold onto a weighted, rope-guided sled for descent. On reaching the target depth, they detach themselves from the sled and pull a pin that releases compressed air from a cylinder into a lift bag, which tows them back to the surface. The current record depths are 214 metres for male divers and 160 metres for female divers. The latter is the longest-standing free diving record at the present time, set by Tanya Streeter in 2002.

The absolute limit of these hazardous 'experiments' remains unknown, but it seems likely that depth record increments will become smaller and smaller as immutable physiological barriers are approached. Death may be precipitated at depth by pulmonary haemorrhage, pulmonary oedema or cardiac dysrhythmias. Cerebral hypoxia is an invariable development during the latter stages of ascent. Quite often these divers require rescue by standby divers because they become unconscious as a result of rapidly developing hypoxia as they approach the surface.

Records are also held for *static apnoea*, which is a motionless, energy-conserving head immersion exposure. The current records are a mind-boggling 11 minutes 35 seconds for male participants and 9 minutes 2 seconds for female participants.

Underwater breath-hold horizontal distances (*dynamic apnoea with fins*) of 281 metres (male swimmers) and 234 metres (female swimmers) have been achieved in 50-metre swimming pools with swimmers using fins for propulsion.

DIVING MARINE MAMMALS

The study of diving animals offers the scientist an ideal opportunity to study the physiological consequences and defence mechanisms required to survive extended breath-holding. It is also of great interest to diving physicians to see how diving animals avoid the perils induced by exposure to pressure and hypothermia.

The northern elephant seal and the sperm whale can dive to 1500 metres. The southern elephant seal can stay submerged for 2 hours, although usual dives are 20 to 30 minutes in duration. The Weddell seal regularly dives for food to greater than 100 metres and can remain submerged for up to 60 minutes. Typical humans, with some practice, can breath-hold underwater for 1 to 2 minutes and descend to 10 to 15 metres.

How are marine mammals able to achieve these remarkable underwater depth and/or duration exposures that appear to defy conventional wisdom with respect to limits of hypoxia? How also do they achieve these feats without developing some of the disorders (e.g. hypoxic blackouts, barotrauma, decompression sickness, nitrogen narcosis, O_2 toxicity or high-pressure neurological syndrome) that are the subjects of subsequent chapters in this book?

Obvious anatomical adaptations include a streamlined shape, low-friction body surface (skin or fur) and the development of flippers or fins. Dolphins can reach speeds of 20 knots with remarkably low energy consumption. A dorsal blowhole in whales and dolphins also aids energy efficient respiration. Of more interest to the diving physician and physiologist are the mechanisms to cope with prolonged apnoea. The adaptations that allow diving animals to achieve long periods underwater are both physiological and biochemical.

Oxygen stores

All diving mammals have an increased total body O_2 store. The relative contribution of the lungs, blood and muscles storage areas depends on the diving pattern of the animal.

Deep diving mammals do not dive at full lung capacity and may exhibit reduced lung perfusion during dives for reasons discussed later, so the bulk of O_2 is stored in blood and muscle. Such animals have increased blood volume (~15 per cent of body mass versus ~5 to 7 per cent for humans), and the blood has a higher haemoglobin concentration. About 70 per cent of the total O_2 store is found in the blood. They also have a markedly increased myoglobin concentration (5 to 12 times that found in a human), especially in the swim muscles, and this myoglobin increase is proportional to the diving capacity of the animal. Myoglobin carries approximately 25 per cent of the total O_2 sore. Only a tiny proportion (~5 per cent) is found in the lungs (versus ~25 per cent in humans).

An intriguing and controversial mechanism for augmenting O_2 storage and delivery during a dive is the pre-dive sequestration of oxygenated red cells in the spleen followed by the release of these cells by splenic contracture during a dive. The time course of release into the systemic circulation may be further regulated by a valve-like sphincter in the vena cava. The fact that this occurs is not disputed, but its role in marine mammal diving adaptation is uncertain. It has been noted that re-sequestration after release on one dive typically takes far longer than the typical surface interval between subsequent dives during a dive series. Thus, any benefit may be restricted to the initial dive. It is possible that this adaptation is more important for keeping blood haematocrit (and viscosity) at optimal levels when the animal is not diving than for improving oxygenation during dives.

Oxygen consumption and the diving response

The increases in blood volume, haemoglobin and myoglobin described earlier all contribute to the seal's impressive O_2 supply, but O_2 still needs to be conserved. Indeed, it can be readily calculated that if the submerged seal continued to metabolize at the same rate as before diving, its O_2 stores would not be sufficient during long dives. Not surprisingly, these animals exhibit multiple strategies aimed at conserving O_2 and ensuring that it is supplied preferentially to vital organs during the period of a dive.

The term *diving response* refers to a sequence of physiological events, including apnoea, bradycardia and redistribution of cardiac output, which are under the control of multiple reflexes. O_2 conservation is thus partly accomplished by selective redistribution of circulating blood. Blood may be preferentially distributed to swimming rather than non-swimming muscles. Studies indicate that pinniped skeletal muscles have an enhanced oxidative capacity to maintain aerobic metabolism under the relatively hypoxic conditions associated with diving and that these adaptations are more pronounced in swimming than in non-swimming muscles. Other tissues that are most critical for survival (e.g. retina, brain, spinal cord, adrenal glands and, in pregnant seals, the placenta) are also selectively perfused. The seal essentially shuts off the flow of blood to non-essential tissues and organs, such as the kidneys, until it resurfaces.

Rapid onset of bradycardia (to as low as 10 per cent of baseline rate) at the start of a dive may be seen in diving species. This reduces cardiac work and O_2 consumption. A substantial reduction in cardiac output has been shown in Weddell seals. Because stroke volume falls by only about 30 per cent, the predominant effector of this reduction is the bradycardia.

Arterial blood pressure is reasonably well preserved despite this reduction in cardiac output, and this is important to maintain perfusion of vital organs. Maintenance of arterial pressure is facilitated by the stretching of the elastic walls of large arteries during systole and their recoil during diastole. This function is augmented in many species of marine mammals by a bulbous enlargement of the root of the aorta, the aortic bulb. The aortic bulb approximately doubles the diameter of the ascending aorta in harbour and Weddell seals, thus providing an elastic capacitance for maintaining pressure and flow into the constricted arterial tree during the long diastolic intervals characteristic of diving. The entire human aorta contains less volume than the aortic bulb alone in seals of a similar body weight. The increase in left ventricular afterload that would be expected as a consequence of elevated peripheral resistance and decreased large artery compliance is reduced by this unique anatomy. The net result is a diminished peak systolic pressure, which reduces cardiac work and O_2 consumption while at the same time maintaining stroke volume.

The *electrocardiogram* of the diving animal shows some progressive changes during prolonged apnoeic dives. In addition to bradycardia, these changes may include the gradual diminution or even abolition of the P wave. Cardiac rhythm is then apparently set independently of the sinoatrial node by a ventricular pacemaker site. Other cardiac dysrhythmias occasionally appear.

Anaerobic metabolism

With prolonged dives certain tissues switch to anaerobic metabolism, which produces lactic acid as a by-product. There is an increased tolerance to lactic acid in the muscles through increased buffering capacity. High levels of lactic acid, however, lower the pH of the blood and can lead to acidosis, causing a weakening of the heart's ability to contract. Acidosis is avoided by confining anaerobic metabolism to the skeletal muscles and other tissues isolated from the blood supply. When the animals resurface, these tissues release the lactic acid into the blood for metabolism by the liver.

Diving technique

Modified diving behaviour to limit muscle activity and thus O_2 consumption has been demonstrated in Weddell seals. Prolonged downward gliding, with minimal muscular effort, as a result of reducing buoyancy with lung compression at depth can result in up to a 60 per cent reduction in energy costs. Gliding is used during dives exceeding 18 metres in depth and occupies approximately 75 per cent of the descent.

Pressure changes

Structural adaptations to accommodate thoracic compression during deep dives include a flexible rib cage, stiffened alveolar ducts and attachments of the diaphragm such as to permit some shifting of abdominal contents into the thorax. These changes help the animal avoid pulmonary barotrauma of descent. Quarantining of pulmonary gas from perfusing blood minimizes accumulation of nitrogen (decompression sickness), which may occur in repetitive diving. It likely also reduces nitrogen narcosis.

Deep diving mammals do not dive on a full lung volume. As well as limiting nitrogen uptake, this means that the animal is not exposed to O_2 toxicity because the partial pressures never reach dangerous levels.

How the elephant seal and sperm whale avoid the high-pressure neurological syndrome during their impressive diving feats is not yet understood.

Hypothermia

A thick layer of blubber and a relatively low surface area to reduce heat loss maintain core temperature. A reduction of blood flow to the skin increases insulation of the fat layer and allows surface cooling, which is not transmitted to the internal core. Well-developed countercurrent heat exchange systems also aid in conserving heat by cooling arterial blood and heating venous blood as it returns to the core. Examples can be found in the fins and flippers of whales and seals. Working muscles are close to the surface and have little fat insulation. Also, many animals, when not diving, have a raised metabolic rate to produce heat.

FURTHER READING

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This chapter was reviewed for this fifth edition by Simon Mitchell.

4

Diving equipment

INTRODUCTION

The first part of this chapter deals with the equipment used by most recreational divers. The more complex and unusual types of diving equipment that are used by technical, commercial or military diving operations are dealt with in the second part of the chapter. Attention is paid to the problems the equipment can cause, particularly for the student or novice. This is of importance in understanding the medical problems that are related to diving equipment. It may also help the reader to understand the stresses experienced by the novice diver.

EQUIPMENT FOR RECREATIONAL DIVING

Snorkeling/breath-hold diving equipment

The simplest assembly of diving equipment is that used by snorkelers – a mask, snorkel and a pair of fins. In colder climates, a wetsuit may be added for thermal insulation and a weight belt to compensate for the buoyancy of the suit. In tropical waters, a 'stinger suit' provides not only a little thermal comfort but also some protection from box jellyfish and other stings.

MASK

A mask is needed to give the diver adequate vision underwater. The mask usually covers the eyes and nose. Traditionally, masks were made from rubber, although now most are made from silicone. The mask seals by pressing on the cheeks, forehead and under the nose with a soft silicone edge to prevent entry of water. Swimming goggles, which do not cover the nose, are not suitable for diving. The nose must be enclosed in the mask so that the diver can exhale into it to allow equalization of the pressure between the face and mask with the water environment. It should be possible to block the nostrils without disturbing the mask seal to enable the wearer to perform a Valsalva manoeuvre. Full-face masks that cover the mouth as well as the eyes and nose, or helmets that cover the entire head, are more commonly used by professional divers and are considered in the section on professional diving equipment.

The faceplate of the mask should be made from hardened glass. A diver with visual problems can choose from a selection of corrective lenses that are commercially available. These are designed to attach directly to certain masks. Alternatively, prescription lenses can be ground and glued to a variety of masks. Ocular damage can occur if hard corneal lenses are used for diving (see Chapter 42). Certain contact lenses may be lost if the mask floods and the diver fails to, or is unable to, take preventive action. Some people with allergy problems react to the rubber of the mask, although this is rarely an issue with silicone.

All masks cause a restriction in vision. With most masks, the diver can see about one third of his or her normal visual field. The restriction is most marked when the diver tries to look down toward the feet. This restriction can be a danger if the diver becomes entangled. However, there are some masks available with a tilted lens to provide a better downward field of vision.

The more nervous beginner may find the visual restriction worrying and may possibly fear that there is a lurking predator just outside the field of vision. The visual field varies with the style of mask. Experimentation is also needed to find which mask gives a good seal, to minimize water entry. The diver needs to master a technique to expel water from the mask. If it is not learned and mastered, a leaking mask can become a major problem, sometimes leading to panic.

SNORKEL

The typical snorkel is a tube, about 40 cm long and 2 cm in diameter, with a pre-moulded or creatable U-bend near the mouth end. A mouthpiece is fitted to allow the diver to grip the tube with the teeth and lips. The tube is positioned to pass upward near the wearer's ear to enable him or her to breathe through the tube while floating on the surface and looking down. Any water in the snorkel should be expelled by forceful exhalation before the diver inhales through the snorkel.

Many attempts have been made to 'improve' the snorkel by lengthening it, adding valves, modifying its shape and some other means. There is little evidence of the success of most of these attempts.

All snorkels impose a restriction to breathing. A typical snorkel restricts the maximum breathing capacity to about 70 per cent of normal. The volume of the snorkel also increases the diver's anatomical dead space. Because of this, increasing the diameter substantially to reduce the resistance is not a viable option. These problems add to the difficulties of a diver who may be struggling to cope with waves breaking over him or her (and into the snorkel) and a current that may force the diver to swim hard. There have also been anecdotal reports of divers inhaling foreign bodies that have previously lodged in the snorkel.

FINS

Fins (or flippers) are mechanical extensions of the feet. Fins allow the diver to swim faster and more efficiently, and they free the diver's arms for other tasks. The fins are normally secured to the feet by straps or are moulded to fit the feet. Various attempts have been made to develop fins that give greater thrust with special shapes, valves, controlled flex, springs and materials, all competing for the diver's dollar. Some of these fins can improve the thrust, but the wearer needs to become accustomed to them. Others have little effect.

Divers often get cramps, either in the foot or calf, if fins are the wrong size, if the diver has poor technique or if the diver has not used fins for an extended period. The loss of a fin may also cause problems for a diver, especially if he or she has to a swim against a current, or fails to attain appropriate orientation underwater or buoyancy on the surface.

WEIGHTS

Even without the buoyancy of a wetsuit, some divers require extra weights to submerge easily. The weights are made from lead, and most are moulded to thread onto a belt. Some weights are designed to fit into pouches, either on a belt or, for scuba divers, attached to a buoyancy compensator device (BCD). Whatever weighting mechanism is used needs to be fitted with a quick-release buckle or other mechanism to allow a diver to drop the weights quickly and so aid his or her return to, or enable the diver to remain on, the surface. The situations in which a quick-release buckle may not be fitted (or may be de-activated) are those where it would be dangerous to ascend, such as in caves where there is no air space above the water.

In some circumstances, it is necessary for a diver to ditch the weight belt to reach, or remain on, the surface in an emergency. Such situations include an emergency in which the scuba diver cannot inflate the BCD, for example, if the diver is out of breathing gas. Unfortunately, divers often fail to release the belt if they are in difficulty. The reason for this omission is not clear, but it is likely often the result of stress or panic. Adequate initial training and practice help to reinforce the skill so that it will become more automatic when required. It also needs to be reinforced periodically. Unfortunately, much of the current training fails to focus adequately on this important emergency drill.

An alternative drill of taking the belt off and holding it in one hand (preferably away from the body) is useful in some situations in which the diver is likely to become unconscious and inflating the BCD is not an option or may not be sufficient (e.g. when deep). In the event of unconsciousness, the belt will hopefully fall away, causing the diver to rise to the surface. Holding the belt away from the body should reduce the chance of entanglement with the diver if it is dropped.

> In many fatal diving accidents the diver did not release his or her weights.

This basic free diving equipment is adequate for diving in shallow, relatively warm water. Experience with this gear is excellent training for a potential scuba diver. The diver can gain the basic skills without the extra complications caused by scuba gear. It allows a more realistic self-assessment of the desire to scuba dive and the subsequent rewards. With the confidence gained in snorkeling and breath-hold diving and the associated aquatic skills, the diver is also less likely to become as dependent on the breathing apparatus. In cold climates, a snorkel diver needs a suit to keep warm. Suits are discussed in Chapter 27.

Self-contained underwater breathing apparatus – scuba

The simplest form of breathing apparatus consisted of a gas source and a tap that the diver turned on to obtain each breath of air. This system was in use until the 1930s, but much of the diver's time and concentration were taken up in operating the tap. In the most common breathing apparatus, the **Aqualung** or **self-contained underwater breathing apparatus (scuba),** the tap is replaced by a two-stage valve system. The flow of gas to the diver is triggered by the diver's inspiratory effort and is closed by expiration or cessation of inspiration.

Figure 4.1 and Figure 4.2 (a) and (b) show the operating principles of a simple regulator and demand valve system. The air is stored in a cylinder at a maximum pressure that is determined by the design of the cylinder. For most cylinders this pressure, called the working pressure, is 160 to 300 bar (2300 to 4350 psi).

The first stage of the valve system (see Figure 4.1) reduces the pressure from cylinder pressure to the equivalent of about 10 ATA greater than the pressure surrounding the diver, and it regulates its outlet pressure at this value. The valve is held open by the force of a spring until the pressure above the first stage piston builds up and forces the valve seal down on the seat, thus shutting off the gas. The first-stage

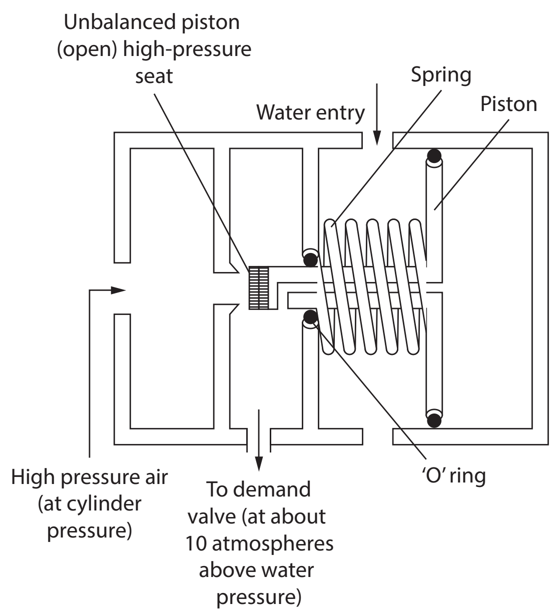

Figure 4.1 First stage reducer valve: the gas escapes from the cylinder until the pressure above the piston increases to a level where the force on the piston can compress the spring, pushing the first stage valve seat down and shutting the gas flow off. The valve opens again when the pressure above the piston (and in the hose to the second stage valve) falls. This is normally because the diver has taken another breath.

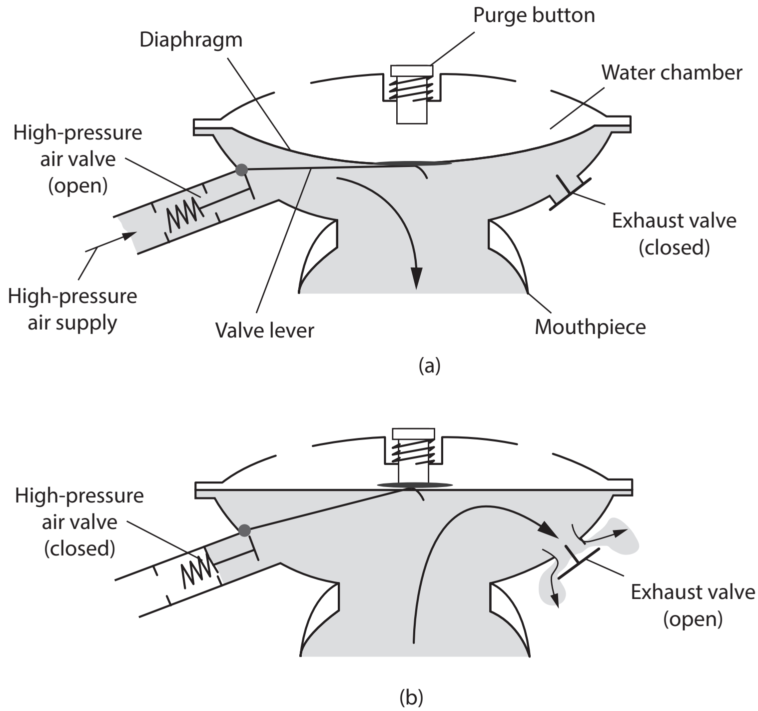

Figure 4.2 SCUBA demand valve **(a)** during inspiration and **(b)** exhalation. The arrows indicate air flow. During inspiration the diver decreases the pressure in the mouthpiece. This causes the diaphragm to curve in and tilt the air supply valve open. At the end of inspiration air continues to flow until the pressure in the mouthpiece equals the pressure in the water chamber, at this stage the diaphragm will return to the position shown in 4.2(b), and the air supply valve shuts. During exhalation the pressure in the mouthpiece is greater than that in the surrounding water. This pressure difference forces the exhaust valve open and allows exhaled air to escape. The purge button is used to trigger a flow of gas from the supply without the need to inhale from the regulator.

valve opens and closes as gas is drawn from the system by the diver. In some regulators, the water can enter the water chamber and helps the spring to hold the valve open. In others, the ambient water pressure is transmitted indirectly. This adjustment of the supply pressure with water pressure is designed to prevent the flow decreasing as the diver descends.

When the diver inhales, he or she reduces the pressure in the mouthpiece chamber, or second-stage valve. As the diver does so, the diaphragm curves inward and depresses the lever (see Figure 4.2 (a)). The inlet valve opens and remains open until inhalation ceases. At this stage, the diaphragm moves back into the position shown in Figure 4.2 (b). The second-stage valve is usually called the demand valve.

Expired gas passes out of the second stage through an exhaust valve. In the demand valve, gas flow increases with respiratory effort because the valve opens more, allowing the diver to breathe normally. The purge button allows the diver to open the inlet valve to force any water out of the regulator. The diver may need to do this if he or she takes the regulator from the mouth while underwater or if the seal around the mouthpiece is poor.

> The scuba regulator is designed to provide the diver with a gas supply matched to his or her respiratory needs.

Most divers have little difficulty using scuba. However, when they first don it, the weight and bulk will make them awkward, and may aggravate back problems. In the water, the buoyancy of the set offsets its weight.

The diver's lips should be sealed around the mouthpiece to prevent the entry of water. Water can enter through a hole in the mouthpiece if the mouthpiece is poorly attached or through the diaphragm or exhaust valve if either is faulty. A leak can generate an aerosol if the water reaches the inlet valve of the second-stage valve. The aerosol can cause distress to the diver and may sometimes cause a syndrome called *salt water aspiration syndrome,* or it may trigger other medical conditions such as asthma or possibly a cardiac dysrhythmia.

Another problem associated with demand valves is that they may cause pain in the temporomandibular joint. This condition is considered in Chapter 42.

In very cold water, the first stage of the regulator may 'freeze up'. This occurs because the air cools as it passes through the first stage and can ice up with the piston frozen in the open position. The problem can be reduced by using a first stage that is designed for operation in cold water.

Because the first stage regulates the pressure to the second stage, the inspiratory effort required to cause a flow does not vary until the cylinder is almost empty. Then the pressure in the hose to the second stage falls and the flow decreases. The diver's first warning that the cylinder is almost empty is increased resistance on inhalation. However, this warning may be minimal or absent with modern regulators.

Most divers have a console that includes a pressure gauge connected to the cylinder by a hose. Some modern systems transmit the cylinder pressure via radiofrequency signals rather than via a hose. The pressure gauge provides the diver with a measure of the remaining air supply. The contents of the cylinder are proportional to the pressure, so the gauge is often called the 'contents gauge'. Divers tend to say they have 50 bar left, rather than the volume this represents. A major problem is that a diver who is entranced by the scenery, concentrating on a task or distracted may run out of air because he or she forgets to check the gauge. An audible low-air warning is incorporated into some systems and is valuable. A diver needs to ensure that he or she has a cylinder or cylinders with adequate gas supply for the planned dive, and an additional reserve.

A traditional and almost obsolete system to prevent divers from running out of air is a reserve valve. In operation it resembles a boiler safety valve; the air escapes to the diver until the cylinder pressure falls to the level at which the reserve valve seats. The remainder of the air can be released by pulling a lever that opens the reserve valve. One problem with this is that the valve lever may be inadvertently put into the 'on' position, causing the diver to use the reserve of gas without being aware of this. Another common problem is valve failure.

Surface-supply breathing apparatus

A diver can also use a demand valve with air supplied by a hose from the surface. This equipment, **surface-supply breathing apparatus (SSBA),** restricts the diver's range and depth to the length of the air supply hose. Its advantages are that the diver is freed from the cumbersome air cylinders and the air supply can be as large as needed, instead of being restricted by the diver's carrying capacity and need for mobility. The air for SSBA may be stored in large tanks or compressed as required. The use of a compressor, often called a '*hookah*' system, is economically attractive because the air is compressed to a lower pressure than that required for storage tanks. However, the compressor needs to be reliable and there needs to be an observer to monitor the compressor during operation.

Two modified forms of SSBA have found support in some circles. In one, a small motor and air compressor are supported on a float on the surface. This apparatus supplies air to one or two divers. In the other, the divers tow a float that supports an air cylinder. An advantage of these systems is that, if the hoses are short, the divers are unable to reach the depth needed to develop decompression sickness (DCS). A significant problem is that the user has no indication of when the gas supply will fail. Therefore, it is prudent for the diver to carry a small bail-out cylinder and regulator. Also, some novice users may forget that they are still exposed to the other hazards of scuba diving, such as pulmonary barotrauma.

In some resort areas, these devices are hired by novices who have had no training and who may be medically unfit to dive. Such use should be controlled and monitored in a similar manner to normal scuba instruction and equipment hires.

Safety and protective equipment

The best safety measures available to a diver are adequate health and fitness, proper training, appropriate and functional equipment and common sense. Almost all accidents are preventable, and the authors do not ascribe the popularly held belief that these accidents are attributable to an 'act of God'. Many accidents involve human, often predictable and thus correctable, mistakes. This point is developed in Chapter 46, in which deaths and accidents are considered. Several items of equipment that reduce the hazards of diving, or assist with coping with them, are discussed here.

EMERGENCY AIR SUPPLIES

Emergency air supplies can take a variety of forms. In the early days it was common to rely on *buddy-breathing*, a procedure in which two divers shared an air supply in the event one of them had an air supply failure. Both anecdote and analysis of diving accident statistics showed that this procedure often did not work in an emergency. The use of a second regulator attached to the scuba set, often called an **octopus rig,** has now become standard fare, and its introduction and widespread use have helped to avoid many serious diving accidents. However, neither buddy-breathing nor an octopus rig will be of use if the diver with gas is not available or is unwilling to cooperate. For this reason, a second source of air (redundant supply) that is available to each diver without external assistance is now favoured. For cave divers this may essentially be a second scuba set. For technical divers with substantial mandatory decompression obligations, a redundant gas supply is also essential, and they often carry what is known as a **stage cylinder**.

For most divers, who have relatively ready access to the surface, a smaller cylinder with an independent regulator can be used. One commercially available device, known as *Spare Air* (Submersible Systems, Inc.), is carried by some divers. However, the air supply is very small, enabling only a few breaths for ascent. For this reason, these devices are not commonly used and are not sufficient for deep dives or dives requiring decompression. It is important that a redundant supply provides adequate gas for a relatively safe ascent.

It is also sometimes possible for a diver to breathe air from the BCD for a short period of ascent. However, this has potential hazards, including aspiration of water, infection and buoyancy control problems. A BCD with an independent air supply is available but not commonly used.

THERMAL PROTECTION

Thermal protection is needed in cold water or on prolonged dives to minimize the risk of hypothermia. This protection is normally provided by insulated clothing, which reduces heat loss. The most common protection is a **wetsuit,** made from air-foamed Neoprene rubber. The water that leaks into spaces between the suit and the diver soon warms to skin temperature. Foamed Neoprene has insulation properties similar to those of woollen felt. Its effectiveness is reduced by loss of heat with water movement and increasing depth. Pressure decreases insulation by reducing the size of the air cells in the foam. At 30 metres of depth, the insulation of a wetsuit is about one third of that on the surface (see Figure 27.1). The compression of the gas in the foam also means that the diver's buoyancy decreases as he or she goes deeper. The diver can compensate for this by wearing a BCD. If the diver does not, he or she needs to limit the weights, but this will mean that the diver is too buoyant when closer to the surface. The buoyancy and insulation of a wetsuit decrease with repeated use.

Another other common form of thermal protection is the **drysuit**. This is watertight and has seals round the head, feet and hand openings. There is an opening with a waterproof seal to allow the diver to get into the suit. The drysuit allows the diver to wear an insulating layer of warm clothes. A gas supply and exhaust valve are needed to allow the diver to compensate for the effect of pressure changes on the gas in the suit. The gas can be supplied from the scuba cylinder or a separate supply.

The diver needs training in the operation of a drysuit or he or she may lose control of buoyancy by excessive addition of air into the suit. This can lead to an uncontrolled ascent, sometimes inverted, when the excess of gas expands, speeding the ascent. If the diver tries to swim downward, or otherwise becomes inverted in the water, the excess gas may accumulate around the legs, from where it cannot be vented through the exhaust valve. The excess gas can also expand the feet of the suit and cause the diver's fins to pop off. The diver can find himself or herself floating on the surface with the suit grossly overinflated, a most undignified and potentially dangerous posture.

Heat can also be supplied to a diver to help him or her keep warm. The commonly used systems include hot water pumped down to the diver through hoses. Various chemical and electrical heaters are also available. External heat supplies are more often used by commercial divers.

Semi-drysuits are essentially wetsuits with enhanced seals at the neck, hands, feet and zippers. These seals help to reduce the amount of water entering and leaving the suit and so reduce heat loss. They are not as effective as drysuits in keeping the diver warm, but they can provide thermal protection similar to that of a significantly thicker wetsuit and so increase the level of comfort for the wearer, as well as reducing the amount of weight carried.

BUOYANCY COMPENSATOR DEVICES

BCDs consist of an inflatable vest (or back-mounted bags [wings]) worn by the diver and attached to a gas supply from the regulator. The BCD allows the diver to adjust buoyancy underwater or helps bring the diver to the surface and/or support him or her there. The ability to change buoyancy allows the diver to hover in the water and adjust for any factor that causes density to increase (e.g. wetsuit compression, picking up a heavy object on the bottom).

Most BCDs can be inflated via a hose from the regulator. Some have a small separate air bottle that can also be used as an emergency air supply, although these are now rare. Several valves to release gas are fitted so the diver can reduce buoyancy by venting gas from the compensator.

Divers can lose control of their buoyancy while ascending. As the diver starts to ascend, the expanding gas in the BCD increases its lift and in turn increases the rate of ascent. Such a rapid, uncontrolled ascent can lead to a variety of diving medical problems including pulmonary barotrauma and DCS.

In the past, BCDs were also designed to float an unconscious diver face-up on the surface. However, with the current designs this useful benefit has been largely foregone.

DEPTH GAUGES

A depth gauge, timer and a means of calculating decompression are needed if an unsupervised diver is operating in a depth or time zone where decompression stops may be needed. Electronic, mechanical and capillary gauges have been used as depth gauges by divers. Capillary gauges, although now rarely used, measure pressure by the reduction in volume of a gas bubble in a graduated capillary tube and were useful only at shallower depths. Most gauges record the maximum depth reached by the diver during the dive, an important feature for tracking decompression status if using tables. Although the modern digital gauges are relatively accurate, there can occasionally be problems (as there often were with mechanical gauges), and the need to check the accuracy of gauges is often overlooked. Faulty gauges have caused divers to develop DCS.

DIVE COMPUTERS

Dive computers use a depth (pressure) sensor, timer, microprocessor, display and various other features. They are encoded with a decompression algorithm – a set of mathematical equations designed to simulate the uptake and elimination of inert gas within a diver's body. By sampling the depth and recalculating every few seconds, these computers enable dive times well beyond those permitted by tables on most dives, especially on multi-level and repetitive dives. Some of the more sophisticated models take into account ambient temperature and/or gas consumption, and some even measure heart rate (Figure 4.3). However, they can still only 'guesstimate' a diver's actual saturation, and DCS remains a significant concern with computer users. In fact, most people diagnosed with DCS these days have been diving within the limits indicated as theoretically safe by their devices. Users are well advised to use more conservative limits than the 'factory settings'. Some models enable the user to adjust the computer to more conservative modes.

Despite this, dive computers have revolutionized diving because of their flexibility and

Figure 4.3 Two of the more sophisticated current model recreational dive computers **(a)** Galileo Sol (Scubapro, USA); and **(b)** Vytec (Suunto, Finland).

the vastly increased underwater times enabled. Possibly their greatest contribution to diving safety is the incorporation of ascent rate warnings to caution the wearer when he or she ascends faster than the recommended rate, which is usually substantially slower than traditional rates used with most decompression tables.

CONTENTS GAUGE

The role of this gauge is discussed earlier. The contents gauge indicates the pressure and, by extrapolation, the amount of gas remaining in the supply cylinder.

COMMUNICATION

Because of the risks in diving, it is generally considered foolhardy to dive without some method of summoning assistance. Most commercial divers do this with an underwater telephone or signal line. Divers who do not want the encumbrance of a link to the surface can dive in pairs, commonly called a ‘buddy pair’. Each diver has the duty to aid the other if one gets into difficulty. The common problem in the use of the buddy system is attracting the attention of the buddy if he or she is looking elsewhere or if separation has occurred, whether intentional or otherwise.

Underwater audible signalling devices are commercially available and are useful in such circumstances. These are generally driven by breathing gas and are attached to the low-pressure hose in series with the BCD inflator.

DIVER LOCATION DEVICES

Sometimes divers can be difficult to sight on the surface after a dive because of the sea conditions and/or divers surfacing distant from the boat, often swept away by current. This can lead to stranding of divers at sea for extended periods, with some lost forever.

Various devices are available to try to prevent this problem. Commonly used location devices include horns, whistles, mirrors, safety sausages and other surface marker buoys (SMBs). There are also commercially available electronic diver location devices. Some consist of a receiver and a number of transmitters. The receiver is located on the boat (or can be elsewhere), and individual transmitters are issued to divers. This system enables a charter operator to track its divers continuously. Suitable electronic position-indicating radio beacons (EPIRBs) have been developed or adapted for use by divers, and these are becoming more frequently used. One such device is

Figure 4.4 Nautilus Lifeline, BC, Canada.

shown in Figure 4.4. They can be especially helpful when diving in remote locations. However, rescue depends on adequate monitoring of distress signals, as well as the willingness and ability of local authorities to perform a search and rescue. This can be a problem in some developing countries.

LINES

A **'mermaid' line** is attached to the stern of the boat and extends down-current. It aids recovery of divers when they surface downstream. (Some call this the 'Jesus line' as it saves sinners – i.e. divers who have erred and surfaced down-current from the dive boat!) This is not needed if a lifeline or pickup boat is being used, or if the current is insignificant.

A **shot line** is a weighted line that hangs down from the dive boat or from a buoy. It is often used to mark the dive site and as a descent and ascent line. It can also be the centre for a circular pattern search. It can be marked with depth markers that can be used to show the decompression stop depths. The diver can hold onto the line at the depth mark. A **lazy shot** line is a weighted line that does not reach the bottom and is used for decompression stops.

A **lead line** is often used to assist the diver on the surface. It leads from the stern of the boat to the anchor chain. It allows the diver, who has entered the water at the stern of the boat, to reach the anchor when the current is too strong to swim to it.

When diving in caves or some wrecks, a 'guide line' should be use. This is a continuous line to the entrance is needed so that it can be followed if the divers become disorientated or when visibility is lost because of torch failure or formation of an opaque cloud by disturbed silt. Each diver should be within arms reach of the main line.

Dive boats

Boats used for diving range from kayaks and canoes to large, specialized vessels that support deep and saturation diving. The facilities required depend on the nature of the diving, but there are minimum requirements. In some conditions, a second safety boat or tender may be needed. Divers may need to be picked up after drifting away from the main vessel.

Propellor guards, or a safe propulsion system such as a water jet, is desirable if there is any chance that the engine will be engaged during diving operations.

A **diving platform** or **ladder** is needed on most boats to facilitate the diver's return from the water. Consideration should be given to the recovery of an unconscious or incapacitated diver, which is ideally done with the diver positioned horizontally. This can be very difficult with both large and small boats, and an appropriate system should be established and practised. Recovery into an inflatable craft is often an easier alternative because the diver can be dragged, rather than lifted, into the boat. Also, the softer air-filled hull is less likely than a rigid hull to injure a diver.

Diving flags, lights or other signals as required by the local maritime regulations should be available. These are designed to warn boat operators to slow down or keep clear. In some places they can offer legal, if not physical, protection from the antics of other craft. Unfortunately, in many places the flag is not recognized or is ignored, and in most areas 'boat propeller attacks' cause more deaths than shark attacks.

The **first aid kit** and **emergency medical equipment** (see Chapter 48) should be chosen depending on local hazards and the distance from assistance.

PROFESSIONAL OR TECHNICAL DIVING EQUIPMENT

This section deals with the more specialized equipment used by professional and military divers, as well as some recreational technical divers. Many of the military diver's tasks, and some of those of the professional diver, involve comparatively shallow depths. Such tasks could be conducted with scuba gear of the type described earlier. Equipment fitted with communication devices allows the diver to confer with the surface support. Communication devices operate better in air, so they are commonly fitted into a helmet or full-face mask. In these devices, the airflow may either be continuous or on demand.

More specialized equipment is used for some military diving where an element of stealth is required. For these tasks, an oxygen rebreathing system that can be operated with no telltale bubbles may be used. In dealing with explosive mines, stealth is again required to avoid activating the noise- or magnetically triggered circuits. If the mine may be too deep for an oxygen set, a rebreathing system with an oxygen-nitrogen mixture may be used.

For even deeper tasks, for which oxygen-helium mixtures are used, some method of reducing the gas loss gives cost and logistical savings. This can be achieved by the diver's using a rebreathing system or returning the exhaled gas to the surface for reprocessing.

Breathing systems

OPEN-CIRCUIT BREATHING SYSTEMS

For most tasks, the professional diver is working in a small area for long periods. Because of this, he or she does not need the mobility of the scuba diver. The breathing gas normally comes from the surface in a hose, either supplied from storage cylinders or compressed as needed by a motor-driven compressor. The cable for the communication system and a hose connected to a depth measuring system are often bound to the gas supply hose. Another hose with a flow of hot water may also be used to warm the diver. It is normal for the diver to have an alternative supply of breathing gas in a cylinder on his or her back. This supplies the diver with breathing gas if the main supply should fail.

Free-flow systems were used in the first commercial air diving apparatus. The diver was supplied with a continuous flow of air that was pumped down a hose by assistants turning a hand-operated pump. The hand-operated pumps have long gone, but the same principle is still in use. In the most common system, called **standard rig,** the diver's head is in a rigid helmet, joined onto a flexible suit that covers the body. The diver can control buoyancy by controlling the amount of air in the suit. The main problem with the system is that the flow of fresh breathing gas must be sufficient to flush carbon dioxide from the helmet. The flow required to do this is about 50 litres/minute (lpm), measured at the operating depth; this is well in excess of that needed with a demand system.

The other problem associated with free-flow systems and the high gas flow is the noise this generates. In the early days, the diver was also exposed to the risk of a particularly unpleasant form of barotrauma. If the pump or air supply hose breaks, the pressure of the water tends to squeeze the diver's soft tissues up into the helmet. This is prevented by fitting a one-way valve that stops flow back up the hose. For deep dives, where oxygen-helium mixtures are used, the cost of gas becomes excessive. A method of reducing the gas consumed may be fitted. For example, some units incorporate a canister of carbon dioxide absorbent to purify the gas. The gas flow round the circuit is generated by a Venturi system that does away with the need for valves to control gas flow. The rig is converted into a rebreathing system, which has a separate set of problems that are considered in a later section.

Demand systems were developed to gain a reduction in gas consumption compared with free-flow systems. They also enable the diver to talk underwater. Several types of equipment are in common use. One type uses a full-face mask that seals round the forehead, cheeks and under the chin. The back of the diver's head may be exposed to the water or covered with a wetsuit hood that is joined onto the face mask.

Another type is fitted in a full helmet. An oro-nasal mask in the helmet reduces rebreathing of exhaled air. The helmets are often less comfortable than the face masks, but they give better thermal and impact protection.

These helmets may also be used at greater depths, where helium mixtures are used. A return hose may be used to allow collection of the exhaled gas at the surface for reprocessing.

When compared with a demand valve held in the mouth, all the systems mentioned earlier have the major advantage of reducing the chance of the diver's drowning. This is important if the diver becomes unconscious and/or has a convulsion while breathing high partial pressures of oxygen (PO_2). The increased safety and the advantages of a clear verbal communication system have led to the adoption of helmets by most diving firms.

> Sets that use a helmet and a full-face mask reduce the risk of drowning and can allow the diver to converse with people on the surface.

REBREATHING SYSTEMS

Respiration is designed to provide our tissues with oxygen and to eliminate carbon dioxide produced by metabolism. When we breathe on the surface, we consume about 25 per cent of the oxygen that we inhale with each breath. Thus, if our respiratory minute volume (RMV) were to be 20 lpm, we would breathe in 4 litres of oxygen each minute, of which 1 litre would be consumed and 3 litres would be exhaled back into the surrounding atmosphere. Although this may not seem very efficient, the situation becomes substantially worse when we descend on open-circuit scuba equipment.

As the depth and pressure increase, the amount of gas we inhale with each breath must also increase to compensate. Thus, at 40 metres (5 ATA), we would need to breathe 100 lpm from our cylinder to achieve the same 20 lpm surface RMV. This 100 litres of air would contain about 20 litres of oxygen, of which 19 litres are being exhaled into the ocean unused!

One solution to this inefficiency of gas consumption is to recirculate the gas, removing the carbon dioxide and adding only the oxygen that is consumed by the diver back into the circuit. This is called a 'rebreather', and such breathing apparatus can offer substantial reductions in gas consumption over open-circuit systems. The following is a summary of some advantages and disadvantages of rebreather systems, which are expanded upon in the following paragraphs:

Advantages

- Vastly reduced gas consumption, especially during deep diving.
- Reduction of cold stress and dehydration by the breathing of warm, humidified gas.
- Lack of bubbles good for photography, covert operations, fragile environments such as caves.
- Improved decompression efficiency because of maintenance of 'optimal PO_2'.
- Excellent duration in relatively small unit.

Disadvantages

- Significant initial cost.
- Greater complexity and vastly increased need for training, vigilance and maintenance.
- Different hazards to diver, higher overall risk.

Rebreathers fall into one of two main types – closed-circuit rebreathers (CCRs) and semi-closed-circuit rebreathers (SCRs). Although both types recirculate all, or part, of the breathing gas, the main difference lies in the way that the oxygen level is controlled and added into the circuit.

In general, SCRs are less complex but less efficient and have depth limitations dependent on the gas selection. CCRs are the most complex but also the most efficient and most capable with regard to depth and duration.

Because of the similarity between SCR and CCR sets, their common features are discussed first, and features peculiar to each type are then highlighted separately.

The usual gas flow pattern found in a rebreathing set is shown in Figure 4.5. The movement of inhaled and exhaled gas is controlled by one-way valves at the mouthpiece as the gas flows round the circuit. For largely historical reasons, rebreathers of UK or European origin usually have a clockwise gas flow pattern, whereas those of US origin have an anticlockwise pattern. However, this is not universally so.

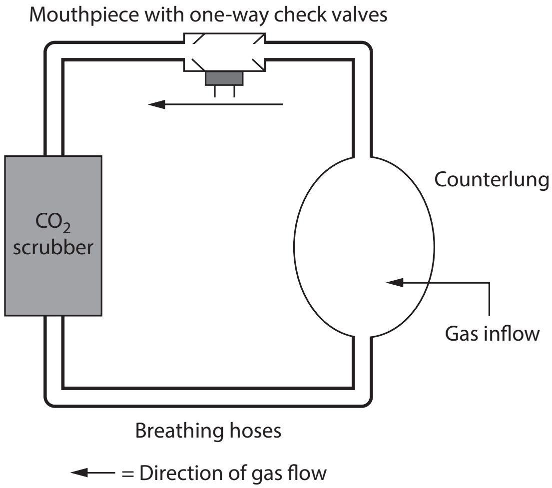

Figure 4.5 A stylised rebreather layout.

As the diver descends, gas must be added from a high-pressure cylinder into the breathing loop so that a constant volume is maintained within the system. In most units, the gas is automatically added via a regulator-type valve (automatic diluent valve [ADV]). A manually controlled valve allows the diver to add extra gas if it is required. This addition of gas will affect buoyancy.

The counterlung acts as a gas storage bag that expands and contracts as the diver breathes. It normally incorporates a relief valve (over-pressure valve [OPV]) that releases surplus gas into the water and prevents excess pressure building up. Venting of excess gas is needed in CCR sets when the diver ascends and the gas in the counterlung expands. In SCR sets, excess gas vents regularly through the relief valve.

The carbon dioxide absorbent is usually a mixture of calcium and sodium hydroxides. These chemicals react with carbon dioxide to form carbonates and water, as shown:

$$M(OH)_2 + CO_2 \rightarrow MCO_3 + H_2O$$

Closed-circuit oxygen systems are the simplest CCR sets. The counterlung is filled with oxygen from the cylinder. As oxygen is consumed, the volume of the bag decreases. In some units, a trigger mechanism that operates like a demand valve releases more gas into the bag. In other units, there is a mechanism that releases a continuous flow of oxygen into the circuit. A manually operated method of adding oxygen to the breathing bag is also usually fitted. This will be needed when the diver puts the unit on, when he or she goes deeper and the gas in the breathing bag is compressed, or when the diver needs to increase buoyancy.

The unit can be operated as a closed system because, unless something goes wrong, the gas in the breathing bag will contain a high concentration of oxygen, diluted with nitrogen that was in the lungs and body of the diver when he or she put the unit on. It is standard practice to flush the counterlung with oxygen at set intervals to 'denitrogenate' before starting the dive to prevent a build-up of diluting gases.

Possible problems with these units include carbon dioxide toxicity if the absorbent fails, dilution hypoxia if the oxygen is impure or the diver neglects to flush nitrogen from the lungs and the counterlung and oxygen toxicity if the diver descends too deep.

To reduce the risk of oxygen toxicity, a depth limit of about 6 to 8 metres is often imposed on the use of these units to limit the PO_2 to 1.6 to 1.8 ATA, a range generally deemed acceptable for military operations, although too high for recreational technical diving, where a lower risk is appropriate and consequently a PO_2 significantly lower than 1.6 ATA is usually maintained.

Closed oxygen rebreathing apparatus has the particular advantage that a small unit may give a long endurance. A unit weighing less than 15 kg can allow dives of more than 2 hours. The lack of bubbles and quietness of this unit are also important in some specialized roles such as clandestine operations.

> Rebreathing units are quieter and have a greater endurance than scuba units. The extra hazards and costs involved restrict their use and demand significant extra training, maintenance and vigilance.

In **closed-circuit mixed gas systems,** oxygen and a diluting gas are fed into the breathing loop at rates required to keep the PO_2 within safe limits and to provide an adequate volume of the mixture.

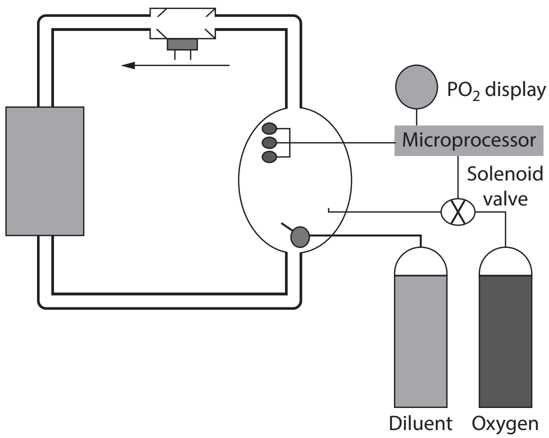

Figure 4.6 Electronic closed-circuit mixed gas rebreather layout.

Figure 4.6 shows the fundamental features of this system.

As with the closed-circuit oxygen unit, the diver inhales breathing gas from the counterlung and exhales through the carbon dioxide absorber back into the counterlung. As the diver consumes oxygen, the PO_2 in the counterlung falls, and this fall is detected by oxygen sensors. At a certain level, a valve injects more oxygen into the circuit. Both mechanically and electronically controlled units are commonly seen in recreational diving, and there has been much controversy as to which arrangement is safer.

Although all rebreather divers should know their PO_2 at all times, the above argument hinges on the requirement for the diver in the manual system to be forced to know his or her PO_2 at all times (although in most systems a basal flow of oxygen is continually bled into the unit). However, the requirement to manage the PO_2 in this system can create problems during times of high task loading. In contrast, there is less obvious compulsion for the diver using an electronic rebreather to know the PO_2 at all times, and should the controlling computer fail, the diver would be at risk, although the chances that the computer will fail in an electronic rebreather are very low. The reality is that, to date, neither system has been shown to offer a survival advantage and all rebreather divers should make a habit of knowing their PO_2 at all times.

Most modern mixed gas CCRs use a series of three redundant oxygen sensors (galvanic fuel cells) to track the PO_2 in the loop. This allows for the comparison of the outputs of the sensors because they are relatively fragile and prone to failure, as well as having a limited life (usually ~18 months).

If the volume of gas in the bag falls, this triggers a second valve that adds diluting gas (diluent) from a separate cylinder. Air, trimix (helium, nitrogen and oxygen) or heliox (helium and oxygen) may be used as the diluent depending on the planned depth and profile of the dive. The selection of the gas is determined largely by oxygen toxicity and work of breathing issues. For the former, the diluent gas should not have a PO_2 greater than a predetermined set-point at depth (preferably a little lower so that an 'oxygen spike' does not happen during descent when diluent is added to the loop). To manage the latter, the diver should calculate the density of the gas at the proposed maximum depth, such that it does not exceed the manufacturer's recommendation and maintains the work of breathing within the specifications of the unit.

Manual controls and displays indicating the oxygen concentration are often fitted to allow the diver to override the controls if the automatic control fails. In many cases, divers also either raise the 'set-point' or flush the unit with oxygen during the final decompression stop at 6 metres to shorten decompression time.

This system would appear to be the most efficient breathing system. It is more economical in terms of gas usage than any other gear apart from the oxygen-breathing apparatus. It enables a diver to go deeper for longer and with fewer encumbrances than other equipment.

As an example of the efficiency of this type of equipment, it has been estimated that in a helium saturation dive program involving a prolonged series of dives to 180 metres, the cost of helium for a CCR apparatus was about 2.5 per cent of the cost of an SCR diving apparatus. These advantages must be balanced against the greater initial cost and complexity of the system. This complexity can lead to fatal malfunctions.

SCRs offer some of the saving in gas obtained in the closed systems while avoiding the depth limitations of the oxygen sets and the greater complexity of the closed mixed gas sets. The basic system is shown in Figure 4.7.

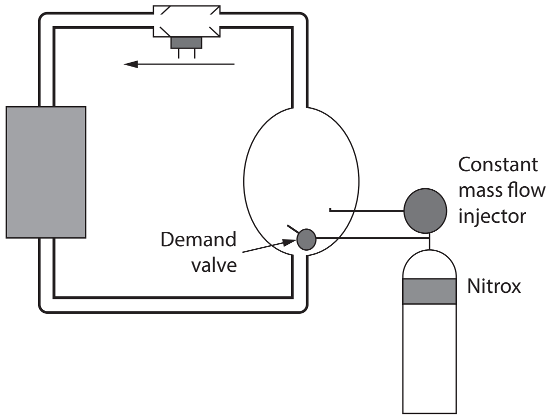

Figure 4.7 Semi-closed rebreathing system.

SCRs typically use oxygen-enriched air (nitrox) as the breathing mix instead of oxygen. Two major types of SCR are in common use. The most common is the constant mass flow (CMF) type, but the keyed respiratory minute volume (RMV keyed) type has some advocates, especially with US cave divers.

In a typical CMF SCR system, the gas flow and composition are chosen for maximum efficiency for the proposed dive. First, the composition of the gas is chosen, with as high an oxygen concentration as possible without creating an unacceptable risk of oxygen toxicity at the planned maximum depth. This level may be changed depending on the duration of exposure. The flow is then chosen so that the diver will receive sufficient oxygen while working on the surface.

The oxygen concentration in the diver's inspired gas is determined by the flow into the system, the diver's consumption and loss through the relief valve. It ranges from close to that in the supply bottle when the diver is resting down to about 20 per cent when the diver is working at the maximum expected rate.

In the RMV keyed sets, a fixed volume of gas is dumped from the circuit with each breath, with 'new' gas added via a demand valve.

As a safety precaution with an SCR, almost invariably an excess of gas is added to the loop and is vented through the relief valve, thus making these devices less efficient on gas than CCRs. However, an SCR system with a flow of 12 lpm gives an eightfold saving of gas compared with a demand system when the diver is consuming 1 lpm of oxygen. This saving would increase if the scuba diver was working harder and consuming more air.

The high oxygen concentrations in both SCR and CCR systems mean that the diver may not absorb as much nitrogen as he or she would if breathing air. This can give a decrease in the decompression needed, but unless the PO_2 in the loop is actually measured, the diver must 'guesstimate' the PO_2 for decompression purposes. On occasion, this has resulted in problems.

Military divers have traditionally been the main users of SCR sets, although they have become increasingly popular in recreational diving. The reduced gas flow with these sets means that they can be designed to make little noise. If they are constructed from non-magnetic materials, they can be used for dives near mines, although CCRs are now more often used for mine countermeasures.

Problems with rebreathers

Both CCR and SCR systems introduce a variety of potential hazards (see Chapter 62):

Carbon dioxide accumulation can occur if the scrubber fails. This can occur if the scrubber material is used for too long, if the scrubber is incorrectly attached or if the scrubber's instantaneous capacity to remove carbon dioxide is exceeded because of a diver's high demand, such as with exertion.

Oxygen toxicity can occur if the diver exceeds his or her depth limit, descends too quickly when diving at a particular PO_2 (set-point) or uses a mixture with too much oxygen in it. This can occur if an excessively oxygen-rich mix was added to the diluent cylinder or if the solenoid or manual oxygen injection valves jam open.

Hypoxia may result if the gas flow decreases. This can be caused by omitting to turn on the gas supply before descending, exhausting the oxygen supply, solenoid or electronics failure, and ascending too rapidly to enable the solenoid to add sufficient oxygen to the loop. Hypoxia can also occur if the diver works harder than expected or if a mix with too little oxygen is used.

A review of the 181 reported recreational CCR-related deaths that occurred between 1998 and 2010 estimated that the fatality rate for CCR users was about 10 times that of recreational open-circuit divers. The author also suggested that CCRs have a 25-fold increased risk of component failure compared with manifolded twin-cylinder open-circuit systems. It was suggested that this risk could be partly offset by carrying a redundant bail-out system.

Chambers, habitats and underwater vehicles

Divers may use several special types of vehicles and living facilities. These include vehicles that are hoisted and lowered to transport divers to and from deep dive sites, propelled vehicles to increase the diver's range and endurance (i.e. diver propulsion vehicles [DPVs], often used by technical divers) and machines to carry underwater equipment. The accommodations to be considered include underwater houses and pressurized houses at the surface.

Submersible decompression chambers (SDCs), often called personnel transfer capsules, are used to transport divers and any attendants from the surface to the work site, and they may also be used as a relay station and store for gas and equipment. The most complex SDC may carry the diver at constant pressure from a deck decompression chamber (DDC) to the work site and back. The simplest SDC consists of a bell chamber that is open at the bottom and allows the diver to decompress in a dry environment, exposed to the same pressure as the surrounding water.

Habitats are underwater houses that accommodate divers in air- or gas-filled environments. They are used by divers to rest between excursions. Divers have lived in some of these habitats for weeks at a time.

Deck decompression chambers (DDCs) can be small and used for surface decompression, a procedure that allows a diver to be decompressed in a dry chamber instead of in the water. Larger chambers can be used to treat divers with decompression illness and other diseases that respond to compression, in which case the chamber may be called a **recompression chamber.**

DDCs are also used to house divers for prolonged periods under elevated pressure. In this case, divers are carried to their work by an SDC or a small submarine that keeps the diver in a pressurized environment. At the end of the job, possibly after several weeks, the pressure in the DDC is lowered slowly to return the diver to atmospheric pressure.

Transport vehicles can carry the divers at normal atmospheric pressure, at ambient pressure in a dry environment or in a wet environment. These include vehicles towed by a boat. A small motor and propeller that pulls the diver along gives increased speed with reduced effort. Some submarines have a lock system to allow divers to leave and enter underwater.

One atmosphere diving equipment, such as the **JIM suit,** seals the diver in a pressure-resistant compartment. It has flexible arms with tools on the 'hands' for the diver to work underwater. The early types of suit had legs that gave the diver the ability to walk on firm surfaces if there was little current. The diver had no control in mid-water and had to be lowered and hoisted from the surface. In other designs, such as the **Newtsuit** and **WASP** system, the diver controls a set of propellers that make him or her a cross between a diver and a one-person submarine.

Life support systems are required to provide the occupants of all these vehicles, habitats and chambers with a respirable atmosphere. These work on the same principles as a diver's breathing apparatus, and in some vehicles the diver may even be wearing a breathing apparatus. The system must be self-contained for transport vehicles, but for habitats and SDCs the gas is generally supplied from the surface.

Gas from the surface can be supplied in a free flow and escape out the bottom or be recirculated through a purifying system. Simple gas purifying systems can involve a hand-powered pump to force gas through a carbon dioxide absorption canister with a manually operated system for adding oxygen. The most complex systems are those found on large submersibles, nuclear submarines and chambers used for deep saturation dives. These have automatic closed systems with provision for removing trace contaminants and odours, and they also regulate temperature, pressure and humidity.

Gas reclaimers are mainly used to recover helium to be used again. They help to lower costs by reducing the amount of gas used. One type cools the gas until the other gases are liquefied, leaving pure helium to be stored and used again. Other types use a chromatographic technique to separate the gases.

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This chapter was reviewed for this fifth edition by John Lippmann.

5

Undersea environments

INTRODUCTION

For the diver who is adequately trained and physically fit, who is aware of the limitations of the equipment and who appreciates the specific requirements of different environmental diving conditions, the sea is rarely dangerous. Nevertheless, it can be hazardous and unforgiving if attention is not paid to all these factors.

Diver training is specific to the environment in which the diver is trained. Specialized techniques are recommended to cope with different environments. They cannot be automatically extrapolated to other diving environments. The induction of fear in the inexperienced diver and of physical stress in the more skilled diver is appreciated only when one examines each specific environmental threat. These environmental stresses are mentioned in this and other chapters. The reason for including them in a medical text is that unless the physician comprehends the problems and dangers, the medical examinations for diving fitness and the assessments of diving accidents will be less than adequate.

Some aspects of the environments have physiological and pathological sequelae and therefore have specific chapters devoted to them. They include the effects of cold (see Chapters 27 and 28), altitude and fresh water diving (see Chapter 2), explosives (see Chapter 34), depth (see Chapters 2, 15, 20, 46 and 68) and marine animal injuries (see Chapters 31 and 32). Other environmental topics that are covered more comprehensively in diving texts are summarized in this chapter.

Being kept underwater and exceeding the limited air supply will result in drowning. This is a situation common to many of the hazardous environments, including caves and wrecks and under ice, overhangs, water flows and so forth. A variety of materials can trap the diver, including kelp, lines (even ‘safety’ lines), fishing nets and fishing lines. If the diver does not have a compromised air supply, then knowledge of the environment, a buddy, a communication facility, a calm state of mind and a diving knife or scissors will cope with most of these circumstances.

ALTITUDE DIVING

The term *altitude diving* refers to diving at an altitude of 300 metres or more above sea level. Non-diving disorders should be considered, such as the dyspnoea and hypoxia induced by high altitude and the altitude sickness that frequently develops above 3000 metres. Diving at altitudes higher than this is strongly discouraged.

The following numerical examples do not represent actual diving conditions and are used to explain the problems as simply as possible, thus avoiding complicated mathematics. The conventional idea of diving is that a diver descends with the sea surface (1 ATA) as the reference point and returns there when he or she has finished the dive. A diver may have to dive at altitude, in a mountain lake or dam, where the pressure on the surface is less than 1 ATA. Problems stem from the physics at this altitude.

For simplicity's sake, the following description is based on the useful, but not strictly correct, traditional theory that the ratio between the pressure reached during the dive and the final pressure determines the decompression required. If this ratio is less than 2:1, then a diver can ascend safely without pausing during ascent. This means that a diver from the sea surface (1 ATA) can dive to 10 metres (2 ATA) and ascend safely, as regards decompression requirements. A diver operating in a high mountain lake, with a surface pressure of 0.5 ATA, could dive only to 5 metres (1 ATA) before he or she had to worry about decompression. This statement ignores the minor correction required with fresh water. Fresh water is less dense than salt water.

Another pressure problem occurs when a diver, who dives at sea level, then flies or ascends into the mountains after the dive. For example, a 5-metre dive (1.5 ATA) from sea level could be followed by an immediate ascent to a pressure (altitude) of 0.75 ATA, with little theoretical risk. Deeper dives or greater ascents may require the diver to pause at sea level if the diver is to avoid decompression sickness. If the diver ascends, in a motor vehicle or an airplane, the reduced pressure will expand 'silent' bubbles or increase the gas gradient to produce larger bubbles, thereby aggravating the diseases of pulmonary barotrauma and decompression sickness.

Thus, exposure to altitude after diving, or diving at altitude, increases the danger of decompression sickness, compared with identical dives and exposures at sea level. It influences the decompression obligations, the depths and durations of decompression stops, the nitrogen load in tissues afterward, the safe durations before flying or repetitive diving, the ascent rates recommended during diving and so forth. Formulae are available to convert the equivalent altitude decompressions to sea level decompressions.

Another problem of diving in a high-altitude lake is the rate at which a diver may have to exhale during ascent. A diver who ascends from 10 metres (2 ATA) to the ocean surface (1 ATA) would find that the volume of gas in the lungs has doubled. Most divers realize this and exhale at a controlled rate during ascent. They may not realize that an equivalent doubling in gas volume occurs in only 5 metres of ascent to the surface, if the dive was carried out at an altitude (pressure) of 0.5 ATA. Equivalent effects are encountered with buoyancy, which can more rapidly get out of control at altitude.

The diver's equipment can also be affected or damaged by high-altitude exposure. Some pressure gauges start to register only when the pressure is greater than 1 ATA. These gauges (oil-filled, analogue and mechanical types) may try to indicate a negative depth, perhaps bending the needle, until the diver reaches 1 ATA pressure. Thus, the dive depth would have to reach more than 5 metres before it even started measuring, if the dive had commenced at an altitude of 0.5 ATA.

The other common depth gauge, a capillary tube, indicates the depth by an air-water boundary. It automatically adjusts to the extent that it always reads zero depth on the surface. The volume of gas trapped in the capillary decreases with depth (Boyle's Law). For a diver starting from 0.5 ATA altitude, this gauge would read zero, but it would show that the diver had reached 10 metres when he or she was only at 5 metres depth. Theoretically, the diver could plan the dive and decompression according to this 'gauge' depth, but only if he or she was very courageous.

Many electronic dive computers do permit correction for altitude, and some need to be 're-zoned' at the dive site. Other decompression meters are damaged by exposure to altitude (e.g. as in aircraft travel), and the applicability of other dive computers to altitude diving or saturation excursions is questionable.

Divers who fly from sea level to dive at altitude, as in high mountain lakes, may commence the dive with an already existing nitrogen load in excess of that of the local divers, who have equilibrated at the lower pressures. Thus, the 'sea level' divers are in effect doing a repetitive dive, and 'residual nitrogen' tables must be employed.

Decompression tables that supply acceptable modifications for altitude exposure include the Buhlmann and Canadian Defence and Civil Institute of Environmental Medicine (DCIEM) tables (see Appendix A).

Altitude exposure and altitude diving are more hazardous extensions of conventional diving. They are not as well researched, and the greater the altitude, the more applicable is this statement. It includes not only the problems already mentioned, but also the complication of diving in fresh, often very cold, water. This water may contain debris that has not decomposed as it would in the ocean and may therefore threaten entrapment. The sites are often distant from diving medical facilities. Undertaking a specialized course in altitude diving is a basic prerequisite.

CAVE AND WRECK DIVING

These enclosed environments are hazardous to open water divers. Cave diving and wreck diving are more complex than they first appear. Completion of the open water scuba training course is inadequate preparation for cave and wreck diving. Planning involves not only the setting of goal-oriented objectives, but the delineation of maximum limits (depths, distances). The main problems are as follows:

- No direct ascent to the surface (i.e. safety).
- Disorientation and entrapment.
- Loss of visibility.
- Enclosed spaces and panic.

Cave diving

The techniques of cave diving are very rigidly delineated. Specialized training includes dive planning, the use of reels and lines and the lost diver protocols. Most people who have difficulties with cave diving have not followed the recommended rules, and unfortunately cave diving problems tend to cause multiple fatalities.

The diver descends, often through a small access, passes down a shaft, goes around a few bends and is faced with multiple passages, in total darkness. Under these conditions, and to make this particular type of diving safe, it is necessary to be accompanied by a diver who has considerable cave experience – in that cave – and whose judgement is trustworthy. It is equally important that the equipment is both suited to cave diving and totally replaceable with spares during the dive. Apart from the obvious environmental difficulties inherent in diving through a labyrinth of passageways, there are added specific problems.

Safety in cave diving is not usually achievable by immediate surfacing. Thus, all necessary equipment must be duplicated for a long return swim, at depth, and possibly while rescuing a disabled companion.

Air pockets found in the top of caves are sometimes non-respirable because of low oxygen and high carbon dioxide levels (especially in limestone caves), so when entering this pocket, breathing should be continued from the scuba equipment. Sometimes the roof of the cave is supported by the water, and when this water is replaced by air from the diver's tanks, the roof can collapse. The common claim that 'the diver was so unlucky for the roof to collapse while he was there' is incorrect. It collapsed because he was there.

The minimum extra safety equipment includes a compass, powerful lights and a safety reel and line. It is a diving axiom that entry into a cave is based on the presumption that the return will have to be carried out in zero visibility.

For visibility, each diver takes at least two lights; however, other factors can interfere with the function of these lights. A great danger is the silt that can be stirred up if the diver swims along the lower part of the cave or in a head-up position (as when negatively buoyant). If there is little natural water movement, clay silts can be very fine and easily stirred up. It is for this reason that fins should be small, and the diver should be neutrally buoyant and should swim more than a metre above the bottom of the cave. Visibility can be totally lost in a few seconds as the silt curtain ascends, and it may remain that way for weeks. Sometimes it is inevitable, as exhaled bubbles dislodge silt from the ceiling. Layering of salt and fresh waters also causes visual distortion and blurring.

The usual equipment includes double tanks manifolded together, making a common air supply, but offering two regulator outlets. With the failure of one regulator, the second one may be used for the air supply – or as an octopus rig. The second regulator must have a long hose, given that often divers cannot swim alongside each other. Because of space limitations, buddy breathing is often impractical under cave conditions. An extra air supply ('pony' bottle) is advisable.

For recreational divers to explore caves, the ideal equipment is a reliable compressed air surface supply, with a complete scuba back-up rig.

All the instruments should be standardized; e.g. the watch goes on the left wrist, the depth gauge above it, the compass on the right wrist and the dive computer (this can include a contents gauge, decompression meter, dive profile display, compass) attached to the harness under the left arm. The gauges and decompression must be modified for fresh water and altitude, if these are applicable. The knife is strapped to the inside of the left leg, to prevent entanglement on any safety lines.

The buoyancy compensator is often bound down at the top, to move the buoyancy centre more toward the centre of gravity (cave divers do not need to be vertical with the head out of water). There is no requirement for excess buoyancy because safety in cave diving is not usually equated with a direct ascent; thus, any carbon dioxide cylinders should be removed and replaced with exhausted ones to prevent accidental inflation of vests. A principle of cave diving is that safety lies in retracing the entry path by the use of lines and not by ascent, as in the normal open ocean diving.

Preferably no more than three divers should undertake a single dive, and on completion of the dive each should have a minimum of one third of the initial air supply. If there is water flow within the cave, and the penetration is with the flow, this reserve air supply may not be adequate because the air consumption is greater when returning against the current.

Vertical penetrations need a heavy shot line moored or buoyed at the surface and weighted or fixed at the bottom. The reel is used for horizontal penetrations, not vertical. Otherwise, entanglement is likely with rapid ascents, especially if divers precede the lead diver. Thin, non-floating lines especially cause entanglement if they are allowed to slacken.

Specialized cave diving training is a prerequisite for this diving environment.

Wreck diving

Wreck diving has potentially similar problems to some cave and ice diving. In addition, it has the hazards of instability of the structure and the dangers of unexploded ordnance, sharp objects, toxic cargo and fuel. Exhausted gas from scuba may cause air pockets and disrupt the wreck's stability.

Silt in wrecks is usually heavier than that in still water caves. Thus, the sudden loss of visibility that can occur when silt is stirred up may be less persistent. The diver should ascend as far as is safe and wait until the silt cloud settles down.

COLD/ICE DIVING

The obvious problems are those of cold and hypothermia. They are so obvious that most people will avoid them by the use of heating systems, drysuits or efficient wetsuits. See Chapters 27 and 28 for the effects of a cold environment on physiological performance.

A major difficulty with cold and ice diving is the tendency of many single hose regulators to freeze, usually in the free-flow position, after about 20 to 30 minutes of exposure to very cold water (less than 5°C). This situation is aggravated if there is water vapour (potential ice crystals) in the compressed air and if there is a rapid expansion of air, which produces further cooling in both first and second stages. The first stage or the second stage may then freeze internally.

Expansion of air as it passes from the high tank pressure to the lower pressure demand valve and then to environmental pressures (adiabatic expansion) results in a drop in temperature. It is therefore not advisable to purge regulators if exposed to very cold temperatures. The freezing from increased air flow follows exertion, hyperventilation or panic. Octopus rigs become more problematic to use under these conditions, or at great depth, because of this increased air flow. An emergency air source (pony bottle) has replaced buddy breathing and octopus rigs.

'External' ice is formed in and around the first (depth compensated) stage of the regulator, thus blocking the orifice and interfering with the spring. Moisture from the diver's breath or water in the exhalation chamber of the second stage may also freeze the demand mechanism, causing free flow of gas or 'internal' freezing with no flow.

Modifications designed to reduce freezing of the water in the first stage include the use of very dry air and the replacement of first-stage water-containing areas with silicone, oils or alcohols (which require lower temperatures to freeze) or with an air flow from the regulator. The newer, non-metallic second stages are less susceptible to freezing. Despite all this, regulator freezing is common in polar and ice diving. Surface supply with an emergency scuba, or twin tank–twin regulator diving, as with cave diving, is probably safer. It must be presumed in under-ice diving that the regulator will freeze and induce an out-of-air situation, and this must be planned for.

Under ice there is little use for snorkels, and so these should be removed to reduce the likelihood of snagging. Rubber suits can become sharp and brittle. Zippers are best avoided because they freeze and may also allow water and heat exchange. Buoyancy compensators should be small and with an independent air supply.

As a general rule, and if well-fitting drysuits are unavailable, the minimum thickness of the Neoprene should increase with decreased water temperatures, as in the following examples:

<5°C – 9-mm-thick wetsuit
<10°C – 7-mm-thick wetsuit
<20°C – 5-mm-thick wetsuit
<30°C – 3-mm-thick wetsuit

Hood, gloves and booties should be of a considerable thickness, or heat pads can be used. Heat pads must not be in contact with high-oxygen gases because overheating can result.

Unheated wetsuits do not give sufficient insulation at depth (beyond 18 metres) when the Neoprene becomes too compressed and loses much of its insulating ability. In that case, non-compressible wetsuits, inflatable drysuits or heated suits are required. In Antarctic diving, to gain greater duration, we had to employ a wetsuit or other thick clothing under a drysuit.

Ice diving is in many ways similar to cave diving. It is essential that direct contact must always be maintained with the entry-exit area. This should be by a heavy-duty line attached to the diver via a bowline knot. The line must also be securely fastened at the surface, as well as on the diver. The dive should be terminated as soon as there is a reduced gas supply or any suggestion of cold exposure with shivering, diminished manual dexterity and so forth.

The entry hole through the ice should be at least two divers wide. Allowing room for only one diver to enter ignores two facts. First, the hole tends to close over by freezing. Second, in an emergency two divers may need to exit simultaneously. There should be a surface tender with at least one standby diver. A bright light, hanging below the surface at the entry-exit hole, is also of value in identifying the opening. If large diving mammals contest the opening in the ice, they should be given right of way.

If the penetration under the ice is in excess of a distance equated with a breath-hold swim, then a back-up scuba system is a requirement, as with cave diving.

DEEP DIVING

'Divers do it deeper' represents a problem with ego trippers and a challenge to adventure seekers. Unfortunately, the competitive element sometimes overrides logic, and divers become enraptured, literally, with the desire to dive deeper. They then move into a dark, eerie world where colours do not penetrate, where small difficulties expand, where safety is farther away and where the leisure of recreational diving is replaced with an intense time urgency.

Beyond the 30-metre limit the effect of narcosis becomes obvious, at least to observers. The gas supply is more rapidly exhausted and the regulator is less efficient. Buoyancy, resulting from wetsuit compression, has become negative, with an inevitable reliance on problematic equipment, such as the buoyancy compensator. The reserve air supply does not last as long, and the buoyancy compensator inflation takes longer and uses more air. Emergency procedures, especially free and buoyant ascents, are more difficult. The decompression tables are less reliable, and ascent rates become more critical.

Overcoming some problems leads to unintended consequences. Heliox (helium-oxygen mixtures) reduces the narcosis of nitrogen, but at the expense of thermal stress, communication and altered decompression obligations. Inadequate gas supplies can be compensated by larger and heavier cylinders, or even by rebreathing equipment, but with many adverse sequelae (see Chapter 62).

Many of the older, independent instructors would qualify recreational divers only to 30 metres. Now, with instructor organizations seeking other ways of separating divers from their dollars, specialty courses may be devised to entice divers to 'go deep' before they have adequately mastered the shallows.

FRESH WATER DIVING

The main problem with fresh water is that it is not the medium in which most divers were trained. Thus, their buoyancy appreciation is distorted. Acceptable weights in sea water may be excessive in fresh water. Depth gauges are calibrated for sea water, and so they need to be corrected for diving in dams, lakes, quarries and so forth. Because these waters are often stationary, there may be dramatic thermoclines, requiring adjustments for thermal protection and buoyancy, as one descends.

There are also many organisms that are destroyed by sea water but that thrive in warm fresh water. Some of these, such as *Naegleria,* are fatal.

KELP DIVING

Kelp beds are the equivalent of underwater forests. Kelp can be useful in many ways to the diver. It allows a good estimate of clarity of the water by assessing the length of plant seen from the surface. The kelp blades indicate the direction of the prevailing current. In kelp beds there is usually an abundance of marine life, and the kelp offers other benefits such as dampening wave action both in the area and the adjacent beach. Kelp can be used as an anchor chain for people to use when they are equalizing their ears, as well as to attach other objects such as floats, diver's flags, surf mats, specimen bags and so forth.

Giant members of this large brown algae or seaweed may grow in clear water to depths of 30 metres. The growth is less in turbid or unclear water. Kelp usually grows on hard surfaces, e.g. a rocky bottom, a reef or, for more romantic divers, a Spanish galleon. It is of interest commercially because it is harvested to produce alginates, which are useful as thickening, suspending and emulsifying agents, as well as in stabilizing the froth on the diver's glass of beer (*après dive,* of course).

Kelp has caused many diving accidents, often with the diver totally bound up into a 'kelp ball' that becomes a coffin. The danger of entanglement is related to panic actions and/or increased speed and activity of the diver while in the kelp bed. Twisting and turning produce entanglement.

Divers who are accustomed to kelp diving usually take precautions to ensure that there is no equipment that can snag the strands of kelp; i.e. they tend to wear knives on the inside of the leg, tape the buckles on the fin straps, have snug quick-release buckles and not use lines. Divers descend vertically feet first to where the stems are thicker and there is less foliage to cause entanglement. The epitome of bad practice in kelp diving is to perform a head first roll or back roll because it tends to result in a 'kelp sandwich with a diver filling'.

The kelp is pushed away by divers as they slowly descend and ascend; i.e. they produce a clear area within the kelp, into which they then move. They ensure that they do not run out of air because this situation will produce more rapid activity. If they do become snagged, divers should avoid unnecessary hand and fin movements. Kelp can be separated either by the use of a knife or by bending it to 180 degrees, when it will often snap (this is more difficult to achieve while wearing gloves). It is unwise to cut kelp from the regulator with a knife without first clearly differentiating it from the regulator hose. Some divers have suggested biting the strands with one's teeth. This may be excellent as regards dietary supplementation, kelp being high in both B vitamins and iodine, but it does seem overly dramatic.

Kelp does float, and it can often be traversed on the surface by a very slow form of dog paddling or 'kelp crawl', in which one actually crawls along the surface of the water, over the kelp. This can be done only if the body and legs are kept flat on the surface, thus using the buoyancy of both the body and the kelp, and by using the palms of the hands to push the kelp below and behind as one proceeds forward. Any kicking that is performed must be very shallow and slow.

NIGHT DIVING

Because of the impaired visibility, extra care is needed for night diving. Emergency procedures are not as easy to perform without vision. There is a greater fear at night. For inexperienced divers it is advisable to remain close to the surface, the bottom or some object (e.g. anchor, lines). Free swimming mid-water and without objects to focus on causes apprehension to many divers.

Preferably the site should be familiar, at least in daylight, without excessive currents or water movements and with easy beach access – diving between the boat and the shore. On entry the diver sometimes encounters surface debris that was not obvious from the surface.

Any navigational aid needs to be independently lighted. This includes the boat, the exit, buoys, buddies and so forth. A chemoluminescent glow stick (Cyalume light) should be attached firmly to the tank valve, and at least two reliable torches should be carried. The snorkel should have a fluorescent tip. A compass is usually required. A whistle and a day-night distress flare are sometimes of great value in summoning the boat operator, who has not the same capabilities of detecting divers at night.

Marine creatures are sometimes more difficult to see. Accidents involving submerged stingrays and needle spine sea urchins are more likely.

Signals include a circular torch motion ('I am OK, how about you?') or rapid up and down movements ('something is wrong'). The light should never be shone at a diver's face because it blinds him or her momentarily. Traditional signals can be given by shining the light onto the signaling hand. Waving a light in an arc, on the surface, is a sign requesting pickup.

WATER MOVEMENTS

Because of the force of water movement, a diver can become a hostage to the sea.

White water

This water is white because of the foaming effect of air bubbles. This dramatically interferes with both visibility and buoyancy, as well as implying strong currents or turbulent surface conditions. A diver in white water is a diver in trouble. Under these conditions, the recommendation is usually to dive deeper.

Surge

The to-and-fro movement of water produces disorientation and panic in inexperienced divers, who often try to swim against it. Other divers use the surge by swimming with it, then hold onto rocks or corals when the surge moves in the opposite direction. This approach may be detrimental to the ecology, but good for survival.

Inlets and outlets

Occasionally, there is a continuous water flow, because of a **pressure gradient** through a restricted opening, which can siphon and hold (or even extrude) the diver. It is encountered in some *caves, blue holes* or *rock areas near surf* (an underwater 'blow hole'), in human-made structures such as the water inlets in *ships' hulls* and in outlets in *dams* and water cocks (taps). The pressure gradient may slowly draw the diver into its source and then seal him or her in, like a bath plug. Protection is by not occluding these inlets and by avoiding the area or covering it with a large grating.

Tidal currents

These currents are very important to the diver. If used correctly, they take the diver where he or she wants to go. Otherwise, they are likely to take the diver where he or she does not want to go. The latter event can be both embarrassing and terrifying, and it can also be very physically demanding.

Frequently, divers are lost at sea because of currents. Sometimes these currents can be vertical and cannot be combated by swimming or buoyancy. Certain popular diving areas, such as at Palau (especially Pelalu), Ras Muhammad, the Great Barrier Reef and Cozumel, are famous for their currents, and multiple fatalities are not uncommon.

Divers sometimes relate their successful swims against 4- to 5-knot currents. In fact, the average fast swim approximates 1.2 knots. For brief periods, it may be possible to reach up to 1.5 knots. The average swimmer can make very slow progress or none at all against a 1-knot current. A half-knot current is tolerable, but most divers experience this as a significant problem, and so it is. They tend to exaggerate the speed of the current as the hours go by, and especially during the *après-dive* euphoria (1 knot = approximately 2 km/hour).

Tidal currents are usually much faster on the surface than they are on the sea bed because of friction effects. A helpful observation is that the boat will usually face the current with its anchor upstream and the stern of the boat downstream. Any diver worth his or her salt knows that it is safer to swim against the current for the first half of the usable air and allow the current to bring the diver back to the boat for the second half of the dive. The '**half-tank rule**' is worked out by taking the initial pressure, say 200 ATA, subtract the 'reserve' pressure (the pressure needed to charge the regulator), say 40 ATA, i.e. 160 ATA, and divide this by 2, i.e. 80 ATA. Thus, for this example, 80 ATA is used on the outward trip, and then the return is made with ample air to allow for misadventure (e.g. navigational error).

Untrained divers tend to make unplanned dives. They submerge and 'just have a look around'. While they are having their look around they are being transported by the current, away from the boat, at a rate of 30 metres every minute in a 1-knot current. When they consider terminating the dive, after they have used most of their air, they have a very hard return swim against the current. They surface, because of their diminished air supply, well downstream from the boat and have to cope with a faster, surface current. This is a very difficult situation and far more hazardous, than that of the experienced diver who used the half-tank rule, who surfaced upstream from the boat and floated back to it, but who also had enough air to descend underwater and return with ease if desired or to rescue a companion.

The **lines** attached to the boat are of extreme importance when there are currents. First, there is the *anchor line,* and this is the recommended way to reach the sea bed upstream from the boat. The anchor chain should not be followed right down to the anchor because this may occasionally move if the boat moves, and it can cause damage to the adjacent divers. More than one diver has lost an eye from this 'freak accident'. How may the diver reach the anchor line? A line may be attached to the top of the anchor line, with the other end to the stern of the boat. It should have enough play in it to allow divers to sit on the side of the boat and to hold it with one hand – the hand nearest the bow of the boat – while using the other hand to keep the face mask and demand valve in place. On entry, the diver ensures that he or she does not let go the line. The diver then pulls himself or herself forward to the anchor line and descends.

Perhaps the most important line, if there is a current, is a *float line* or '*Jesus' line.* This line drags 100 metres or more behind the boat, in the direction of the current, and it has some floats to ensure that it is always visible to divers on the surface. It is often of value to have one diver on this line while the others are entering the water. The diver on the line virtually acts as a backstop to catch the odd stray diver who has not followed instructions and is now floating away with the current. The Jesus line is also of immense value at the end of the dive when divers have, incorrectly, exhausted their air supply or when they come to the surface for some other reason and find themselves behind the boat. This would not have happened had a dive plan been constructed and followed correctly. Occasionally, however, it does happen to the best divers, and it is of great solace to realize that the Jesus line is there and ready to save the sinner – irrespective of religious persuasion.

Even divers who surface only a short way behind the boat in a strong surface current may find that it is impossible to make headway without a Jesus line. If this is not available, they can descend and use their compass to navigate back to the anchor line or inflate the buoyancy compensator, attract the attention of the boat lookout and hope to be rescued.

Buddy breathing while swimming against a strong current is often impossible. Even the octopus (spare) regulator is problematic at depth or when two people are simultaneously demanding large volumes of air, typical of divers swimming against a current. An alternative air supply (a reserve or pony bottle) is of value, if it has an adequate capacity.

In dive planning, there should be at least one accessible fixed diving exit, easily identifiable, that serves as a safe haven. This may be an anchored boat, in areas with tidal currents. The safety boat is a second craft – not anchored – and this, like any boat that is driven among divers, needs a guard on its propeller. To attract the safety boat, various rescue options include the following:

- A towed buoy.
- An inflatable 2-metre-long bag, called the 'safety sausage', to attract attention.
- Pressure tested distress flare (smoke/light).
- Personal floatation devices.
- Personal electronic, sonic or luminous location devices.

Divers can now carry a personal location beacon or emergency position-indicating radio beacon (EPIRB), especially of value if diving in fast currents. These devices need to be pressure protected and are of value only once on the surface.

There are other problems with currents, and these are especially related to general boat safety and ensuring that there is a stable anchorage.

When the current is too strong or the depth or sea bed is not suited to an anchored boat, a float or **drift dive** may be planned. This requires extreme care in boat handling. Divers remain together and carry a float to inform the safety boat of their position. It allows the surface craft to maintain its position behind the divers as they drift.

The concept of 'hanging' an anchor, with divers drifting in the water near it and the boat being at the mercy of the elements, has little to commend it. The raising of the diver's flag under such conditions, although it may appease some local authorities, is often not recognized by the elements, reefs or other navigational hazards, including moored boats.

Some currents are continuous, e.g. the standing currents of the Gulf of Mexico, the Gulf Stream off Florida and the Torres Strait, but tidal currents are likely to give an hour or more of slack water with the change of tide. At these times diving is usually safer and more pleasant because the sediment settles and enhances visibility. To ascertain the correct time for slack water, reference has to be made to the tidal charts for that area. The speed of the current can be predicted by the tidal height.

Surf

Entry of a diver through the surf is loads of fun to an experienced surf diver. Otherwise, it can be a tumultuous moving experience and is a salutary reminder of the adage 'he who hesitates is lost'. The major problem is that people tend to delay their entry at about the line of the breaking surf. The diver, with all his or her equipment, is a far more vulnerable target for the wave's momentum than is any swimmer.

The warning given to surfers, referring to water colour, is that 'White is right but green is mean and blue is too'. This ensures that the surfer enters the surf and avoids rips. For the diver, it is the opposite. The diver may use the apparently calmer water to ride the rip into the ocean.

When the surf is unavoidable, the recommendation is that the diver should be fully equipped before entry and not re-adjust face masks and fins until he or she is well through the surf line. The fins and face mask must be firmly attached beforehand because it is very easy to lose equipment in the surf. The diver walks backward into the surf while looking over his or her shoulder at the breakers and also toward a buddy. The face mask and snorkel have to be held on during the exposure to breaking waves. The regulator must be attached firmly to the jacket, with a clip, so that it is easily recoverable at all times.

When a wave does break, the standing diver presents the smallest possible surface area to it; i.e. he or she braces against the wave, sideways, with feet well separated, and he or she crouches and leans, shoulder forward, into the wave. As soon as possible, the diver submerges and swims (in preference to walking) through the wave area. If the diver has a float, then this is towed behind. It should never be placed between the diver and the wave.

Exit should be based on the same principle as entry, except then the surf is of value. The wave may be used to speed the exit by swimming immediately behind it or after it has broken. The float then goes in front of the diver and is carried by the wave.

FURTHER READING

Australian Antarctic (ANARE) Diving Manual, Australian Antarctic Division, Kingston, Tasmania, Current edition.

British Sub-Aqua Club Diving Manual. ISBN: 9781905492220. Hutchinson, U.K. Current edition.

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Exley S. *Basic Cave Diving.* Jacksonville, Florida: National Speleological Society; 1981.

National Oceanographic and Atmospheric Administration. *NOAA Diving Manual.* 5th ed. Washington, DC: US Government Printing Office; 2013.

Royal Australian Navy Diving Manual, ABR 155. Dept of Defence, Royal Australian Navy, Canberra, ACT, Australia Current edition.

US Navy Diving Manual Revision 6 SS521-AG-PRO-010 (2008). Washington, DC: Naval Sea Systems Command; 2008.

This chapter was reviewed for this fifth edition by Carl Edmonds.

PART 2

Dysbaric Diseases: Barotraumas