10.2 Decompression Practice

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DECOMPRESSION CONCEPTS AND TERMS

Decompression practice is simply developing and implementing decompression procedures for operational diving with the goal of avoiding decompression sickness (DCS). Operationally useful procedures take into account not only the decompression procedure required to avoid DCS but also factors such as the time required for decompression, the number of different breathing gases required, the complexity of the ascent profile, and other factors which may make the procedure too complicated for routine use. In addition to diving some other situations require decompression; several of these are covered also.

CONCEPT OF DECOMPRESSION

Because some jargon is involved, it is first necessary to clarify the meaning of the word 'decompression' as used in the context of this book. 'Decompression' in the engineering sense means any reduction of pressure. As used in reference to diving or compressed air work or some of the other situations covered here, 'decompression' means reduction of pressure in a specific and planned way. Thus when 'decompression' is required or a diver has to 'decompress,' it means in a controlled way. A 'decompression obligation' means it is not acceptable for the individual to have the pressure reduced abruptly. In diving practice 'abruptly' might mean ascending at a rate exceeding 10–20 msw (30–60 fsw) per minute. Dives that allow direct ascent to the surface at such rates are called *no-stop* or *no-decompression dives*, while dives that incur a decompression obligation require either a much slower ascent rate or require decompression stops during ascent.

TERMS

Although many are covered elsewhere in this book and later in this chapter, some of the more important terms and concepts used in this chapter are referenced here as they are used in this community. The changes in pressure or depth and breathing gas as a function of time during a dive and its decompression constitute the *dive profile*. Ascent from a dive is a reduction of pressure, and the profile to be followed is contained in a *decompression schedule*. A set of decompression schedules organized in some systematic way, such as by depth and time, is called a *decompression table*. However, in common usage the term *table* is used interchangeably with *schedule*, and may refer to a single profile or a set of profiles. Proper decompression is carried out by ascending slowly, with the ascent pattern or constraints on ascent carried out by following such a decompression schedule. This schedule may have been based only on past experience, or may have been prepared mathematically by a decompression computational algorithm or model. Decompression tables are usually based entirely or at least primarily on the inert gases (normally nitrogen or helium) in the diver's breathing mixture, with consideration for the oxygen in some cases.

Ascent may be continuous or in stages or stops. In *continuous decompression*, sometimes called *linear*, ascent is performed continuously at some specified rate, although that rate may change. *Stage* or *staged decompression* means that ascent is fairly rapid until a specified *stop depth* is reached, at which point ascent is halted for a period of time called the *stop time* until ascent to the next stop depth is begun. The time from leaving bottom depth and beginning decompression until reaching the surface is called the *total decompression time*. The time from leaving the surface, descending to depth and leaving depth to begin decompression is the standard definition of *bottom time*, but there are variations on this. The time actually spent at depth disregarding the descent time is the *working time*. Note that the classical bottom time is the sum of the descent time and working time. As the bottom time increases the decompression time will increase asymptotically up to some maximum time. This maximum time occurs when the divers tissues are in complete equilibrium with the ambient gas partial pressures, a condition known as *saturation*. In saturation, additional bottom time does not require more decompression time. Saturation diving techniques are useful when a job may require many days or weeks to complete.

A *repetitive dive* is any dive where a preceding dive must be taken into account to determine the proper decompression table. The time spent at the surface between repetitive dives is called the *surface interval*.

We refer to disorders that may result from improper decompression as *decompression sickness*, or DCS. DCS is thought to arise from gas phase separation in body tissues resulting in bubble formation, which cause symptoms either by blocking blood supply, by causing damage from direct mechanical effects, or by later biochemical actions. *Arterial gas embolism* (AGE) is a condition that occurs usually when lung tissue ruptures during ascent allowing gas bubbles to enter the arterial circulation, forming emboli that generally target the brain; other conditions may also cause arterial bubbles. The term *decompression illness* (DCI) refers to any disease that can occur during decompression and includes both DCS, AGE, and other gas-related forms of barotrauma of ascent. While DCS seems to be a function of inert gas taken up by tissue during a dive, AGE is not necessarily associated with an increased *gas loading*.

It is important to remember that DCS is a probabilistic event and it has a chance of occurring on nearly any dive, although that probability may be very small (Weathersby et al 1984). This not only means that DCS may occur, no matter what decompression procedure is used, but that the occurrence of only a few cases may (because of the binomial distribution – DCS either occurs or it does not) tell us little or nothing about the true incidence of DCS on that profile.

Today we talk of the *risk* of DCS from a given dive-decompression table combination and expect that the higher the risk of DCS, the more cases we would expect to see. However, deciding which of two dive-decompression table combinations has the higher risk may not be obvious from simple inspection because factors other than the decompression time may bear on the actual risk. There are, however, mathematical methods for estimating risk that can take into account most aspects of a dive profile. Because there is nearly always some risk of DCS, we refrain from using the term 'safe' to describe a decompression profile.

In the past the term *missed decompression* (or *omitted decompression*) was used to describe incidents in which a diver ascended in less time than called for by the decompression table. Rules were set out to describe emergency procedures to be used when this happened. If DCS occurred as a result of missed decompression, it was said to be *deserved DCS*. If DCS occurred after following the prescribed decompression table it was said to be *undeserved DCS*. Today these latter terms have little relevance because there are decompression tables and decompression computers in use that give decompression schedules of varying decompression times for the same dive. This is not to say, however, that missed decompression does not have to be made up in some way.

One cannot discuss decompression without occasional reference to the 'patron saint' of this technology, John Scott Haldane, who provided a scientific basis for computing decompression tables. He used a differential equation describing exponential uptake and elimination of gas. Haldane visualized the body as being made up of several *compartments* whose gas kinetics are essentially exponential, each with a different time constant. The compartments, also called *tissues*, are not specific anatomical entities but they do exchange gas at different rates, some rapidly, some more slowly. Haldane ascribed an empirical maximum supersaturation ratio to each compartment, and theorized that so long as this maximum ratio was never exceeded, DCS would not occur. He used exponential kinetics (see Ch. 10.1) to calculate how much gas was taken up while the diver was at depth, and how fast it was eliminated during decompression. Ascent was allowed to the point where one of the compartments was just at its maximum *supersaturation ratio* and then a stop was taken of sufficient duration such that all compartments had eliminated enough gas so that ascent to the next shallower stop was allowed with no compartment exceeding its maximum ratio. This was continued until the surface was reached (Boycott et al 1908). This process of ascending and then waiting for inert gas values to clear is known as stage decompression.

Haldane's concept was embellished by Workman (1965) who replaced the maximum supersaturation ratio with a depth-dependent set of empirically determined maximum tolerated partial pressures called *M*- (maximum) *values*. Decompression tables based on exponential uptake and elimination of gas along with some constraint on the maximum inert gas partial pressure allowed at each stop depth are called *Haldanian*. The term *neo-Haldanian* is sometimes used for decompression profiles that incorporate some aspects of Haldanian tables but not all. Almost all decompression tables in current use are Haldanian. One exception are the British Royal Navy Tables which used equations describing gas diffusion kinetics for uptake in slabs (Hempleman 1969).

UNITS

Diving depths are expressed as units of length, meters and feet, but the concern here is really pressure, which takes the specific gravity of seawater into account. Since salt water specific gravity depends on salinity it is not the same throughout the world's oceans and therefore must be defined. *The US Navy (USN) Diving Manual* (US Dept of the Navy 1999) assigns a specific gravity of 1.02480 or a density of 64 lbs/ft^3 to sea water. A depth of 1 foot of seawater (fsw) is thus defined such that 33.066 fsw equals 1 atm. This is commonly rounded off to 33.00 fsw/atm. In Europe the meter of seawater (msw) is defined such that 10 meters of seawater (10 msw) is exactly equal to a pressure of 1.0 bar (100 kPa), giving a specific gravity of seawater of 1.01972. This means that converting from msw to fsw is not simply a matter of converting meters to feet. Using 33.066 fsw/atm the conversion is 3.2633 fsw/msw, and for 33.0 fsw/atm the conversion is 3.2568 fsw/msw. In this chapter units are given in the primary unit of the source; conversions to and from SI/metric units may be approximate when the original value refers to a range or is categorical.

GENERAL PRINCIPLES OF DECOMPRESSION

Given the above definitions, a general understanding of how decompression tables are derived is needed next. When a person is exposed to pressures above atmospheric the body takes up additional dissolved gas. How much additional gas – the gas loading or gas burden – depends on the depth or pressure of the exposure, the duration, and the breathing gas. On decompressing, the gas can theoretically be transported to the lungs in solution and leave the body without forming bubbles if the decompression is slow enough.

If the decompression is too rapid, current theories predict that gas will come out of solution and form bubbles in body tissues. Using precordial (on the chest) Doppler ultrasound instruments, gas bubbles can be heard entering the right heart from the venous circulation, even after decompressions regarded as benign (Dunford et al 1993), and in experimental animals bubbles are seen in tissues harvested from those suffering from DCS (Francis et al 1990). These and other findings suggest, although in the minds of some do not prove, that DCS occurs as a result of bubble formation (see Ch. 10.1). At any rate, no matter what the ultimate cause, the object of designing a proper decompression procedure is to avoid DCS; whether or not this involves avoiding bubble formation altogether or by keeping the amount of bubble formation at or below a tolerable level is still a subject for debate.

Decompression procedures may be empirical, mathematical, or mechanistic (or a combination). An empirical procedure is based on some sort of past experience. Empirical procedures are generally not linked, and changing one does not necessarily lead to or require changing others in a set. Some procedures used by the early tunnel workers (Morita et al 1979) and by native fishermen all over the world (Lepawsky & Wong 2001) fall into this category. A mathematical procedure is one where there is a standardized method of computing decompression tables, and if the method is changed a recomputation changes all the schedules in a set. Mathematical procedures do not necessarily describe a physiologically plausible mechanism although that may have been the original intent. Most decompression procedures developed since Haldane fall in this category. Mechanistic procedures are based on mathematical descriptions of the actual physiologic and biochemical events which are thought to take place during decompression and where model parameter values have physiologically plausible values. While many decompression models start out as mechanistic, they usually end up as mathematical because physiologically implausible parameter values may be required to compute operationally useful procedures. Although they differ from the purely empirical procedures, the useful mathematical procedures uniformly have an empirical basis; that is, they are ultimately based on experience.

Another basic tenet of decompression is that oxygen does not significantly contribute to the gas burden. Rather, breathing a gas mix with a higher P_{O_2} than called for by the decompression schedule is assumed to lower the risk of DCS. Conversely, for a given level of DCS risk, the higher the P_{O_2} breathed, the shorter the decompression. The rationale here is based on the fact that oxygen is metabolized, resulting in undersaturation of tissue, a phenomenon called the oxygen window (Behnke 1967). This is discussed in Chapter 10.1 and is dealt with in more detail below. This is the basis for allowing one to use air decompression tables on dives where higher oxygen fractions are breathed using O_2–N_2

mixes by considering only the nitrogen partial pressure, the so called *equivalent air depth* (EAD) procedure. This is discussed in more detail later.

This situation makes it advantageous to maximize the oxygen in decompression breathing gases, but this has to be tempered by taking account of the toxicity of oxygen (also covered below and in Ch. 9.4). Oxygen tolerance becomes a major component of sophisticated decompression planning.

PATTERNS OF DECOMPRESSION

Consider the role of diving equipment on the patterns shown in Fig. 10.2.1. For the most part, the equipment and the dive pattern tend to go together. The patterns identified here are covered in more detail below.

Some categories of diving are covered in Chapter 2. These are classified as commercial, recreational, scientific, and military diving. Military divers often use tethered equipment and procedures essentially the same as commercial diving, but a great deal of military diving activity is also done with self-contained apparatus – that is, untethered, with no hose. Much of this is done with *rebreathers*, but military divers also do a lot of diving with scuba (see Ch. 2), whereas this equipment is rarely used in commercial diving. Of course scuba is the main mode of recreational diving, but rebreathers are becoming popular in that community also. Scientific divers for the most part use the same techniques and equipment – principally scuba – as recreational divers, but because their objectives are different they generally have more rigorous organization, training, and responsibility. In recent years new techniques have been developed for diving to depths well beyond the traditional limits of recreational diving; these methods, known collectively as 'technical diving,' involve a great deal more equipment, training, and sophistication in decompression techniques.

Open Circuit Scuba: No-stop Dives

The traditional pattern for recreational diving is with open circuit scuba. This also applies to most scientific diving and some military diving, but scuba is rarely used in commercial diving. The overwhelming proportion of scuba dives are no-stop or no-decompression dives, dives for which direct ascent to the surface is allowed at some relatively rapid rate without the requirement to take decompression stops. In some current decompression models the decompression accomplished during the actual ascent is taken into account, so the no-stop times are applicable only with a specified maximum ascent rate.

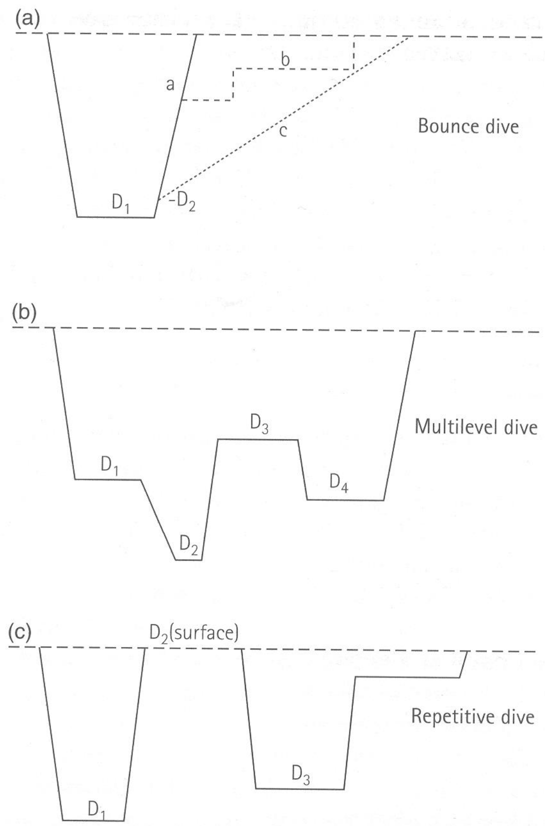

Fig. 10.2.1 Types of dives. The top depth/time profile (depth on the vertical axis, against time, units optional) shows a typical bounce dive, where the diver descends to depth D_1 and remains there until beginning decompression. If the dive is a no-stop or no-decompression dive a path similar to trace (a) may be used, directly to the surface. For longer working times, in which case the procedure calls for decompression, a profile similar to trace (b) might be used if the procedure calls for stage decompression; two decompression stops are shown. If the procedure calls for continuous decompression the diver might follow a path similar to trace (c). This shows a small rapid ascent to some depth D_2 followed by slow ascent to the surface, a pattern typical of saturation decompression. The center profile shows a multilevel dive where the diver spends time at several depths, D_1, D_2, D_3, and D_4 before ascending to the surface, in this case using a no-decompression profile after the last depth. The bottom profile shows that after ascent from the first dive the diver spends some time at the surface, D_2, which may be minutes or hours. If the diver then does another dive to D_3, this is a repetitive dive, which calls for a decompression procedure that takes the first dive into account; a single decompression stop is shown in this example. The bottom profile (c) can also illustrate a surface decompression dive, in which case the time at the surface, D_2, is very short, 3–7 min being typical. The remainder of the profile is performed in a recompression chamber, perhaps at two pressures as shown here, or only one. The depths, times, and gases (usually oxygen, for surface decompression (sur-d)/O_2) of the chamber stops are all prescribed by the decompression procedure in use.

Surface-Supplied Equipment: Bounce Dives With In-water Decompression

A *bounce dive* or *square dive* is one involving descent to some depth which remains or is considered to be essentially constant until the final ascent to the surface; the ascent may include required decompression stops. The term 'bounce' is also used by some to specify a 'spike' type dive with no appreciable bottom time at all. During ascent, stops are taken at depths and times required by the decompression schedule. In surface-supplied diving descent and ascent are usually managed by having the diver ride a 'stage' or partially dry 'open bell,' which is raised or lowered by a crane from the diving vessel to provide precise depth control during decompression. Alternatively, the diver may hang on a line held to the bottom by a weight (ascent/descent line), or in deeper water on a weighted line that does not reach the bottom (lazy shot).

Dry Chamber Decompression

There are three specific patterns in which the diver completes the decompression in a dry pressure chamber: surface decompression, deep bell diving, and saturation diving.

Surface Decompression: Sur-d

Sur-d is designed to minimize the amount of decompression time in the water by allowing some of the decompression to be done in a dry decompression chamber. This is the pattern of choice for most commercial dives since getting the diver out of the water sooner minimizes thermal problems as well as in-water depth control problems. In this pattern the in-water stops may be much shorter than those required when decompression is all done in the water. Alternatively, in some procedures the diver may surface directly from the bottom. Immediately after surfacing, the diver has the helmet removed and gets into a deck decompression chamber (DDC) for the remainder of the decompression. The amount of time allotted between reaching the surface and recompressing in the chamber is usually quite short, 3 to 7 min. The chamber is recompressed to the pressure (depth) of the first chamber stop and then the chamber portion of the procedure is followed to the surface. Procedures are available to allow air breathing in the chamber, but in almost all current sur-d diving 100% O_2 is breathed in the chamber – usually in cycles alternating with chamber air to decrease the risk of oxygen poisoning – because these sur-d/O_2 decompressions are not only shorter, they also appear to have a lower incidence of DCS then when air is used.

Bell Diving With a Deep Diving System

In this pattern, divers are sealed in the bell component of a deep diving system and lowered to working depth with the bell still at atmospheric pressure. When things are ready the bell is pressurized to working depth, the hatch is opened, and the working diver locks out for work. The bellman acts as tender for the working diver. When work is complete the diver returns to the bell, the bell is sealed and then hoisted. Decompression proceeds in the bell, and the divers transfer under pressure to the deck chamber. Decompression is completed in the chamber.

Repetitive, Yo-yo, and Multilevel Diving

A repetitive or 'repet' dive is begun after spending some time at surface pressure after a previous dive, and the previous dive profile must be taken into account in determining the required decompression. The longer the surface interval, the less impact the previous dive has, and eventually enough time is spent at the surface that it has no impact. At this point the diver is said to be 'clean' and his next dive will not be a repetitive dive. Not equipment specific, repetitive dives may use scuba or surface supplied equipment. Repetitive dives are widely practiced in recreational diving, much less so in commercial and military diving.

Yo-yo dives are several short repetitive dives with very short surface intervals. This type of diving is seen in certain aquatic industries such as fish farming where typically a diver might require 10 or 15 min at some relatively shallow depth followed by 5 or 10 min at the surface, repeated successively many times, perhaps for hours. In yo-yo diving it is often the case that the total time spent at depth, summing all times throughout the day, is less than the no-decompression limit. However, it is felt by some that in spite of this the sequence of multiple ascents and descents puts the diver at a higher risk of DCS than if the same cumulative time were spent on a single bounce dive. This risk is not handled well by most models. In fact, DCS has been reported on a series of such dives under circumstances that would be 'acceptable' by most dive computers (Douglas & Milne 1991).

A *multilevel dive* is one with significant portions of the work time or bottom time spent at different depths. It has been the lore of scuba diving that in multilevel diving the deeper portion of the dive should take place first and subsequent portions should be to progressively shallower depths; whatever the risk, this is always the most efficient way to do it. If the shallower portions are done first it is known as a reverse dive profile, and this has been thought to result in a higher risk of DCS. However, a recent workshop on this subject produced no definitive evidence that reverse profiles are any riskier than any others, and offered recommendations (Lang & Lehner 2000).

Multiday diving occurs when several dives are done on successive days. Some decompression models would consider such dives as repetitive while others would not. In any case, some experts feel that doing multiday diving for 3 days or more continuously may increase the risk of DCS on subsequent dives no matter what the decompression model predicts (Marroni 1995).

Rebreathers

Rebreathers, both closed and semiclosed, represent another distinct hardware system that may be used with any of the patterns described, or may use procedures unique to rebreathers. These are dealt with in their own part of the mixed gas section.

Saturation and Saturation-excursion Diving

Saturation diving occurs when the divers have been at depth long enough that their tissues are in equilibrium with the breathing gas, a point where additional time at depth has no effect on the required decompression. Saturation decompression tables are very long, approximating 1 day of decompression for each 30 msw (100 fsw) of depth for USN and common commercial heliox procedures. (US Department of the Navy 1981 and others). Saturation diving is used for jobs requiring many hours or days, and offers decompression efficiency in those cases. Saturation diving requires complex and expensive equipment and specialized training.

Yet another pattern based on saturation is *saturation-excursion diving*. This involves saturating a dive team at a given *storage depth* and having them excurse to the working depth for the work, which may be below or above the storage depth.

NON-DIVING APPLICATIONS REQUIRING DECOMPRESSION

The preceding section of this chapter discusses decompression terms and patterns used in diving. Here we discuss other endeavors where decompression is required.

TUNNEL AND CAISSON WORK: DECOMPRESSION AFTER COMPRESSED AIR EXPOSURES

The earliest problems with decompression were first seen in caisson and tunnel work with compressed air (see also Ch. 2). Until recently a complex tunnel or caisson job might involve more than 100 000 individual exposures to pressure (Hempleman 1982). Because of its early history of taking a devastating toll on human life and well-being, compressed air work became and continues to be highly regulated, and many of the decompression procedures are legislated. Unfortunately the regulations have not kept up with decompression technology, and workers are still being given inadequate decompressions when they follow the legislated procedures. In addition, there is some reluctance by the compressed air community to adopt practices found beneficial in diving, such as breathing 100% oxygen during decompression (Faesecke et al 2001, Kindwall 1997).

Compressed air exposures are generally longer (4 to 8 h) and at lower pressures (2–4 atm abs; 200–400 kPa abs) than dives, but the procedures allow less decompression time than would diving procedures for similar exposures. DCS in caisson workers is statistically associated with aseptic bone necrosis (Davidson 1976, Ohta & Matsunaga 1974, Zhang et al 1991) (see also Ch. 11.2).

One solution to the problem of decreasing morbidity from DCS without unduly increasing decompression time is 100% oxygen breathing, as amply shown in diving. Oxygen breathing has been used in Germany during decompression from pressures in excess of 4 atm abs (30 msw; 100 fsw; 400 kPa abs, Faesecke et al 1990). The incidence of DCS was 0.6% in 3400 exposures.

Still another approach has been used in a caisson for unusually high exposure pressures where narcosis becomes a problem. Although trimix diving has been around for some time, a project in Japan borrowed a technique from extended range recreational ('technical') diving of using a 'trimix' of oxygen, helium, and nitrogen to reduce narcosis (Kobayashi et al 1995). Workers breathed the trimix by mask, with the gas supplied by hose.

OTHER DECOMPRESSION APPLICATIONS

Several activities outside of diving and compressed air work call for a need for planned decompression. These include medical applications, exposures related to aviation and space travel, and various other excursions to pressure required in industry.

Hyperbaric Medicine

Clinical Hyperbaric Oxygen Therapy (HBO_2T) consists of pressurizing the patient to a pressure of 1.5 to as much as 3.0 atm (150–300 kPa) while the patient is breathing 100% oxygen. A major use of HBO_2 is as a primary treatment for DCI. Clinical HBO_2 is also widely used to treat other conditions, including carbon monoxide poisoning, gangrene, radiation-induced tissue damage, osteomyelitis, and skin flaps constructed during plastic surgery which have a compromised blood supply, to name a few.

While treatment of DCI requires following a specific depth/time/oxygen profile called a *treatment table*, patients undergoing clinical HBO_2 therapy do not usually require decompression because they breathe oxygen when in the chamber and thus do not pick up enough of a gas burden to require decompression. On the other hand, attendants breathe the chamber atmosphere in the air-filled chambers and are often exposed to compressed air long enough to need proper decompression. This is usually accomplished by having the tenders breathe 100% oxygen during the final part of the pressure reduction.

Aviation, Space, and Altitude

High altitude flying and space travel subject the aircrew and astronauts to reduced pressure. Just making the transition to some of these lower pressures may itself be a significant decompression and require special procedures. Sometimes those exposed to reduced pressures – e.g. aircrew members or individuals in altitude simulation chambers – may get DCS in the process, and in some cases this does not resolve on return to sea level and the affected individual may then require recompression treatment in a chamber just like divers with DCS. Techniques for avoiding DCS with these decompressions include 'prebreathing' of oxygen to 'denitrogenate' the body, or to use staged reduction of pressure, or both.

Also, diving at altitude, such as in a mountain lake, requires special procedures similar to and derived from those for conventional diving at sea level. Further, divers or others exposed to pressure who then go to altitude soon afterwards are especially vulnerable to getting DCS. Special procedures for ascent to altitude, diving at altitude, and flying after diving are discussed below.

Industrial Excursions to Pressure

A few other situations in industry require pressure exposures sufficient to require decompression. One such environment is the internal pressure testing of the containment vessel of a nuclear power station or a nuclear submarine. During these tests, the interior pressure is raised to about 1.5–2.0 atm abs (150–200 kPa abs). Workers performing tests inside these structures may be exposed for many hours, such that some sort of decompression is required. Some industrial processes have equipment in vessels that may be at pressure appreciably higher or lower than sea level, and these may cause people to be subjected to pressure either intentionally or inadvertently (Kolesari & Kindwall 1982). One food processing chamber has employees working at 18 psig (221 kPa abs) for shifts of several hours in duration, and this requires decompression procedures to be used (Milleville 1964).

Submarines

Submarines normally maintain internal pressure at or near 1 atm, but if there is an accident in which the submarine becomes disabled and is sitting on the sea floor, the interior may be pressurized up to several atm and still allow prolonged survival of crew members. Depending on the time course, this is likely to leave the crew in serious need of a careful decompression plan if they are to be returned to surface pressure during a rescue attempt (Harvey et al 1992). In an effort to accelerate the decompression from such a situation the USN has conducted decompressions from simulated long duration exposures. These have led to a serendipitous finding that using oxygen breathing to hasten decompression works much better if the oxygen is breathed before any appreciable pressure reduction has been made (Latson et al 2000).

Also, it is possible to reduce the fire hazard in a submarine's atmosphere by reducing the oxygen fraction to around 17% but maintaining its partial pressure at 0.21 atm by increasing the overall pressure (Knight et al 1990).

MODELS TO TABLES: IMPLEMENTING DECOMPRESSION ALGORITHMS

DECOMPRESSION TABLES

The various modes of diving, compressed air work, and industrial and medical pressure exposures have the common trait that they all can require a planned or programed reduction of pressure – decompression – in order to return the personnel to sea level or some other lower destination pressure without incident or injury. This section covers the mechanisms for implementing these decompressions. Normally the system that caused the pressure increase in the first place is accompanied in some way with a method of reducing pressure in a controlled way. This could be by ascending in the water, or bleeding or venting pressure from a chamber or the like, according to some specified time course. The issue, then, is what pressure and breathing gas profile – as a function of time – one should follow.

Concept of a Table

Like the word decompression, the word 'table' or 'decompression table' has a special meaning. A table – or more properly a schedule – is a listing, usually in tabular format, of the specified ascent pattern for a particular pressure exposure. A table may also be an array of schedules that applies to a set of exposures. A schedule is usually presented in terms of breathing gases, pressures, and ascent (i.e. depressurization) rates as a function of time. A table may specify more (or less) than breathing gas and ascent rates (rates of pressure reduction), but these parameters are the ones traditionally used, mainly because they are the most obvious and have the biggest influence on the quality of the decompression. Diving jargon is dominant in discussions like this one, albeit paradoxical; for example, 'ascent' is often used to specify a reduction of pressure in a chamber.

Table Types

Most diving decompression tables use 'stage' decompression, whereby the decompression is divided into stages or 'stops,' and a schedule mainly consists of a listing of the stop depths and times and their respective breathing gases, with ascent rates for travel to and between stops (Fig. 10.2.1). The idea of decompression tables can be attributed to JS Haldane (Boycott et al 1908), and the basic concept has not changed. A different approach at about the same time was advocated by Leonard Hill (1912; Vallantine 2000), reflecting the practice of decompressing compressed air workers by a series of linear rates of depressurization. Even today there is no general agreement as to whether either of these is better from a physiologic perspective, but managing a diver's ascent in the water is much easier operationally if done in stages, and this tends to influence the format of tables. Chambers, locks, caissons, or tunnels can be decompressed in stages also, or gradually in a profile that might be linear or follow some other path; this is standard practice for decompressing from long 'saturation' exposures.

Haldane's tables led to the format used by the various navy tables and these were followed by many others. It is interesting to note how the configuration of tables and their implementation affects the theory. For example, Lanphier (1990) reflects that the 18 msw/min (60 fsw/min) ascent rate was a convenient compromise between staging for hard hat divers (who wanted slow ascent) and direct ascent for underwater swimmers (who wanted fast ascent), by a navy that wanted uniformity.

It is the nature of tables that they come in groups. These are usually grouped with several bottom times for each one of a series of depths. Actual dives will not usually fall exactly on the depths and times given for a table group, so the table is used in a conservative way such that the schedule for the next deeper depth or next longer time is used. This of course tends to make the overall reliability of a set of tables more conservative.

Another type of 'table' deals with repetitive dives. As mentioned above, a subsequent dive is affected by a previous one. The usual method of dealing with this is by means of a chart or other display device that provides modifications to the subsequent dive, often by referring to a different schedule in the same table set.

'Flat' Tables

It is worth pointing out that the presentation of the basic schedules and tables is in tabular form in manuals, on pages, or on plastic sheets. These are often referred to as 'flat tables' in contrast to the display of a dive computer or computational program, or a 'wheel' or slide rule type calculator.

HOW MODELS ARE USED TO COMPUTE TABLES

If the biophysical and biochemical processes leading to DCS were well known and could be described mathematically then one could, in principle, compute the one and only correct decompression schedule for a given dive, given the depth-time-gas profile up to the beginning of decompression. That this is far from the case is evidenced by the multitude of decompression models given in the previous chapter (Ch. 10.1) and the wide variety of decompression tables in use throughout the world. That is not to say that decompression models are not without value, one just has to be careful not to forget the assumptions used in constructing the model before accepting its predictions as 'accurate' or 'safe.' While initially computed by some mathematical model, operationally useful decompression tables are modified based on the results of formal testing and/or field experience with the goal of reducing the incidence of DCS to some acceptable level, depending on the application. Commercial diving companies will usually strive for a very low DCS incidence, because the cost of potential litigation from divers suffering DCS is perceived to be greater than the cost of spending extra time decompressing. The military, on the other hand, may want to minimize decompression time and therefore accept a higher incidence of DCS according to mission requirements. Further, it is assumed that if DCS does occur it can be treated successfully.

In computing the USN Standard Air Tables, which are still in current use, USN investigators had to make a number of assumptions and compromises. They started with a six-compartment Haldanian model, and simplified it by assuming that all gas was inert; that is, the oxygen was included with the nitrogen in air. Decompression was regulated by a set of permissible 'tissue ratios,' which were a function of depth as described by an empirical 10th power relationship computed using a Univac computer (see Ch. 10.1). Initially some 88 single-dive schedules were tested with 483 man-dives. During subsequent phases the tissue ratios were changed by manipulating the tissue ratio vs depth function. A schedule was considered reliable or 'safe' once no DCS occurred in four to six man-dives, and such schedules were not retested. As schedules were modified, they were recomputed, again using some computational compromises. One was that only the schedules producing DCS were recomputed. The other was that once the tissue ratio was computed at the first stop it was kept constant until the final stop where the surfacing ratio (which controlled the no-stop limits) was used. Having to compute the tissue ratio only once saved considerable time because it was computed by a relatively slow iterative process. After testing was completed, the tables were recomputed based on the final form of the tissue ratio to depth relationship.

In developing the more recent 0.7 atm constant-P_{O_2}-in-N_2 decompression tables a similar process was used (Thalmann 1984, Thalmann et al 1980). In this case, instead of having to solve an equation to get tissue ratios, a table of maximum permissible tissue tensions (MPTTs) or *M*-values was constructed for each 6 msw (19 fsw) increment stop depth. The MPTTs for the last stop were chosen to give a set of no-decompression limits that were felt to be safe based on previous experience. Initially, gas kinetics were Haldanian and exponential during both uptake and off-gassing. Single-dive schedules, repetitive diving tables, and multilevel diving tables were tested in real time. That is, the decompression model was cast as a real-time algorithm that continuously monitored chamber depth and continuously updated the decompression schedule based on the actual depth-time profile up to that moment. As testing progressed, the table of MPTTs was changed to lengthen profiles that had resulted in an unacceptable level of DCS, while having minimal impact on acceptable profiles. However, a point was soon reached where further lengthening of unsafe profiles was not possible without shortening the no-decompression limits, which themselves were considered acceptable. The solution was to change the decompression model so that kinetics changed from exponential to linear during off-gassing, resulting in the so called linear-exponential (LE) model (see Ch. 10.1, Thalmann 1984). This had the result of introducing an asymmetry into the model which resulted in prolonging decompression times without affecting no-decompression limits (which depended only on gas uptake). At the completion of manned testing, involving some 673 man-dives, a final set of MPTTs was constructed that encompassed all the acceptable dives. This algorithm (Mk 15/16 Real Time Algorithm or VVAL-18) was then used to compute a set of air decompression tables and was also later programed into a diver-carried decompression computer (Butler 2001).

Both the efforts described above were similar in that the model parameter values at the start of testing were changed based on experience to produce a set of 'safe' decompression tables. The method of parameter manipulation was based on the judgment and experience of the investigators, as was the concept of what constituted a 'safe' table. No formal mathematical procedures were used to improve the model 'fit.' One disadvantage to this approach is that large numbers of replicated dive profiles are required in order to determine what is acceptable and what is not. In the original trials of the standard air tables only three to four man-dives was considered sufficient to make this judgment, while in testing the 0.7 atm-constant P_{O_2}-in-N_2 tables, 25 to 30 dives were usually done on each profile. If a dive profile deviated even slightly from what the algorithm computed, there was no way to tell how that would impact DCS incidence.

More recently probabilistic decompression models have been developed that circumvent many of these problems. These are covered in detail in the previous chapter (Ch. 10.1) and are only briefly reviewed here. These types of models require postulating a mathematical risk function whose time integral is used to compute a probability of DCS occurring. These risk functions have several adjustable parameters whose values are determined by 'fitting' the model to a database of actual dives where the outcomes (DCS or no DCS) are known. The fitting algorithm determines an optimal set of parameter values such that the model does the best job it can of predicting the observed outcomes, that is, DCS or no DCS. The database does not have to contain large numbers of replicated profiles; profiles that have only a few exposures can be lumped with those having many exposures. Once a set of optimal parameter values is determined the model can be used either to predict the probability of DCS occurring on a given dive profile or to compute a decompression profile for a given dive and a given target probability of DCS occurring, a target P_{DCS}. In the case of a probabilistic model developed for the USN, called the NMRI 93 model, once the optimal parameter set was determined it was subjected to a prospective study that verified the model's ability to compute a reasonable P_{DCS} prospectively.

At this point USN selected a target P_{DCS} to be used in computing a set of tables. The existing USN air no-decompression limits had a P_{DCS} around 2.3% according to the optimized model. This target risk was retained for no-stop limits and dives with short total decompression times. For dives with longer bottom times the resulting decompression proved unworkably long. The only way to keep the decompression times within operational feasibility was to allow the target risk to assume a higher value for the longer dives, making them riskier (Survanshi et al 1996, 1997). Although a complete set of NMRI 1993 decompression tables were eventually computed, they were never promulgated for Fleet use for a variety of reasons.

ELECTRONIC DECOMPRESSION: DIVE COMPUTERS

As noted above, when the USN tested its constant 0.7 atm PO_2-in-N_2 tables in 1976 to 1980 it did so in real time. In fact the Navy was not testing tables, it was testing a computer algorithm which read chamber depth and updated the decompression schedule every two seconds. This setup had all the elements of today's dive computers. It would take the Navy another 20 or so years before they finally approved a dive computer for operational use, but once dive computers were introduced into the recreational dive community and as they became more reliable and sophisticated, their popularity took off.

Function of a Dive Computer

In sharp contrast to the decompression schedule which provides a diver with a 'flat' decompression profile from a predetermined and presumed dive exposure, a diver-carried dive computer (DC) follows the diver's actual exposure and provides a decompression profile based on that actual exposure, continually updated as the dive progresses (Lang & Hamilton 1989).

Central to the computer is the decompression algorithm that contains the mathematical framework for computing a decompression schedule. A set of parameter values governs the actual quantitative output. These may be constant, or in some computers change according to some input from the diver or the environment. The computer may give the diver a choice of inert gases, oxygen partial pressures, or specify a fixed oxygen fraction or PO_2. Usually these are specified before a dive begins and cannot be changed during a dive, but with some computers changes may actually be made as the dive progresses. A depth transducer inputs depth to the algorithm, at time intervals governed by a clock. Thus at any given time the computer has an accurate record of the depth-time-breathing gas profile up to that point, from which it computes a decompression schedule. After the next time increment, usually only a few seconds, a new depth-time-breathing gas is supplied to the algorithm and a new schedule is computed. The decompression schedule is usually displayed as the depth of the first stop, the 'ceiling' or so called 'safe ascent depth' along with the decompression time. If the diver is within no-stop limits, the ceiling will read zero and the remaining no-stop time will be displayed. To decompress, the diver matches his actual depth to the ceiling and follows it to the surface as the ceiling depth is reduced by the algorithm. Once at the ceiling, the remaining time at that depth is displayed. So at any time a diver knows how shallow one can safely ascend, the remaining time at the ceiling, and the remaining decompression time. Depending on the model, other information may be displayed, but the depth, time, ceiling, and total decompression time are the minimal requirements to perform proper decompressions.

Development of Commercially Available Dive Computers

Reliable, diver-carried digital electronic dive computers have been around since the early 1980s and have become highly sophisticated (Lewis & Shreeves 1993, Loyst et al 1991). For a half century before that a number of other 'instruments' or 'decompression meters' of different sorts were tried. These early efforts used a variety of mechanisms, including analog electronics, gas diffusion through membranes, and various types of pneumatic flow through precision orifices (Huggins 1989). Much of this early development was done in Canada, and this is well summarized by Nishi (1989). One of the most successful of these developments began as the Kidd-Stubbs pneumatic analog computer, which used four gas-filled compartments in a series configuration. With the proper choice of orifices it did a reasonable job of emulating the profiles of the USN air decompression tables (in the early days this was the goal of most of the designers of dive computers and the algorithms that drove them). This was later converted to a program which could be run on a digital computer, and which in due course was used to generate the highly-regarded Defense & Civil Institute of Environmental Medicine (DCIEM) air tables (Nishi 1987).

The first commercially successful digital dive computer was the Orca *Edge*, which used a Haldanian algorithm designed by Karl Huggins that was based on the USN air tables and Spencer's Doppler ultrasound data; the *Edge* was tested in dry chamber dives before release (Huggins 1992). Extensive testing, whether chamber or field, has not been reported much since then by manufacturers of dive computers, but instead they rely on the historical reliability of the algorithm or comparison of output with tables of known reliability (Lewis 1992). This approach seems to be working, but is not without its critics (Edmonds 1995).

Algorithms

Many current dive computers use the algorithms of Dr AA Bühlmann, not only because they work reasonably well, but because they have been published with details necessary to implement them (Bühlmann 1984, 1995). Many dive computers are also supplied with software for detailed planning and records keeping including recording detailed dive profiles. Dive computers that use gases other than air such as oxygen-enriched air ('nitrox') or trimixes usually have algorithms for dealing with the oxygen exposure and warning the diver when oxygen exposure limits are approached.

Although dive computers do a commendable job on 'square' dives (in which the entire bottom time is spent at one depth) they are really at their best for multilevel and repetitive dives, which are inefficient and somewhat difficult to do with flat tables. Another big 'plus' for dive computers is that many incorporate an ascent rate meter that warns the diver if the ascent is too fast. That this has had an impact on diver safety is strongly suggested by the fact that computer users account for a smaller fraction of AGE (embolism) injuries than non-computer users (Vann & Uguccioni 2001).

Decompression Reliability of Dive Computers

As noted above, there is no 'gold standard' algorithm which accurately describes the events leading to DCS to which other algorithm performance can be compared. In fact, a variety of proprietary algorithms are used in decompression computers that may compute different decompression schedules for the same dive profile. Computer users extol the virtues of both aggressive algorithms, those which give longer no-stop times and shorter decompression time, and conservative algorithms, those which tend toward shorter no-stop times and longer decompression times (see for example Hardy 1999). The problem is establishing some sort of track record for the reliability of algorithms. The USN has developed statistical tools based on actual dive experience that can estimate the risk of DCS given a specific dive profile (Thalmann et al 1995, Weathersby et al 1984) but these have not been adopted by commercial manufacturers. There are few if any formal methods of feedback from actual users of commercially available dive computers, so reliability must be judged from anecdotal evidence at best.

The first users of dive computers were likely to have been the more aggressive divers, but today such a large fraction of divers use computers this is no longer likely to be relevant (Vann & Uguccioni 2001). Vann and colleagues performed an analysis on diving incident data compiled by the Divers Alert Network (DAN) that revealed that the incident reports do not offer compelling evidence for a higher incidence of DCS with computers (Vann et al 1989).

One direct but somewhat anecdotal comparison between computer and table incidence is from recreational diving aboard an enormous liner-size dive resort ship, the *Ocean Spirit*, where there were no reported incidents of DCS in 44 277 computer dives and seven incidents in 33 403 table dives ($p<0.02\%$; Gilliam 1992).

Dive Computers in Commercial and Military Diving

Although dive computers often serve as time and depth display devices and as dive loggers, virtually none of the decompression from commercial diving is done relying on diver-carried dive computers. This is partly because surface supplied dives are managed from the surface by the dive supervisor and usually do not involve multiple depths. Also, use of decompression methods not well proven (or regarded as not well proven) can leave the diving contractor open to additional liability. One company, expanding on a system required for diver online monitoring, has addressed this matter by using a computer that looks up legislated tables according to need (Imbert 1992).

Much of the diving in the USN is controlled from the surface and computers have not found favor for this type of diving for the same reasons as in the commercial sector. However, recent changes in the missions of divers in the Special Forces (combat swimmers) have provided an impetus to develop a military decompression computer. The reason is that combat swimmers swim untethered using a rebreather and do multilevel and multiple repetitive dives on missions many hours long.

The USN has put considerable effort into acquiring a database of dives and an algorithm for use in a diver-carried computer for special operations divers. Thalmann and colleagues carried out a multiyear program involving over 3000 simulated dives in the Ocean Simulation Facility of the Navy Experimental Diving Unit, Panama

City, Florida (Thalmann 1983, 1984, 1985a, 1986). Results indicate that algorithms for both air and oxygen–nitrogen gases in fully closed rebreathers have met the operational need, and a fully functional USN dive computer manufactured by Cochran (Dallas, TX) is now in field service. It uses the algorithm for air and nitrogen-based mixes, designated as the MK15/16 Real Time Algorithm or VVAL18 (Butler 2001).

DIVE PLANNING SOFTWARE: THE DO-IT-YOURSELF APPROACH TO DECOMPRESSION

The 'technical diving' movement which uses trimixes of oxygen, helium, and nitrogen to dive beyond the usual range for recreational scuba diving (described in more detail below) has as one of its elements the need for special decompression tables (Hamilton & Irvine 1996). At first these custom tables were provided by decompression specialists, but as interest spread some proficient divers learned to write programs to do these calculations. Just as with most dive computers, most of these rely on the work of Professor Bühlmann (Bühlmann 1984, 1995), but some are based on newer bubble models like the VPM (Variable Permeability Model) of Yount (Yount & Hoffman 1986, Yount et al 2000) and the RGBM (Reduced Gradient Bubble Model) by Wienke (1995, 2001). Not so many years ago the idea would be unheard of for divers to calculate their own decompression tables, and in the commercial diving world even today such an idea would still belong in the world of fantasy. Although the software may generate (the vernacular is 'cut') tables, because most parameters are adjustable by the diver these may not be at all like established tables and many of them must be regarded as 'untested'.

Many of these programs generate tables which have proved to be successful in actual use, but all require some learning time, and some are quite limited. All work best when the user has experience in decompression. Among the various programs the user has the choice of selecting a wide variety of gas mixtures, depths, times, and other parameters. In some cases the programs are too versatile. Another universal problem with all of them is that it is difficult to assess the degrees of conservatism. Two of the leading ones, Abyss® and Pro Planner®, are configured to work with and emulate their companion trimix dive computers. Some quite effective programs are available as freeware.

OTHER DIVE PLANNING DEVICES

Still another category of decompression planning could be classified as 'dive planners.' These essentially display

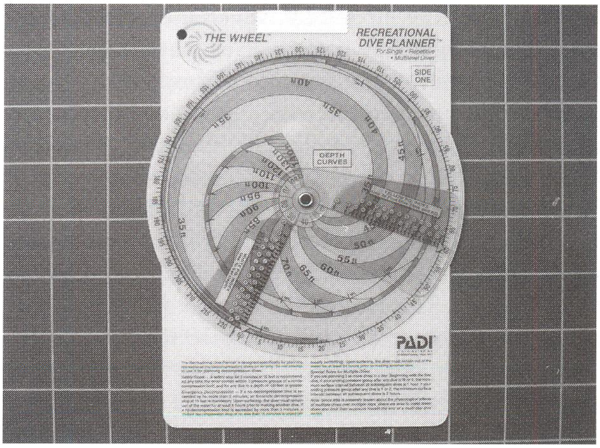

Fig. 10.2.2 The PADI-DSAT Recreational Dive Planner, 'The Wheel.' This permits calculation of sequential repetitive no-stop dives against the Rogers algorithm. (Hamilton et al 1994)

the information from a table on a plastic card or device somewhat like a circular slide rule such that the user sets up a problem by moving a slide or by rotating a disk, and can see calculated results in a small window or under a cursor.

Commercial recreational diving training agency – the Professional Association of Diving Instructors (PADI) – offers a device known as 'The Wheel®' or PADI's Recreational Dive Planner® (RDP). This is specifically for planning no-stop dives, and it can do that quite effectively. Using the circular slide rule format it allows a diver to calculate a sequence of repetitive, multilevel dives, all without decompression stops, by moving from the end of one dive or level right into the next one (see Fig. 10.2.2). The device has a procedure for 'emergency decompression' in the event the no-stop time is exceeded, a good idea but labeled with an unnecessarily intimidating term (needing a decompression stop is hardly an emergency). Surface interval durations are calculated using the 60 min Haldanian compartment instead of the 120 min one that the Navy tables use. This causes the RDP to give the diver significantly more repetitive and multilevel dive time, apparently without sacrificing conservatism (Hamilton et al 1994, Rogers 1988), but perhaps not as much as is expected (Thalmann et al 1995). The RDP can also be used as 'flat' tables, and these are also available for use with two popular enriched air mixes, 32% and 36% oxygen.

Various agencies, including National Oceanic and Atmospheric Administration (NOAA), issue plastic decompression planning cards designed to be carried by the diver. These are 'tables,' but most are rigorously oriented toward no-stop diving; as is recreational practice, they are usually presented so that repetitive dives can easily be calculated.

The British Sub-Aqua Club (BSAC), on the other hand, offers a folder of tables explicitly called 'decompression tables.' These are conservative, and they allow for easy calculation of decompression stops, surface intervals, and repetitive dive times; tables for diving at altitude are available as well (British Sub-Aqua Club 1988). BSAC take the reasonable attitude that divers properly trained and equipped to make short stops at 9 and 6 msw (30 and 20 fsw) are at no greater risk than no-stop divers.

EMPIRICAL DECOMPRESSION

A final category of methods for managing decompression is to do it empirically. One time-honored but fortunately disappearing practice is that of the 'caisson masters' of Japanese tunnel and caisson operations. Tradition allowed these experienced chamber operators to decompress teams of workers by their experience, without written tables. A study by Morita et al (1979) found three to four times as much DCS from the empirical procedures as with the Japanese Ministry of Labor Tables or the Blackpool Tables. All compressed air work decompressions were empirical in the early days (Phillips 1998).

Another category of divers that use empirical decompression methods are the commercial sea harvesters of the world. These operations range from some that are as trouble-free as naval diving to others that are simply appalling and take a heavy toll on the divers and their families. These have recently been reviewed in a workshop by Lepawsky & Wong (2001) and are addressed in Chapter 2.

DECOMPRESSION PRACTICE: AIR AND OXYGEN–NITROGEN MIXTURES

Most of the different modes of decompression relate to different types of diving practice, mentioned above. As might be expected, naval air diving practices have had a strong influence on development of these diving patterns.

CONVENTIONAL AIR DIVING

Development of Air Decompression Tables

The 1958 USN Standard Air Decompression Tables involved tests on 88 schedules in some 500 to 600 trials with an overall incidence of DCS of about 5% (Des Granges 1956). The acceptance criterion was four incident-free trials per schedule. The supersaturation ratios of the Haldane decompression model used for profile calculation were adjusted as testing proceeded based on observed DCS incidence. In addition to the original Navy reports, these and most USN trials since that time have recently been documented in a comprehensive report, along with manifestations of the DCS observed and detailed tables and graphic profiles (Temple et al 1999). Operational records report an overall incidence of DCS for the USN Air Tables of 1.25% (Berghage & Durman 1980). It is indeed remarkable that the USN tables have worked so well over so many years with such a limited test program, at least by modern standards. This strongly suggests that a great deal of experience and judgment of the authors were involved, not just the four trials per schedule.

The 1983 DCIEM Air Tables were developed from the Kidd–Stubbs pneumatic analog computer and electronic versions that followed it, resulting in a database of over 5000 dives (Nishi 1987). Including tests on the interim versions, the model has been tested at DCIEM in 1371 trials of nearly 100 profiles with a 3% incidence of decompression sickness (Nishi & Lauckner 1984). There were approximately 11 trials per profile. The trials included no-stop dives, in-water air and oxygen decompression, repetitive dives, and surface decompression. When DCS occurred, it was usually at the limits of the diving range. The Kidd–Stubbs decompression model was modified once in response to a perception (based on experience and anecdotes) that bottom times for short and long dives were too long, while tables for medium length dives were too short (Nishi & Lauckner 1984). Nishi reports that the surface decompression tables have been used by commercial companies, and the standard air tables are widely used and respected. No formal report on the performance of the tables is available, but a number of dives are in a North Sea database (Lambertsen et al 1997).

The air tables produced in 1986 by the French diving company COMEX were developed from the field records of 64 000 commercial dives using the 1974 French Air Tables (Ministère du Travail 1977), which had an overall 0.22% incidence of DCS (Imbert & Bontoux 1987, 1989). The incidence increased as depth-time zones became more severe, with incidences ranging from <0.5% to 3%. COMEX was tasked with generating a new set of tables that would preserve the parts of the 1974 tables that were satisfactory and improve the more stressful zones. A three-parameter model with a single *M*-value and an unlimited number of Haldane compartments was fit to the field data by maximum likelihood, considering only the Type I DCS (Imbert et al 1992a); this model was also used for the calculation of new tables. The new tables were found to have an incidence of 0.1% DCS in 32 000 dives and in 1992 became part of the French Ministry of Labor regulations for exposure to pressure at work (Imbert & Bontoux 1989, Direction des Journaux Officiels 1992). A comparison of field data for the 1974 and 1986 French tables showed that increasing decompression time by 30–40% reduced the overall incidence of DCS from 0.22% to 0.1% (Imbert 1991).

The pattern of acquiring and examining large numbers of operational dives, using a database to calibrate a computational model for generation of new tables, then validating the new tables, is an exemplary application of the recommendations of the UHMS Workshop on Validation of Decompression Tables for bringing new tables on line without laboratory testing, and in fact it was a major element of the Validation Workshop itself (see below, and Schreiner & Hamilton 1989, Imbert & Bontoux 1989).

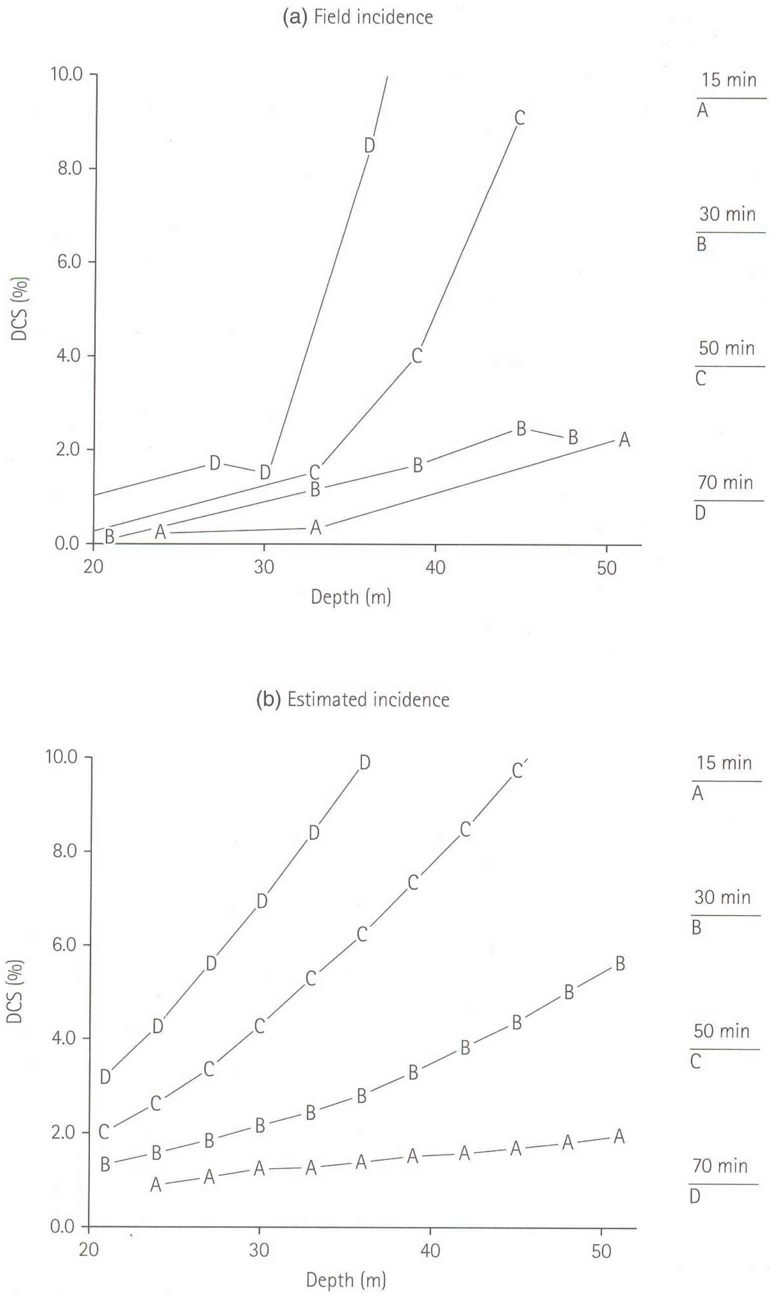

Fig. 10.2.3 Field incidences. (a) Field incidence of DCS taken from company records for the 1974 French Air Tables (Imbert & Bontoux 1987). (b) Estimated risk of DCS for the 1974 French Air Tables.

Fig. 10.2.3 shows the field incidences of the 1974 French Air Tables (Imbert & Bontoux 1987) and the risk estimates of a recent USN model (Weathersby et al 1992). Both indicate increasing risk of DCS with depth and bottom time. In agreement with laboratory trials, however, the field incidences are lower than the risk estimates. Thalmann (1985b) found that a 180 min dive at 18.4 msw (60 fsw) when done under controlled conditions required triple the USN Standard Air stop time, while dives of 40 min at 46 msw (150 fsw) and 30 min at 58 msw (190 fsw) required double the USN stop times. For dives of 60 min at 45 msw (150 fsw) and 40 min at 58 msw (190 fsw), triple the stop time was inadequate to prevent DCS. Thus, while field data provide important indications of operational performance, they may not be good estimators of risk for tables when used under severe, controlled laboratory conditions to their maximum limits.

Probabilistic models and statistical verification techniques offer the promise of air decompression tables with the same risk for all dives from no-stop to maximum bottom time. If these tables are desired to be of low-risk, however, they may require significantly more decompression time than existing tables. The USN Standard Air Tables, for example, require 8 min of decompression after an 80 min dive at 18.4 msw (60 fsw) This dive has an estimated risk of 2.8% by a current USN model (Weathersby et al 1992). If one accepts the validity of the model, to reduce the risk to 2.0% might require as much as 80 min of decompression. Thus, long decompression requirements could make the depth-time limits for low-risk air decompression significantly more restrictive than current limits.

Other Air Decompression Developments

Arntzen and Eidsvik set out to create tables that incorporated the somewhat arbitrary and anecdotal conservative field modifications made to USN sur-d/O_2 tables by diving supervisors in order to compensate for extra stress on a dive, the so-called 'J' factors. These modified sur-d/O_2 tables have been quite successful in the field (Arntzen & Eidsvik 1980). The main modification was to add 1 min to the time used for selecting the table for each msw of bottom depth deeper than 20 msw (65 fsw).

Another significant multiyear effort sponsored by the British Department of Energy and later the Health and Safety Executive (HSE) built on the 'bubble growth index' model (Gernhardt 1991, Lambertsen et al 1995). After a series of iterations during which extensive field testing was performed (EBRDC 1995, Lambertsen et al 1997) a final set of Lambertsen–Gernhardt Tables, the Mark II, has been produced. HSE acknowledged the success of the Mark II Tables but made the decision not to require their use in the British Sector (Robertson & Simpson 1997).

Several other sets of air diving tables different from the USN tables have been created. These include a complete set of tables developed by Wouter Sterk for the National Diving Center of The Netherlands (1988) that has proven successful in the field, and the DCIEM tables just mentioned.

IN-WATER DECOMPRESSION WITH OXYGEN

The first use of oxygen during decompression may have been in 1928 for deep air diving with a submersible decompression chamber in which a diver breathed oxygen from a closed circuit apparatus at 18 msw (60 fsw) (Davis 1962). Since that time, oxygen decompression has become an integral part of deep and long-duration diving.

Oxygen can be used during in-water decompression to reduce decompression time and the risk of DCS. The 1986 COMEX tables, which are also the 1992 French Ministry of Labor Tables (Direction des Journaux Officiels 1992), have an option that offers oxygen breathing during in-water decompression at 6 msw (20 fsw). Compared with the corresponding air table, the oxygen table reduces the decompression time by 50% for 15 msw (50 fsw) dives and by 30% for 60 msw (200 fsw) dives. The incidence of DCS with oxygen decompression was two to three times lower than with air decompression for dives of the same depth and bottom time (Imbert & Bontoux 1987). Other tables that include procedures for in-water oxygen breathing include the 1983 DCIEM Tables, the 1974 French MOL Tables (Ministère du Travail 1977), The Netherlands National Diving Center Tables (1988), the Mark II Lambertsen–Gernhardt Tables, the JAMSTEC Special Air Tables, and those of several recreational groups.

Breathing oxygen underwater does incur the risk of oxygen convulsions, but experience has shown that oxygen decompression can be both safe and efficient if diver selection, training, equipment, and supervision are appropriate. During the excavation of a Bronze Age shipwreck offshore Turkey, for example, the Institute for Nautical Archaeology conducted 7500 air dives at depths of 50–60 msw (150–180 fsw) with in-water oxygen decompression at 3 and 6 msw (10 and 20 fsw) (Fife et al 1992, Vann et al 1999). There were three incidents of DCS and no symptoms of oxygen toxicity.

During a series of experiments on pulmonary physiology in immersed exercising divers (Thalmann et al 1979), dives as deep as 58 msw (190 fsw) (685 kPa abs) for 60 to 80 min on air were sometimes required. These deep long tables had a high risk of DCS. A procedure was developed following the USN air decompression tables but having divers breathe 100% oxygen for half the decompression time beginning at the 9 msw (30 fsw) stop. There was no DCS in almost 50 exposures at 58 and 31 msw (190 and 120 fsw), even on schedules that were calculated using the USN Haldanian model; this was done because no schedules were available for 70 and 80 min times at 58 msw (190 fsw). Later, this concept of using air schedules with 100% oxygen breathing was successfully used in managing a diving accident involving several divers, and it was eventually incorporated into the USN diving medical procedures as an emergency abort procedure (US Department of the Navy 1993). This technique was also adopted by early technical divers.

SURFACE SUPPLIED DIVING: IN-WATER, SUR-D, AND BELL DECOMPRESSION

In-water Decompression

Surface supplied diving is the oldest and most widespread form of work oriented diving, used by both commercial and military communities, but rarely by recreational and scientific divers. The diver has breathing gas supplied by hose from the surface and wears a 'hard hat' helmet, or a full-face mask with head protection (Zinkowski 1971). The diver stands on a 'stage' that is hauled up by a hoist a step at a time, or may be hanging on a line. At the surface managing the operation and controlling decompression is a dive supervisor. In addition a tender or standby diver may also be present.

Surface Decompression

In surface decompression the diver completes some decompression in the water and then surfaces, enters a 'deck decompression chamber' (DDC) and is recompressed to finish the decompression breathing oxygen. This minimizes hazards associated with in-water decompression and allows the diver to finish long decompressions in a warm, comfortable environment. This method may be used for either air or helium-oxygen diving, and 100% oxygen is usually breathed in the chamber.

During salvage of silver from the *Empress of Ireland* in 1914 and gold from the *Laurentic* in 1917–1924, the weather or military situation sometimes forced British Royal Navy divers to surface before completing decompression and be recompressed in a shipboard pressure chamber (Damant 1926, Davis 1962). Salvage of the USN submarines *S-51* in 1925 and *S-4* in 1927 were also conducted with surface decompression (Van der Aue et al 1945). Subsequent work by Hawkins & Shilling (1936) and Van der Aue et al (1951) refined the technique, but the most important step was the use of oxygen in the chamber, first as an ad hoc measure by Gouze (1944), and later in chamber trials by Van der Aue et al (1951).

Surface decompression using air, where air is breathed both in the water and in the chamber, has generally been done by rule rather than using a decompression model. In fact, when the USN adopted its new air decompression tables in 1958, a series of test dives was done to ensure the old rules to get the diver out of the water still applied. In developing its surface decompression using oxygen procedures the USN used a model to compute the in-water air stops, taking into account 100% oxygen breathing in the chamber (Van der Aue et al 1951). The sur-d/air procedures are only used if oxygen cannot be used for some reason (Workman 1957).

Van der Aue limited the use of oxygen to 12 msw (40 fsw) but still noted a 1% incidence of 'minor' central nervous system symptoms (i.e. not convulsions). Fire is a further hazard of oxygen use in a chamber. Chamber fires were distressingly common until fire safety procedures were worked out (Shilling et al 1976). Oxygen equipment must be oil-free, sources of ignition controlled, flammable materials kept to a minimum, and exhaled oxygen exhausted outside the chamber.

The USN Surface Decompression Tables Using Oxygen (sur-d/O_2) and other equivalent tables enable long working bottom times in rough seas and strong currents with minimal in-water decompression. USN sur-d/O_2 has been adopted and modified by military and civilian divers worldwide (e.g. Arntzen & Eidsvik 1980). Some reports, however, suggest that sur-d/O_2 is associated with a higher incidence of neurologic symptoms than in-water decompression (Imbert 1991, Imbert et al 1992a, Shields & Lee 1986). Other observers take issue with this conclusion and argue that the procedures (i.e. the tables), not the mode of diving is the problem (Beyerstein 1992, Mills 1992, Overland 1992, Sterk, personal communication, Sterk & Hamilton 1991). Shields points out in his 1986 report that the dives that used sur-d/O_2 were almost invariably the more stressful dives and therefore would be expected to have a higher DCS incidence.

A related finding from the same survey (Shields & Lee 1986) is that divers wearing hot-water suits (as opposed to drysuits or other passive insulation) are significantly more likely to get DCS. This is not expected to be a matter of suits, but of the divers' temperatures. Being warm during the working and thus the gas uptake part of the dive will increase gas uptake as compared with a diver who might be slightly cold. Conversely, warmth during decompression should improve circulation and out-gassing and thus be beneficial.

The reaction of the UK authorities to the Shields & Lee report (1986) and to subsequent reports in that series (there were several) was to limit the extent of diving exposure, mainly by restricting the duration of the dives, the allowable bottom time. This was regarded as a successful solution (Robertson & Simpson 1997). However, this restriction was felt to be detrimental to North Sea industry because it made it difficult to get underwater jobs done. However, since all the contractors have the same restriction, they have accommodated to this rule. They have also implemented transfer-under-pressure and saturation techniques.

NO-STOP AIR DIVING

The simplest and most common form of decompression control for compressed gas diving, no-stop or no-decompression diving, does not require decompression stops during ascent to the surface, but it nevertheless represents a planned decompression profile. It is in fact a subset of stage decompression. Mostly used with scuba, it is listed here after conventional stage decompression diving because historically scuba did not begin to be used until after about a century of diving practice with surface supplied equipment and (normally) stage decompression. No-stop diving profiles include a maximum 'bottom time' or time at pressure, and a rate of ascent. Often referred to as 'no-d,' the current trend is to call it 'no-stop' diving to avoid the implication that decompression is not involved. It is indeed involved, because virtually all dives involve some degree of decompression obligation, and the diver should understand that. No-stop diving is almost universally used with open circuit scuba gear, and a predominant proportion of scuba diving is no-stop.

Ascent Rates

The 18 msw/min (60 fsw/min) ascent rate chosen by the USN for the USN Air Tables published in 1959 has become a de facto standard for virtually all types of diving (Lanphier 1990), particularly in the recreational diving community. More recently, a 10 msw/min (33 fsw/min) ascent rate has been recommended and adopted by a wide variety of dive computers, the USN, and training organizations. Some dive computers require rates as slow as 6 msw/min (20 fsw/min) (Lang & Egstrom 1990). As mentioned earlier, at first the ascent rate was assumed to be as fast as possible, but later algorithms have included it as part of the no-stop decompression procedure.

The Safety Stop

Another recent development in no-stop recreational diving is the recommendation for a 3–5 min 'safety stop' at 3–5 msw (10–16 fsw) (Lang & Egstrom 1990, Pilmanis 1990). A safety stop may achieve the same effect as a slow ascent in reducing the risk of DCS due to barotrauma or arterialized venous gas emboli, but this has not been adequately validated experimentally. One possible benefit to the safety stop is that in order to perform it a diver has to have good buoyancy control during the ascent.

No-stop Limits

Over time, the no-stop dive exposure limits have become more conservative. For example, after caring for caisson workers affected by DCS at the St Louis bridge, Jaminet (1871) proposed no-stop limits for compressed air exposure of 120 min at 24 msw (80 fsw) and 60 min at 36 msw (120 fsw). The present and well established USN limits are 40 min at 24 msw (80 fsw) and 15 min at 36 msw (120 fsw). In testing a real time decompression algorithm for air diving, Thalmann (1985b) noted some 107 dives at or exceeding current USN no-decompression limits were done with no cases of DCS. This would seem to attest to the reliability of USN no-decompression limits, but the recreational diving community has seen the need to develop more conservative limits in an attempt to further reduce DCS risk during no-stop dives (Fig. 10.2.4). Newer tables and dive computers have even more conservative limits (Lewis 1992, Lewis & Shreeves 1993).

REPETITIVE AND MULTILEVEL DIVING

The second of two dives made in close succession is a repetitive dive, and the time between dives is a surface interval. The repetitive dive bottom time must be reduced or its decompression time increased to compensate for residual inert gas remaining from the previous dive. The simplest scheme for determining repetitive dive decompression requirements takes the sum of the bottom times of the two dives at the greatest depth, but this is inefficient for long surface intervals. Of the many methods for determining repetitive dive bottom times, that of the USN's 1958 Standard Air Tables is the most flexible, albeit somewhat complex.

Despite this, no single universally accepted algorithm has been produced for computing a repetitive dive.

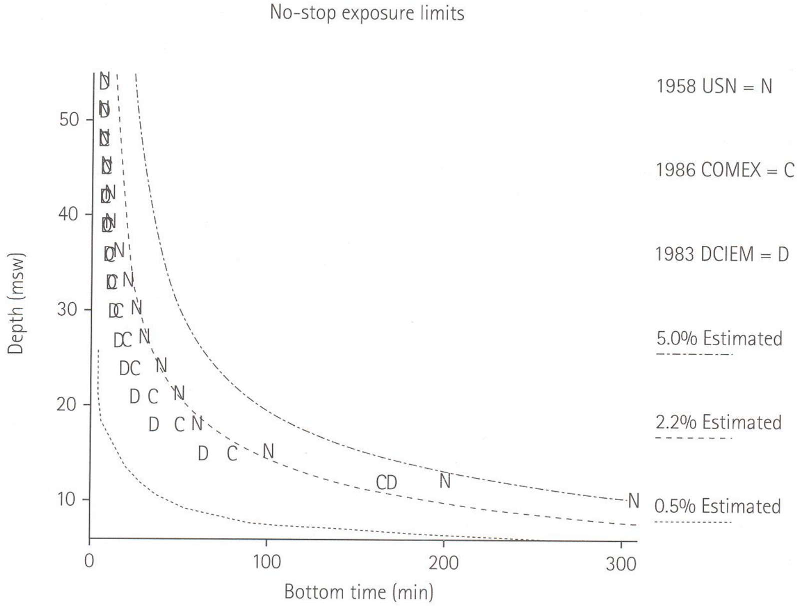

Fig. 10.2.4 No-decompression limits for three well established tables. Actual limits shown as points. Also shown are theoretical iso-risk curves representing 0.5, 2.2, and 5% risk estimates for no-stop diving according to a current USN decompression model (Weathersby et al 1992). (The DCIEM tables have been changed slightly since the 1983 edition.)

Most available techniques, including dive computers, use the gas loading of the previous dive, adjusted to account for the surface interval, and take little or no account of the possible generation or destruction of bubble-generating micronuclei.

Computing Repetitive Dives

Repetitive diving using a decompression computer is straightforward; the computer is left running during the 1 atm surface interval, and it carries the gas loadings from the previous dive over to the next. Putting these procedures in tabular format is more challenging and usually involves accepting some degree of conservatism (shorter no-stop times, longer decompression times).

The 'ideal' way to do repetitive diving should be with a dive computer, which logs the exact profile of the first dive and the surface interval, so starts the repetitive dive with the 'exact' hypothetical gas loading. To the extent that gas loading is all that is needed to prepare for a repetitive dive this is the ideal approach.

The USN method for repetitive diving is a rather clever scheme utilizing the basic Haldanian method of accounting for the residual gas loading of the previous dive. The USN method in effect monitors the gas loading in the compartment that has a 120 min half-time, the longest compartment in use at that time, accounting for its exponential decay during the surface interval (Dwyer 1955). The allowable overpressure in that compartment was divided into 16 'groups,' with designations 'A' through 'O' each group accounting for the amount of gas remaining in the 120 min compartment, 0.6–10 msw (2–33 fsw) in 0.6 msw (2 fsw) increments. The gas loading at the end of the first dive determines the group, and a surface interval chart is used to determine how much gas has been eliminated up to the point of beginning the next dive, resulting in a lower (closer to A) repetitive group. This value is then used in another chart that determines how long one would have had to spend at the depth of the next dive for the 120 min compartment to accumulate gas to the value designated by the repetitive group. This time is added to the actual bottom time of the dive, and this is what carries over as the effect of the previous dive. This chart can be used for successive dives. A repetitive group is provided even for no-stop dives.

The selected half-time is considered to clear all compartments of residual nitrogen in a 12 h surface interval, and the next dive is no longer considered repetitive. The actual surface interval for complete nitrogen clearance is unknown. Theoretical intervals for various other tables are: 6 h for Rogers (1988), 8 h for 1974 French, 12 h for 1986 COMEX, and 18 h for DCIEM.

The USN Repetitive Tables were tested in four to six trials of 61 two-dive profiles (des Granges 1957). All trials were of decompression dives, and DCS occurred in three subjects on profiles with maximum depths of 67 and 80 msw (220 and 260 fsw).

Unless the decompression from the first dive is controlled by the 120 min compartment – that is, the 3 msw (10 fsw) stop is determined by how long that compartment takes to reach its theoretical *M*-value or MPTT. Repetitive dives done according to the USN scheme will be more conservative than if the algorithm used to compute the air tables were to be run in real time. In the 1950s when this was developed, however, real-time decompression was not possible using the computers of the day, and the tabular method developed by des Granges was considered a breakthrough.

A more liberal adaptation of this same algorithm has been developed and validated for recreational diving, where the assumption is that only no-stop dives are done (Hamilton et al 1994, Rogers 1988). Rogers computed recreational diving tables with shorter surface intervals using a 60 min rather than a 120 min Haldane compartment half-time to clear residual nitrogen in 6 h rather than 12 h surface intervals. This was based on Rogers perception that the longer half-time tissue were rarely involved in determining decompressions from no-stop dives. These tables were subjected to one of the most extensive repetitive dive trials ever conducted outside the military (Hamilton et al 1994). There were 1400 man-dives of 40 profiles including single-day, multilevel dives and multiday dives with four and six dives per day for six consecutive days. Except for 228 open-water dives, however, all were dry chamber trials and did not involve exercise. There were very few 'square' dives. There was only one incident of DCS, which occurred on the second day during chamber trials of six dives per day. Thalmann et al (1995) included some of these profiles in an analysis, and found their predicted DCS scores to be higher than the original 1959 USN tables or the new 1993 probabilistic ones. However, field use of these procedures for 12 years has been satisfactory and no adjustments have been necessary.

Performing Repetitive Dives

Repetitive and multiday diving is common in all diving communities, but especially in recreational diving. Recreational diving incident data suggest that multiple dives have a greater incidence of DCS than single dives (Vann et al 1989), but precise information on risk or incidence is scarce. Risk estimates for selected two-dive profiles using the DCIEM Sport Diving Tables are 1.1–3.3% (Tikuisis & Nishi 1992). Field records for the 1974 French Air Tables indicate a 0.3% incidence of minor symptoms (none neurologic) in 5400 two-dive repetitive profiles including both no-stop and decompression exposures (Imbert et al 1992a). Dive trials by the USN indicated that the USN no-stop repetitive dive procedures may be overly conservative (Thalmann 1985b).

Multilevel Diving

A multilevel dive is one where time is spent at several depths during descent, ascent, or both. If additional depths are visited during ascent, the stops are presumed to be taken at depths and for times other than those required by the decompression table.

Multilevel diving is a variant of repetitive diving in which a diver works at several depths before returning to the surface. Commercial, recreational, and military diving is frequently multilevel. Although it need not be, the practice is normally that successive depths become shallower as the dive proceeds. The diver is in effect conducting a sort of 'decompression.' Categorically this should result in a more effective decompression, but the question remains as to how to determine the decompression profile. Prior to the general availability of dive computers, ad hoc methods were worked out on how to do multilevel diving using the repetitive diving tables.

In the past (using the USN Standard Air Tables), decompression for multilevel dives was determined by the deepest depth attained at any time during the dive, no matter for how short a time, over the entire time from beginning descent to beginning decompression. This approach is regarded as conservative and, depending on model assumptions, can result in longer decompression times than might otherwise be required. In order to decrease the long, conservative decompression procedures resulting from applying this rule, commercial diving companies have adapted the USN Repetitive Diving Tables to allow extended working times during 'repet-up' diving in which a dive begins deep and approaches the surface in gradual stages (Merriman 1992, Overland 1992). This involves doing the deepest portion of the dive first followed by subsequently shallower portions. Each shallower portion is treated as a separate repetitive dive assuming an instantaneous ascent to the surface followed by descent to the next shallower depth. The decompression for each subsequent section is computed for the shortest surface interval according to the repetitive dive procedures in use. Other repet-up or multilevel dive procedures have been developed (Gernhardt et al 1992, Imbert et al 1992a, Lewis 1992, Rogers, in Hamilton et al 1994). The USN has modified the USN Repetitive Dive Tables to allow long multilevel dives where the deep and shallow stages – i.e. deeper or shallower than 9 msw (30 fsw) – can be in any order (Thalmann & Butler 1983). Today, decompression computers can actually measure the minute by minute dive profile and compute a decompression schedule exactly suited to the actual multilevel dive profile.

Reverse Dive Profiles: Deep After Shallow

The above discussion, as with most others on repetitive diving including the programs in dive computers, makes the tacit assumption that if the gas loadings can be monitored and used for calculations, then doing a repetitive dive is a straightforward thing. Not all decompression modelers agree with this viewpoint. These views were exercised in a recent high level workshop dealing with a special aspect of repetitive diving, reverse dive profiles (Lang & Lehner 2000).

A reverse dive profile is one of a series of repetitive dives or segments of a single dive in which dives or segments are at deeper depths than the preceding parts of the dive. There is a long standing 'prohibition' of reverse dive profiles in the recreational diving community, but a rigorous basis for this is elusive.

Military and commercial diving do not prohibit reverse dive profiles, and recreational and scientific diving groups perform such dives occasionally if not frequently. No convincing empirical evidence was presented at the Workshop to argue against doing reverse dive profiles within the no-stop limits, but some computational models suggest that they could be detrimental under some conditions. It was also shown quite clearly that doing dives from deeper to shallower is more efficient. As a first step, the Workshop concluded that there was no reason to prohibit reverse dive profiles for no-stop dives less than 40 msw (130 fsw) in depth and for depth differentials less than 12 msw (40 fsw).

OXYGEN–NITROGEN MIXES OTHER THAN AIR

Oxygen-enriched Air

The most practical application of the oxygen window principle (see Ch. 10.1) is for use with oxygen-rich mixtures. Basically the oxygen window principle says that breathing high oxygen partial pressures displaces inert gas from the arterial blood but does not increase the venous partial pressure of oxygen. This increases the gradient for inert gas elimination without increasing the venous gas burden. Diving with oxygen-rich breathing gases, 'oxygen-enriched air' (OEA), 'O_2–N_2,' 'N_2–O_2,' 'enriched air nitrox,' or just 'nitrox' is highly fashionable in the recreational diving community, and is used by scientific divers (NOAA Diving Manual 2001), and for selected commercial and military diving operations.

The common contemporary practice with some operational advantages is to use mixtures of oxygen and nitrogen that have a larger fraction of oxygen than the 0.2095 normally found in atmospheric air. The advantages of these mixes are entirely a matter of reduced decompression obligation. The price for this is special effort in mixing and handling the breathing gas and an increased probability of oxygen toxicity, and of course these mandate the need for appropriate training.

Toxicity and benefit converge as depth increases; enriched air diving is most effective in the range of about 15–35 msw (50–115 fsw). Decompression tables for oxygen-enriched mixtures may be calculated as custom tables specifically for the gas mixture in use, or may be selected from a set of prepared tables (NOAA Diving Manual 2001). Another method is to use the oxygen window principle and select a table with the same $P\text{N}_2$ but a shallower depth, covered in the next section.

Equivalent Air Depth; EAD Practice

The 'Equivalent Air Depth' or EAD principle is based on the assumption that decompression is determined only by the inert gas partial pressure, and that oxygen plays no role. It involves determining the inert gas (here nitrogen) partial pressure ($P\text{N}_2$) at a specific depth, then selecting a standard air table that has the same or higher $P\text{N}_2$ and using that table to perform the decompression. For gas mixtures with more oxygen than air the resulting table will be for a shallower depth and will thus require a shorter decompression. The equivalent air depth (EAD) is calculated using the following equation:

$$\text{EAD} = \left(\frac{(D + 10)(1 - F\text{O}_2)}{0.79}\right) - 10 \qquad (1)$$

where D is the depth in meters of seawater, 10 is atmospheric pressure in msw, $F\text{O}_2$ is the fraction of oxygen in the breathing mixture, and 0.79 is the fraction of nitrogen in air (for non-metric units, use fsw instead of msw and replace 10 msw with 33 fsw). This method allows one to use existing air tables for decompression involving different oxygen–nitrogen mixtures, and new tables do not have to be calculated. In order to minimize error, air tables may be transcribed with depths already adjusted for the EAD of specific gas mixtures. For example, the new *NOAA Diving Manual* has transcribed the USN Standard Air Tables in this manner for 32% and 36% oxygen (NOAA Diving Manual 2001).

When used for decompression dives, the EAD principle results in conservative schedules. The reason is that only the bottom depth is adjusted, but all decompression stops assume air is breathed, whereas a gas mix with a higher PO_2 is actually breathed.

In some decompression computers, the diver may enter the oxygen fraction of the breathing gas and the computer will determine the decompression schedule based only on the inert gas partial pressure. In these cases the stop time are adjusted to take the higher oxygen partial pressure into account. Whether this is reasonable awaits accumulating enough experience on these enriched air 'nitrox' computers to see if the DCS incidence is higher than with air dives using air computers.

DECOMPRESSION PRACTICE: MIXED GAS DIVING

Mixed gas diving is diving with any breathing gas mixture other than air. In commercial diving the term 'mixed gas' has a more specific meaning, implying diving with heliox, mixtures of oxygen and helium. This section covers this type of diving and also considers diving with other non-air mixes. Diving with oxygen–nitrogen mixtures is covered in the preceding section. Although not a mixture, use of pure oxygen is included also. Whether mentioned specifically or not, all breathable gas mixtures contain oxygen, so the focus is on the inert gases.

Air is our evolutionary gas, known to be eminently breathable, so why use others? Clearly, the most important reason for using mixtures other than air is to avoid the narcosis of nitrogen. A close second as depths increase is to be able to manage the level of oxygen and thus avoid oxygen toxicities; tactics for this are covered later in this chapter, toxicities and their mechanisms are covered in Chapter 9.4. A third reason is that the nitrogen in air is soluble and hard to unload from the body, so hypothetically decompression can be improved, sometimes significantly, by selective use of mixtures based on other inert gases. Also, at the same pressures where narcosis and oxygen are problems air becomes quite dense, creating resistance to breathing and a cascade of other problems linked to that; this can be mitigated with lighter gases.

INERT GASES

This is a brief review of the alternate 'inert' gases used in diving practice. Of these hydrogen is anything but inert chemically, but with proper procedures it can be used for diving.

Helium, Molecular Weight (MW) 4

Helium is not known to cause narcosis (Lambertsen et al 1977), and its low density makes it much easier to breathe than air or air-like mixtures. It has low solubility so is easier to unload during decompression than nitrogen, but its high diffusivity allow it to be taken up by the body more quickly. Helium has a higher thermal conductivity than air so it feels cold and can chill divers immersed in it, as in a diving bell or chamber, and at depths deeper than the air diving range can cause significant heat loss via cold breathing gas. However, helium has a lower heat capacity than air, so it does not carry as much heat from the lungs as air. (Nuckols et al 1996, Schmidt 1982).

Argon, MW 40

Argon makes up about 1% of atmospheric air. It is more dense and more narcotic than nitrogen, and more difficult to remove during decompression (Lillo et al 1985). The argon component at atmospheric air is usually lumped with nitrogen in decompression calculations. Argon is of concern to divers for two reasons: it is used as a shield gas for welding, and one of the separation mechanisms used for breaking air into its components (pressure swing adsorption, a method that depends on selective adsorption of gases onto synthetic zeolites or 'molecular sieves') puts the argon component along with the oxygen of air, so 5% of 'oxygen' made by this method is actually argon.

Hydrogen, MW 2

Lighter than helium, hydrogen's low density gives it an advantage for breathing at very great depths, deeper than, for example, 400 msw (1300 fsw). At those depths divers can work harder and sleep better when hydrogen is a major component of the breathing mix (Gardette et al 1987). Hydrogen is more soluble than helium so decompression is more difficult, and it causes narcosis. It counterdiffuses against helium (counterdiffusion is covered just below). Hydrogen's flammability can be managed by keeping the oxygen level in a mix lower than 5%; the logistics of handling hydrogen is quite complex.

Neon, MW 20

Neon has not been found to be narcotic to pressures as great as 3.6 MPa (36 ATA) (Lambertsen et al 1977). It is less dense than nitrogen, but is not nearly as light as helium. It does not distort voice nor conduct heat as much as helium, and these properties give neon advantages under certain conditions. In decompression it is about the same solubility as helium but diffuses more slowly so for some specific profiles neon can have a slight but still somewhat theoretical decompression advantage.

HELIUM–OXYGEN DIVING

Helium was originally proposed as a diving gas because of its lower solubility and the theoretical assumption that it would be more favorable for decompression (Sayers et al 1925). Behnke & Yarbrough (1938) determined that helium did not cause narcosis, and this remains the main incentive for its use for dives deeper than about 50 msw (165 fsw). The first helium dive trials were conducted in the 1920s by the US and British Navies (Momsen 1942) but resulted in a worrisome incidence of DCS.

Experiments resumed in the 1930s when Edgar End (1937, 1938) demonstrated the practicality of helium–oxygen diving to 120 msw (400 fsw), and the USN developed the USN Helium Partial Pressure Tables (Momsen 1942) which were used while still under trial for the salvage of the *USS Squalus* in 1939 (Behnke & Willmon 1939). Further testing was done to extend the range of diving down to greater depths and to adjust tables because it was felt that the decompressions were too long for shallower dives and too short for deeper dives. These investigations were not altogether successful (Alexander et al 1970, Molumphy 1950, Summitt & Crowley 1970), and the original tables were retained with bounce diving relegated to depths 107 msw (350 fsw) and shallower. There is little other documentation on short, deep helium–oxygen 'bounce' diving by the Navy. USN helium–oxygen experience is better documented for shallow water diving with the semiclosed Mk 6 underwater breathing apparatus (UBA) (Workman & Reynolds 1965) and the closed circuit Mk 16 UBA (Thalmann 1985a) for which rig-specific decompression procedures were developed. The Canadian Forces have recently developed helium–oxygen decompression tables (Nishi 1990) which are more suited to their specific missions.

The commercial diving industry modified the USN Helium Partial Pressure Tables for its own use in the 1960s and carried out active table development through the 1970s. The resulting tables are usually proprietary, unpublished, with largely undocumented history and performance. The development of helium decompression procedures for 30–60 min dives at 120–180 msw (400–600 fsw) proved to be a significant challenge (Hamilton 1976). Deep commercial helium bounce diving became less common in the 1980s and 1990s with the acceptance of saturation diving and the development of remotely operated vehicles (ROVs). Large diving companies which may have made 1000 helium bounce dives per year in the 1970s might now make only 50 (Imbert et al 1992a).

Because helium is less soluble and exchanges more rapidly than nitrogen, helium dives might be expected to permit faster decompression than nitrogen dives. This is clearly true for saturation decompression, but differences for short, deep dives are small at best and difficult to demonstrate with statistical significance because of many other factors (Duffner & Snider 1958, Hempleman 1967, Thalmann 1985a, Thalmann et al 1989). Momsen (1942) reported the need for deep, and unanticipated, decompression stops to accommodate the 'initial out-rush' of helium upon leaving the bottom. Cabarrou et al (1978) reported a similar need, and the need for deep stops is a major theme of current decompression workers (Lang & Lehner 2000).

Decompression after helium diving usually involves switching to air and/or oxygen to save helium and decompression time, and consequently there are few data on which to base a direct comparison of helium and nitrogen decompression. Such information is available, however, from recent Mk 15 and Mk 16 UBA studies for similar dives with no gas changes during decompression (Thalmann 1984, 1985a, 1986, Thalmann et al 1980, Vann 1982). The overall incidences of DCS were 3.7% for helium (64 of 1723 dives) and 5.2% for nitrogen (103 of 1976 dives), but serious symptoms accounted for 40.1% of all helium incidents (26 of 64) and 15.5% of all nitrogen incidents (16 of 103; $p < 0.001$).

The original USN helium tables were complicated to use. In 1991 the tables were simplified, mainly by specifying three bottom mixes of 10, 12, and 16% oxygen and introducing a switch to a 40% O_2-in-He mix at the first stop [30 msw (100 fsw) or shallower] until 15 msw (50 fsw) was reached, where the switch to 100% O_2 was made. At the end of the 12 msw (40 fsw) stop the diver quickly ascends to the surface where he enters a deck decompression chamber, is compressed to 12 msw (40 fsw), and completes decompression in the chamber. The schedules themselves were not changed, but bottom times were reassigned based on results of the Canadian program mentioned above (Nishi 1990).

In using the USN procedure, episodes of oxygen toxicity were reported at 15 and 18 msw (50 and 60 fsw) (Molumphy 1950). When commercial divers in California began using heliox in the 1960s they immediately modified the USN tables to avoid the oxygen in the water. In 1998 the USN made the same move. The 100% oxygen breathing was replaced with

40% oxygen in helium for all in-water stops but were otherwise unchanged; the chamber stops breathing 100% oxygen were unchanged. These latter changes were based purely on judgment of decompression experts (an 'interpolative change' according to the Validation Workshop, see Validation of Decompression Procedures, below), but preliminary use in the field (over 350 dives in the salvage of the *USS Monitor*) showed the judgment to be good, with only one case of DCS and no oxygen convulsions.

There has also been development in the use of helium by the recreational ('technical') diving community (see Technical Trimix Diving: Scuba With Mixed Gases, below). Much of this helium use has been in the form of trimixes of oxygen, helium, and nitrogen. Unfortunately these developments are largely anecdotal and not well documented. For dives with short bottom times the use of more helium in the trimix requires a longer decompression, but this switches as bottom times get longer (Lang & Lehner 2000).

The use of trimixes for caisson and tunnel work at pressures beyond about 40 msw (130 fsw) is now accepted practice (see Tunnel and Cassion Work: Decompression After Compressed Air Exposures, above) (Faesecke et al 2001, Kobayashi et al 1995).

DEEP MIXED GAS 'BOUNCE' DIVING WITH A DEEP DIVING SYSTEM

In the late 1960s the offshore petroleum industry had the requirement for divers to work for about 40 min at depths in the range 100–200 msw (325–650 fsw), followed by decompression to the surface (Hamilton 1976). In a typical deep bounce dive two divers would descend to the work site while at atmospheric pressure in a closed diving bell (also called a personnel transfer capsule, PTC, or submersible decompression chamber, SDC). Pressure in the bell would then be equalized with the ambient water pressure, the hatch opened, and one of the divers would 'lock out' to work, breathing by mask or helmet via an umbilical hose. The other diver, the bellman, would serve as tender. The gas mix in the bell and on the hose was usually 'heliox', an oxygen–helium mixture with enough oxygen to give a PO_2 on the bottom of 1.0 to 1.2 atm.

Once work was complete or the available time was up the diver would re-enter the bell, the hatch would be sealed at the appropriate depth, and the bell would be hauled to the surface. Pressures were controlled to match the required stops on the decompression table in use. Gas was switched once or twice to intermediate mixtures with increased oxygen, and eventually to air. The divers would transfer to the deck compression chamber as soon as possible for greater comfort and environmental control, and would complete the decompression there, usually with oxygen breathing by mask. DCS incidence has not been reported formally, but it was probably in the range of 10 to 20% for the more stressful dives (Hamilton 1976).

Despite considerable development effort this operational approach was eventually replaced. The DCS incidence was high, and although treatments were usually successful they were disruptive and required considerable resources such as stored treatment gas, crew training, and medical support. Eventually the clients, the oil companies, accepted the use of saturation techniques for dives beyond about 100 msw (300 fsw).

COUNTERDIFFUSION: RELATION TO DECOMPRESSION

'Counterdiffusion' is the term used to describe the physiologic effects of an individual's being exposed to two inert gases of very different diffusion properties. It relates to decompression in two ways. First, the symptoms of the two 'gas lesion diseases' – DCS and counterdiffusion sickness – are similar and the etiology is apparently the same – bubbles in the skin or gas emboli elsewhere. Second, counterdiffusion situations can complicate decompression or can aid it, and counterdiffusion lesions can happen with or without pressure changes. There are two categories of inert gas counterdiffusion as defined by Lambertsen, a 'superficial' condition and a 'deep tissue' condition (Lambertsen 1989).

Superficial Counterdiffusion

Superficial counterdiffusion occurs through body surfaces when a heavy or slowly diffusing gas is breathed (e.g. N_2 or Ne) and the external environment is a lighter, more rapidly diffusing gas (e.g. He). A net inward flux of the lighter gas into the skin causes subcutaneous supersaturation and extravascular bubble formation, which can occur without pressure change. In human exposures at elevated pressure, intense itching was accompanied by hard, raised, bloodless lesions and severe vestibular dysfunction (Harvey & Lambertsen 1978, Lambertsen et al 1977).

An opposite effect occurs when a breathing gas switch is from helium to nitrogen as the background inert gas. If a diver breathes helium–oxygen at depth and changes to air during decompression, helium leaves his tissues faster than nitrogen enters and the resulting undersaturation appears to allow accelerated decompression, does not appear to cause counterdiffusion problems, and is a well-established practice for most deep helium–oxygen bounce diving (Hamilton 1976).

Deep Tissue Counterdiffusion

'Deep tissue' counterdiffusion can occur when different inert gases are breathed in sequence. Perfusion and diffusion transport the more rapidly diffusing gas into tissue faster than the slower diffusing gas can be eliminated. A transient supersaturation occurs, the magnitude of which increases with pressure (D'Aoust & Lambertsen 1982).

In experiments using animals surrounded by helium at sea level while breathing nitrous oxide, bubbles dissected into subcutaneous tissue causing capillary damage manifested as severe bruising, and continued counterdiffusion resulted in fatal venous gas embolization (Idicula et al 1976). When three divers switched from a nitrogen to a helium mixture at 30 msw (100 fsw), all developed severe itching within 1 h and developed joint pain within 5–7 h suggestive of DCS. Similar experiments at 20 msw (66 fsw) caused less itching and no pain (Harvey 1977, Hamilton et al 1982).

The permeation of tissue by a gas is governed by its diffusivity-solubility product, the permeability, so helium can counterdiffuse against hydrogen, a lighter but more soluble gas. In a deep saturation dive at COMEX, Hydra V, divers decompressing from exposure to a hydrogen–helium–oxygen 'hydreliox' mix at 46 atm switched to a helium–oxygen mixture at 25 atm and then developed symptoms from counterdiffusion that resembled those of DCS and that responded to DCS treatment techniques (Gardette et al 1987, Rostain et al 1987).

Lambertsen (1989) lists some hints for avoiding trouble with counterdiffusion. Divers may switch the inert gas from helium to nitrogen, but if switching from nitrogen to helium a concomitant compression should be used (Peterson et al 1980). One should not breathe helium mixes by mask while surrounded by or saturated with nitrogen. Recompression and oxygen breathing are effective in treating counterdiffusion sickness just as for DCS, and decompression can exaggerate the effects.

Even so, anecdotal experience suggests that even after 'favorable' switches during decompression from deep dives there can be a detrimental effect on the decompression after the switch. Some of these anecdotes are likely to be a reflection of a basically inadequate decompression table, especially in cases where the ascent rate is slightly (and perhaps inappropriately) accelerated as a result of the switch. However, other cases, including cases, of vestibular decompression – or possibly counterdiffusion – sickness, are not easily explained and may be related to the switch. This remains as an area of continuing uncertainty.

GAS SEQUENCING

Professor Albert Bühlmann and Hannes Keller used the favorable aspect of inert gas differential diffusivity to perform decompression from very deep dives, both in the chamber and at sea. This technique was used in the first dives to 300 msw (1000 fsw) (Bühlmann 1969, 1975, Keller & Bühlmann 1965).

Despite standard operational practice, however, Thalmann (1985a,b) found no difference in the incidence of DCS after helium–oxygen dives when air or helium–oxygen was breathed during decompression. Momsen (1942), moreover, reported unspecified adverse effects in divers shifting from helium–oxygen to air deeper than 50 msw (165 fsw), and subsequent experiments which used rapid shifts deeper than 33 msw (110 fsw) noted vertigo and nausea suggestive of vestibular or inner ear DCS (Hamilton 1976), or as we have just seen, counterdiffusion sickness. Another possible mechanism could be the abrupt exposure to nitrogen narcosis.

Interestingly, the current methods used by technical divers for accelerating decompression (next section) are very similar to the techniques reported by Bühlmann and Keller.

TECHNICAL TRIMIX DIVING: SCUBA WITH MIXED GASES

A new form of diving began to be used in the recreational diving community in the late 1980s, centered around open circuit dives with trimixes of oxygen, helium, and nitrogen to depths in the 60 to 100 msw (200 to 325 fsw) range. Some techniques were known, such as the gas switching of Professor Bühlmann as just mentioned, but neither the commercial nor military sectors were fruitfully engaged in this sort of diving at the time, and no military heliox tables were adequate.

Origin of Modern Technical Diving

The modern form of 'technical diving' began when some Florida cave divers wanted to reduce narcosis for a specific penetration at about 75 msw (250 fsw) and added helium to the mix resulting in a 'trimix' of oxygen, helium, and nitrogen (Hamilton & Turner 1988). During decompression the divers switched to an intermediate enriched air 'deco' mix, and they breathed oxygen in the shallow stops. This pattern has persisted, with refinements. The reason such mixes had not been widely used before was that there had been no readily available decompression tables for these kinds of mixtures. Other practical considerations were the management of oxygen toxicity and narcosis, the ability to carry enough gas, thermal protection, and other exposure-related factors having to do with long decompression times.

Technical Diving Terms

The term 'technical diving' has developed as a description of this category of special-mix diving, and it has come to represent a reasonably well-defined technology. Strictly speaking, as it has developed this is still 'recreational' diving. It is recreational in the sense that most practitioners do it for fun rather than employment, but is still a highly disciplined and professional undertaking that is not at all like traditional recreational diving.

Technical diving is a method of self-contained or untethered diving (that is, no gas hose or lifeline to the surface) that extends well beyond the traditional envelope of 'recreational' diving; it relates to that as technical mountain climbing does to hiking. By one definition the minimal requirement of a technical dive is that the diver uses more than one breathing mixture. Strictly speaking deep air diving alone is not technical diving, with or without decompression stops, nor is diving with a single oxygen enriched air ('nitrox') mix. A dive with rebreather apparatus would be regarded as a technical dive. UK terminology, especially with respect to military diving, has regarded diving with rebreathers as 'technical diving' for over half a century.

Previous Technical Trimix Diving Operations

In the 1970s Italian coral gatherers with the help of diving physiologists began performing dives remarkably similar to the technical diving practice described here (Zannini & Magno 1987). Their practice included routine dives in the 70–100 msw (230–328 fsw) range. Their breathing mix was 10% oxygen, 40% helium, and 50% nitrogen. Decompression procedures were based on a Haldane–Workman–Schreiner algorithm (Schreiner & Kelley 1971) very similar to the one used for the procedures mentioned below, and the dive profiles appear to be similar in shape and duration, except that these coral gatherers performed surface decompression in a deck chamber. Decompression from a 30 min dive to 80 msw (262 fsw) required 140 min of decompression time, and about half that was on oxygen. In a series of 860 trimix dives no DCS was reported.

The British Navy began a 'trimix' program in the late 1970s using a mix of 20% oxygen, 40% helium, and 40% nitrogen with a target depth/time of 75 msw (246 fsw)/15 min (Shields et al 1978). The technique was intended to be used for mine countermeasures when diving from small craft. Laboratory trials of no-stop decompressions after 15 min at 75 msw (246 fsw) resulted in a computational model. From this, a series of tables were tested successfully prior to trials under operational conditions (Shields 1982a,b). These trials led to two decompression incidents; the trials were not reported due to newly imposed limits on oxygen partial pressures used in Royal Navy diving. The project was abandoned in favor of the heliox diving tables that are still in use.

Implementing Trimix Diving

The key to making technical trimix diving practical was the ability to perform an efficient and reliable decompression from a dive with minimal narcosis and without posing a substantial risk of oxygen toxicity. The first tables were worked out with field trials (Hamilton & Turner 1988) based on an oxygen-tolerance algorithm that had been empirically developed and laboratory validated for extreme exposure air dives (Hamilton et al 1988b). Other workers quickly began to generate tables, and soon software and tables became generally available (see Dive Planning Software, above).

Selection of the optimal breathing mixtures is a key part of planning a trimix decompression. For the bottom mix one wants enough helium to eliminate significant narcosis, but with Haldanian calculations for these short, deep dives the more helium in a trimix the longer the decompression (and the greater the cost for the gas). In calculating the 'equivalent narcotic depth' of a trimix there is some evidence that not all the oxygen should be ignored as it is when calculating decompression (Bennett 1970, Linnarsson et al 1990).

Technical trimix diving techniques have been adopted by the scientific diving community. One example of this is the diving program of the NOAA. NOAA had custom tables developed for diving on the wreck of the *USS Monitor* and have used them for several seasons, but the USN used its own recently modified heliox tables.

DECOMPRESSION WHEN USING REBREATHERS

A 'rebreather' is a self-contained diving apparatus that conserves all or much of the exhaled oxygen and inert gases from each breath and makes it suitable for reuse by scrubbing carbon dioxide and adding oxygen as necessary. There are two main types, the electronically controlled 'constant P_{O_2}' and the 'semiclosed,' of which there are several variations. This section discusses how decompression is managed using the different types. Oxygen diving is mentioned as well; it is done with rebreathers, but does not require decompression.

Semiclosed Rebreathers

Semiclosed circuit rebreathers inject a gas with a fixed oxygen percentage (frequently 32.5, 40 or 60% oxygen) into a recirculating breathing system that absorbs carbon dioxide (Barsky et al 1998, Morrison & Reimers 1982, Richardson & Menduno 1996), usually at a fixed rate that may be 10 to 20% of the minute ventilation (breathing volume). The oxygen partial pressure in the breathing loop is several percent lower than in the injected gas because some oxygen is consumed by the diver. The first consequence of this is that if the diver is working hard enough to consume more oxygen than is being injected – 'beating the flow' – then the diver may face the consequences of hypoxia or relative hypoxia, one of which is that the estimates for decompression Po_2 can be incorrect.

Some semiclosed rebreathers try to match the oxygen inflow to the needs of the diver. Normally the oxygen component is injected at a constant mass flow rate, but its injection may be mechanically controlled to be matched to activity level and/or depth, so that the set can provide an approximately constant oxygen fraction (not constant Po_2, but this does make it possible to use standard tables and minimize some of the wide swings in Po_2 seen with changes in activity level). Some units use nested bellows so a fixed fraction of the breathing volume is discarded out of each breath (Nuckols et al 1996), which provides a fair match to activity. Another more sophisticated semiclosed unit takes advantage of the fact that the physiological ratio of minute ventilation to oxygen consumption is constant over a wide range of exercise. These units actually measure the divers minute ventilation and inject a fixed amount of breathing gas each time a certain volume of gas has been breathed. In some units this compensates for depth.

Decompression is conducted according to specially computed tables or EAD corrections to standard air tables, perhaps using an weighted average Po_2 or Fo_2, or just using the 'worst case,' assuming that the lowest expected Po_2 is breathed for the entire dive. To do this properly requires that oxygen profiles be determined empirically using manned trials for the specific rebreather for the various conditions of use.

Closed Circuit Constant Po_2 Rebreathers

Rebreathers in this class maintain a fairly constant Po_2 at or close to the 'set point' (the Po_2 value at which O_2 is injected into the breathing loop) during the steady state part of a dive, but whenever the diver changes depth, the Po_2 will change and the unit will respond. The oxygen level, therefore, may be a series of 'ramps' of changing Po_2 rather than a constant value. During ascent since the Fo_2 changes slowly the Po_2 will tend to fall; to minimize this fluctuation the diver may add oxygen manually. During descent the Po_2 may increase; this is corrected by adding diluent gas, either by the diver or by the unit. The response will depend on the amount of oxygen in the diluent gas (there should always be some oxygen, for safety). Increased inspired Po_2 may cause concern about oxygen toxicity, but is conservative with respect to decompression. Gas, usually diluent, must be added during descent to keep the breathing bag from collapsing. Two versions of constant oxygen rebreathers, the Mk 15 (now out of Navy service, but many are still used by non-military divers) and Mk 16 UBAs (underwater breathing apparatus), have been used by the USN (US Department of the Navy 1999), and several other types are available to the civilian community. If operated as mentioned, the set point can be used as the average or typical inspired Po_2 value and the decompression can be calculated based on that exposure. Originally a set point of 0.7 atm was chosen as the highest set point that could be used and still guarantee that the UBA would not try to add oxygen when the apparatus was at the surface. A current version of the Mk16 has electronics that can change the set point as a function of depth. In this case the set point is 0.7 atm at 5 msw (15 fsw) and shallower and increases to 1.3 atm deeper (Johnson et al 2000).

If the Po_2 set point is as high as the diver can reasonably tolerate for the duration of the dive then the decompression will be as efficient (short decompression time) as it can be for a single background inert gas. This was pointed out by Vann (1982) for a limit of 1.4 atm, and was implemented by Clough and colleagues in the field shortly after that (Hamilton et al 1987).

SATURATION AND SATURATION-EXCURSION DIVING

SATURATION OPERATIONS

After an exposure of 24 to 48 h at constant pressure a diver's tissues become 'saturated' with the inspired inert gases; further time at depth requires no additional decompression. Saturation dives are logistically complex but avoid the stresses of multiple decompressions. In circumstances where long bottom times are needed, decompression efficiency and the ratio of bottom time to total decompression time, may be much greater than for bounce diving. The inspired oxygen partial pressure while in saturation 'storage' is generally limited to 0.3–0.5 atm to avoid pulmonary oxygen toxicity, but may be raised to 0.4–0.6 atm during decompression. Traditionally, commercial heliox saturation diving occurs at depths deeper than 60 msw (200 fsw). In the British Sector of the North Sea where stringent rules control air diving, heliox saturation is being used in the traditional air range. At depths of 300 msw (1000 fsw) and deeper, nitrogen or hydrogen may be added to the helium to ameliorate the tremor effects of the high pressure nervous syndrome (Ch. 9.3). Nitrogen narcosis limits nitrogen–oxygen saturation diving to depths shallower than about 36 msw (120 fsw), but in that range it is used effectively, mostly for scientific work.

HABITAT DIVING

Stimulated by the success of Ed Link's *Man-in-the-Sea* operations, Captain Cousteau's *Conshelf* undersea habitats, the USN's *Sealab* program, and the commercial development of saturation diving, beginning in the 1960s there was a worldwide interest in living and working in the sea (Miller & Koblick 1995). These operations and the ones that followed are undersea or sea floor 'habitats.' Miller & Koblick give a detailed listing and history of virtually all the habitats through the early 1990s; a listing can also be found in the *NOAA Diving Manual* (1991, 2001). The NOAA manuals also provide information about the life support and operational aspects of habitat diving. NOAA operates an active habitat, *Aquarius*, in the Florida Keys.

Habitats are not about decompression, but rather about avoiding or at least delaying it. They permit people to live and work for extended periods at the work site and then deal with decompression at the end of a mission. Methods for the final decompression from nitrox saturation have been revised over the years (Barry et al 1984, Hamilton et al 1982, 1988a, Hennessy et al 1985, Miller et al 1976, NOAA Diving Manual 2001). One decompression-related aspect of habitat diving is the use of excursions, covered in the next section.

EXCURSIONS FROM SATURATION

During working saturation dives, divers live in a deck chamber or habitat and commute to the work site usually in a diving bell or by swimming. The living chamber determines the storage depth (or pressure), and since the work may be at deeper or shallower depths the divers excurse to the work site depth with a vertical excursion dive, ascending or descending. Air is usually used as the excursion gas from nitrogen–oxygen saturation; oxygen partial pressures during excursions range from 0.4 to 1.6 atm. No-stop air excursions that permit direct return to nitrogen–oxygen storage without decompression have been tested and published along with complete operational procedures (Hamilton & Schane 1990, Hamilton et al 1988a, Hennessy et al 1985). Emergency access to the surface can be regarded as an upward excursion (Eckenhoff et al 1986).

Since times at the working depth are much greater during saturation excursions than are normally possible with air dives from the surface, the oxygen exposure is a factor to be considered and becomes part of the operational procedures. Excursions from air saturation using mixtures containing helium have had limited testing and are not yet fully operational (Hamilton et al 1996, Muren et al 1984). These require attention to the matter of counterdiffusion (Peterson et al 1980).

The allowable vertical distance of an excursion increases with the storage depth, and excursions of unlimited duration are allowed within a restricted depth range above and below storage (Larsen & Mazzone 1967). Excursions from helium–oxygen saturation were initially tested by the USN during the development of saturation decompression procedures. Revised operational limits were published in 1978 for storage depths from 304 to 46 msw (1000 fsw to 150 fsw) (Spaur et al 1978). Later the excursion range was extended all the way to the surface, and also the deeper excursion limits were made more conservative based on reports of DCS from the field (Thalmann 1989). The use of unlimited helium–oxygen excursions is illustrated in Fig. 10.2.5, where the storage depth can lie anywhere on a vertical line between the ascent and descent limit lines.

During descending excursions, a diver absorbs inert gas in excess of that present at storage, and during ascending excursions, inert gas may be eliminated or retained as bubbles. A recent descending excursion has to be taken into account at the beginning of saturation decompression; one method is to delay saturation decompression, but a satisfactory algorithm for determining the duration of the delay has yet to be worked out. As one approach, if a descending excursion on an oxygen–nitrogen mix occurs within 36 h of beginning decompression to the surface during nitrogen–oxygen saturation the NOAA Repex procedures call for starting the decompression with a compression (descent) up to 11 msw (35 fsw) deeper than the storage depth, followed by decompression back to storage

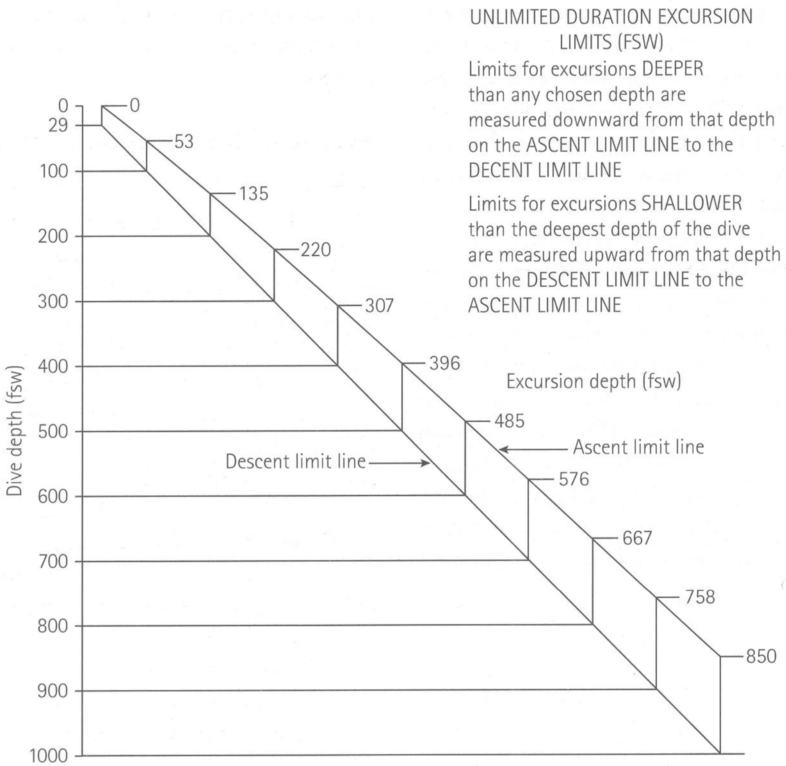

Fig. 10.2.5 USN unlimited duration helium–oxygen saturation excursion limits. Upward excursion limits in 100 fsw increments are shown. Breathing gas is at least 0.42 bar Po_2 in helium. (see Thalmann 1989)

which may take as long as 6 h (Hamilton et al 1988a); this is much quicker than waiting for many more hours.

For helium–oxygen, the USN allows an immediate upward (ascending; toward lower pressure) excursion before final decompression. The extent of this excursion is measured from the deepest point of the dive on the descent limit line, upward to the ascent limit line (Fig. 10.2.5). COMEX begins final decompression from storage without an upward excursion and normally uses more modest excursions than those in Figure 10.2.5 (Imbert et al 1992b). Saturation decompression procedures developed during the Atlantis dive series at Duke University and continued at the German GKSS laboratory (with remarkable success) also begin without an upward excursion (Bennett et al 1987, Vann 1984).

SATURATION DECOMPRESSION

USN and Commercial Procedures

After the initial start just mentioned, the current USN saturation decompression procedure calls for ascent rates of 1.84 msw/h (6 fsw/h) until 61 msw (200 fsw) is reached, 1.54 msw/h (5 fsw/h) from 61 to 31 msw (200 to 100 fsw), 1.23 msw/h (4 fsw/h) from 31 to 15.4 msw (100 to 50 fsw) and 0.92 msw/h (3 fsw/h) to the surface. In addition decompression is only done 16 h out of 24, a total of 8 h of stops being required in every 24 h period. This stop may be taken as a single 8 h stop or divided up and taken at different depths to suit operational requirements. During decompression the Po_2 is kept above 0.4 atm. Some commercial diving companies use somewhat slower rates and Po_2 levels may go as high as 0.7 atm. Note that these saturation decompression schedules were developed largely by trial and error and were not based on any particular decompression model. In practice, using a reciprocal rate is more easily executed, such that the rates 1.84, 1.53, 1.23, and 0.92 msw/h (6, 5, 4, and 3 fsw/h) become 32.6, 39.1, 48.9, and 65.1 min/msw (10, 12, 15, and 20 min/fsw), a bit awkward but still easier than msw/h).

Ascent rates for nitrogen–oxygen saturation schedules had been well established by the 'habitat diving' community since the 1970s; they are slower than for helium–oxygen. Investigators at the Navy Experimental Diving Unit, in developing a saturation treatment schedule from 18.4 msw (60 fsw) using air, first tried to use the helium–oxygen decompression ascent rates (Buckingham & Thalmann 1981). This produced an unacceptable level of DCS, and the rates had to be reduced to 0.92 msw/h (3 fsw/h) to 12 msw (40 fsw), 0.61 msw/h (2 fsw/h) to 6 msw (20 fsw), and 0.31 msw/h (1 fsw/h) to the surface to produce an acceptable schedule (65.1, 98, and 195 min/msw; 20, 30, and 60 min/fsw). These rates are currently specified for the USN 18 msw (60 fsw) saturation Treatment Table 7, which has been used successfully many times.

The Role of Oxygen and the Vann k Function

As saturation decompression tables evolved during the 1960s through 1980s, the ascent rate, inspired oxygen partial pressure, inert gas species, and saturation depth emerged as factors that might influence the risk of DCS. During decompression from helium–oxygen saturation dives, Vorosmarti et al (1978) after observing that the British Navy had fewer cases of DCS at similar ascent rates found that raising the inspired oxygen partial pressure from 0.22 atm to 0.4 atm reduced the incidence of DCS from 52% (14 incidents in 27 dives) to zero (no incidents in 42 dives; $p < 0.0001$).

A simple model relating the rate of ascent from a saturation dive to the inspired oxygen partial pressure (P_{IO2}) assumes that ascent rate is a linear function of oxygen partial pressure (Eckenhoff & Vann 1985, Hamilton et al 1988a, Hennessy 1978, Vann 1984, 1986, Vann & Dick 1981).

$$\text{rate} = k \times P_{IO2}, \qquad (2)$$

where

rate is ascent rate,

P_{IO2} is oxygen partial pressure,

k is an empirically determined constant.

To develop a saturation decompression procedure, the value of k (sometimes called 'Vann k') in Equation 2 and the resulting ascent rate is adjusted in successive dives until the incidence of DCS becomes acceptably low.

The estimates of k indicate that ascent rates for helium can be two to three times faster than ascent rates for nitrogen at the same saturation depth (Vann 1984). The ascent rates are approximately equal for helium–oxygen saturation at 600 msw (2000 fsw) and nitrogen–oxygen saturation at 30 msw (100 fsw). This is supported by empirical data.

Effect of Depth

An effect of saturation depth on ascent rate was suggested by a comparison of DCS incidences for air or nitrogen–oxygen dives deeper and shallower than 30 msw (100 fsw) (Barry et al 1984), supporting the concept that ascent rate has to be slower for deeper saturation depths. Ascent rate was shown to be a decreasing function of depth using a bubble model and likelihood analysis of 233 man-decompressions (Vann 1986).

Acclerated Decompression for Submarine Rescue

In recent experimental work by the USN Experimental Diving Unit attempts were made to accelerate decompression from air saturation with extra oxygen as part of a submarine rescue plan (Latson et al 2000). This acceleration was necessary because in some operational scenarios additional personnel could not be rescued until decompression on the preceding group had been completed. Subject divers were exposed for 72 h at a P_{O_2} level simulating the inert gas partial pressure at saturation depths on air of 12.3 and 15.4 msw (40 and 50 fsw). Decompression involved breathing oxygen continuously at five graduated stage pressures during the decompression to the surface. Outcome of the initial decompressions was disappointing, with an unacceptable level of DCS including several neurological cases (Latson et al 1999).

When oxygen was 'prebreathed' for 4 h prior to starting decompression the results were much better. The isobaric nitrogen elimination allowed ascent in 5.3 h, in contrast with 10.3 h for the case in which oxygen was breathed during the decompression (Latson et al 2000) with a much lower incidence of DCS. Interestingly, the divers who breathed the oxygen at the deeper depth prior to ascent had less pulmonary oxygen toxicity (Maurer et al 2000). Studies on these prebreathing procedures continue.

HYPOBARIC DECOMPRESSION

ALTITUDE AND DIVING

Diving at Altitude

Diving at high elevations is different from diving at sea level, with respect to both decompression and operations. Water is usually fresh so has a lower density, ambient pressure is lower at the surface, and consequently the tolerated supersaturation (in Haldane terms, or its equivalent) may be lower. There is a great difference in the risk of bends depending on whether the diver has been at altitude for some time and is acclimated to the lower pressure at the ambient altitude or has recently arrived and maintains gas loadings near those of sea level. Some dive computers are equipped for diving at altitude; if used properly these may be quite effective.

To develop tables for diving at altitude the reference point, the surface, needs to be shifted to a new pressure, and some adjustment may need to be made in determining the ascent limits. One successful system has divers reset their seawater gauges to zero at the surface and carry out the tables in the same manner as at sea level, using tables adjusted for altitude. There is no need to use freshwater gauges if this resetting can be done, as long as the pressures of the dive profile match the tables (but note: gauges and dive computers made in Switzerland are all calibrated in freshwater units!).

The best known of the adjustments to altitude of tables are the widely used Cross Corrections (Cross 1967, 1970). These are conservative but useful. They have been reviewed in detail by Bassett (1979) and by Bell & Borgwardt (1976). The Cross Corrections use the ratio of atmospheric pressure at sea level to that at the elevation of the dive site to provide an equivalent sea level dive depth, which can then be used with regular tables (procedure described in NOAA Diving Manual 2001); there is also a term for dealing with the relative densities of fresh- and seawater. Wienke (1993) has provided a useful set of guidelines addressing decompression aspects of diving at altitude, offering criteria that, briefly, might be said to use phase based critical tensions that decrease exponentially as pressure is reduced.

Another method is that proposed by Bühlmann, which calculates the tolerable maximum allowable $P\text{N}_2$ at a particular ambient pressure from functions of the compartment half-times and ambient pressure (Bühlmann 1984, 1989, 1995). His method uses a linear decrease in tolerated $P\text{N}_2$ with ambient pressure. Surface values computed from half-times are then extrapolated linearly to different ambient pressures. Bühlmann's method has always had a strong empirical element to it, with both retrospective and prospective data.

Egi and Brubakk have performed a comprehensive analysis of several of the 'strategies' for preparing tables for diving at altitude, or more specifically, for translating the critical tensions to reduced pressures (Egi 1998, Egi & Brubakk 1995). These methods include linear extrapolation (LEM), constant ratio translation (CRT), and constant ratio extrapolation (CRE) of permissible supersaturations (*M*-values, critical tensions, MPTT, tolerated $P\text{N}_2$, etc.). They found that CRT and CRE give the same no-stop times, and are more conservative than LEM. When stops are used, CRT is more conservative than CRE.

Flying After Diving

A first cousin to the problem of diving at altitude is that of flying after diving. A diver at 1 atm with a gas loading from a recent dive is at extra risk when subjected to lower pressure, as might be the case when flying or otherwise going to a higher altitude. In fact, altitude provocation is a research tool that can magnify the stress of an exposure (Lanphier 1989). Most of the algorithms used for diving at altitude have been applied to predicting the flying after diving situation. Few have been tested. USN and other groups have had reports of DCS on flying after saturation diving, even after several days.

There is a need for rules as to when a recreational diver after a few days of diving at a resort can fly home, or when an offshore commercial diver can board a helicopter to return to shore. Any rule, unless it refers specifically to the diver's recent history, has to cover a wide range of exposures, basically the worst case. One proposed method based on repetitive groups determines when it is 'safe' to fly after a dive. For example, a diver might be required to have a repetitive group designation of 'D' or less before flying. Another more common configuration for such rules is to set a delay time from diving to flying. Sheffield has reviewed the available data and opinions (Sheffield 1990).

Responding to requests for guidance from helicopter pilots serving offshore oil operations, in 1982 the UK Diving Medical Advisory Committee (DMAC) convened a workshop to examine the matter of flying offshore divers back to shore (DMAC 1982). This group recommended delay times for nitrogen and helium based diving, for ascent to cabin altitudes of 610 and 2438 m (2000 and 8000 feet). The DMAC later revised the times conservatively for ascent to 2438 m (8000 feet) altitude (DMAC 2000). As an example, for most normal diving and heliox saturation, the 'pre-flight surface interval' (PFSI) should be 12 h for flights to 600 m (2000 ft) and 24 h for flights to 2438 m (8000 ft). More stringent rules apply to divers who have been treated for DCI. This does not mean that all divers have tested the limits, only that they have followed the rules. Even so, there have been very few incidents in commercial diving.

A workshop of experts was convened in 1989 by the Undersea and Hyperbaric Medical Society to address this issue for recreational divers (Sheffield 1989). This workshop suggested a delay of 12 h after less than 2 h of diving (specifically no-stop diving) in the last 48 h, and a 24 h delay for multiday, decompression or unlimited diving, with 48 h recommended after decompression dives. It was pointed out by Dr Lambertsen that oxygen breathing was the only way to reduce the duration of the PFSI.

The recreational community objected to these limits because they resulted in a risk level that was lower than that for the dives themselves. This is explained very well by Gerth et al (1993), who used statistical analysis to match risk levels with the various major dive patterns. They found that the traditional risk level (the USN no-stop tables have a P_{DCS} of 2.3%) could be maintained after 12 h PFSIs, especially if the dives were short and deep, but that it would be less conservative after long, shallow dives. Longer PFSIs would be needed to achieve a 1% predicted incidence. Flying after multiday recreational-type diving incurs only slight additional risk.

DECOMPRESSING TO ALTITUDE

Although it is not a part of diving medicine, the matter of decompressing to altitude is one of the most active areas of decompression research. The main objectives here are for astronauts to be able to work in space, and for high altitude pilots to carry out their missions without DCS. One of the differences between altitude and diving DCS is that neurological DCS is rare as a result of altitude decompressions, the vast majority of symptoms being joint pain.

To work in space – extravehicular activity (EVA), sometimes called a 'space walk' – the US astronaut has to be decompressed from about 1 atm in the space shuttle or space station to the suit pressure, 4.3 psi (0.293 atm; 29.7 kPa). Most people saturated with air at 1 atm will get DCS on going to this pressure unless they do oxygen prebreathing. NASA has determined that 4 h of oxygen breathing will reduce the incidence of DCS to a satisfactory level (Conkin et al 1990, 1996, Van Liew et al 1996). For Space Shuttle operations the cabin pressure is reduced and the entire crew (the entire spacecraft) is decompressed overnight to 10.2 psia (0.694 atm; 70.3 kPa). From storage at this pressure, only 45 min of prebreathing is needed before decompressing to suit pressure. For International Space Station operations the internal pressure cannot be reduced, so another method is being used, having the astronaut perform selective intense exercise during a short (e.g. 45 min) prebreathe period (Loftin et al 1997, Webb et al 1996).

An interesting bit of decompression physiology has been observed in these profiles. When simulated in a pressure chamber, a pressure profile that works well enough in space causes an unacceptable level of DCS. Although it may not always be easy to recognize DCS symptoms when working in a spacesuit because of restricted movement, a hypothesis offered by Dr Michael Powell suggests that this lack of symptoms is believed to be because the astronaut in a weightless or microgravity environment with reduced stresses on joints does not generate enough of the microbubbles that act as nuclei for the bubbles causing DCS. Simulations in which subjects are kept in bed rest conditions for a day or so before being decompressed have about the same lower DCS incidence as being in space (Conkin & Powell 2001, Powell et al 1993).

The other situation exposing people at work to very low pressures is military pilots in SR-71 and U-2 very high altitude surveillance aircraft and the newer fighters (F-22; Eurofighter; JSF), and other special forces problems such as high altitude parachutists. This situation has been reviewed in two workshops (Pilmanis 1992, Pilmanis & Sears 1995). At the aircraft's service ceiling the cabin pressure of a modern fighter is 6858 msw (22 500 feet) altitude (0.414 atm; 42 kPa), which is well above the altitude threshold for DCS (Hankins et al 2000). There are many other operational considerations, and some physiologic ones such as the fact that the risk begins to go down after a while in an aircrew breathing oxygen but above the bends altitude, just as it does after prebreathing of oxygen. One consideration is that DCS cases developing in training for such operations may be as troublesome operationally as those in flight. In order to be able to predict the decompression effects of these exposures the US Air Force has developed a predictive model based on empirical data and supported by laboratory exposures, and have installed this into a small computer (Kannan et al 1998, Pilmanis et al 1999). First operational use suggests that this is quite reliable.

THE ROLE OF OXYGEN IN DIVING

BACKGROUND OXYGEN PHYSIOLOGY: THE OXYGEN WINDOW

The benefits of oxygen in decompression have been known for over a century (Bert 1878) and it is almost axiomatic in decompression table calculation that for a given table, the higher the P_{O_2} breathed, the lower the risk of DCS. In fact, many decompression models do not even take oxygen into account, and track only inert gas partial pressure. Oxygen is different from inert gas because it is metabolized by tissue. Because of this, at 1 atm tissue is usually undersaturated. This was put in perspective by Behnke in 1967 by the introduction of the term 'oxygen window.' This describes a 'partial pressure vacancy' in body tissues due to the metabolic consumption of oxygen (Momsen 1942). The window is the difference between the oxygen partial pressure (tension) in the arterial blood and the level prevailing in the tissue. This has been termed the 'inherent unsaturation' by Hills (1977).

What makes oxygen especially useful in decompression is amply illustrated in Fig. 10.1.7 of the preceding chapter. The bottom panel shows that as the arterial PO_2 is increased, the total tissue gas tension (which is usually considered equal to the venous) remains relatively constant over a range that depends on the tissue O_2 extraction, i.e. the metabolic rate. At some point the tissue gas tension (oxygen) begins to rise and becomes linear. This occurs when the venous hemoglobin is saturated and any additional oxygen is carried dissolved in the plasma. When this occurs, venous oxygen tension increases at the same rate as arterial and the oxygen behaves like an inert gas. It is in the range before this where the total tissue gas tension remains constant that increased oxygen partial pressure can play a role. The increased arterial O_2 partial pressure causes the arterial inert gas partial pressure to drop, increasing the elimination gradient while the total tissue inert gas tension does not increase, and this reduces the degree of supersaturation and the possibility of gas phase separation and bubble formation. If one simply switched inert gases, say from nitrogen to helium, the elimination gradient would change but the total tissue gas tension would remain the same since inert gas is not metabolized. However, once the point is reached where venous hemoglobin is 100% saturated, oxygen loses any additional benefit.

A slight complicating factor is that oxygen is a vasoconstrictor (Plewes & Farhi 1983), and therefore elevated oxygen partial pressures may decrease blood flow and therefore inert gas elimination (Anderson et al 1991).

OXYGEN'S APPLICATION IN DECOMPRESSION

Were it not for its toxicity, oxygen would be the ideal gas for diving from the decompression perspective. Decompression is not required after dives using 100% oxygen rebreathers, and when breathing high oxygen partial pressures in diving, decompression requirements are greatly reduced. Without toxicity, the practical limit would most likely be oxygen's density as a breathing gas, which would not likely become limiting until depths beyond perhaps 100 msw (328 fsw) had been reached. Narcosis due to oxygen could perhaps be an even more important factor at these depths, but there is little quantitative information about this (Bennett 1970).

As noted above, the only problem with increasing the oxygen partial pressure is the specter of oxygen convulsions, so the oxygen partial pressure must be managed in such a way that the likelihood of this occurring is minimized.

The mechanism by which oxygen decreases the risk of DCS differs in different types of diving. In dives requiring decompression, at the stops the higher arterial oxygen will increase the gradient for inert gas elimination without adding to the tissue tension itself. In no-stop diving it is the total gas tension in tissue that is important, since little or no elimination will take place during ascent to the surface. Breathing high oxygen partial pressures increases the tissue undersaturation, that is, the amount by which tissue tension is less than ambient. During ascent, arterial tension stays equal to ambient but the gas dissolved in tissue takes time to be eliminated. Eventually a point is reached where the tissue gas tension exceeds ambient, so called supersaturation. Since the high O_2 has reduced the total tissue gas tension, the degree of supersaturation is reduced, reducing the probability of bubble formation and the risk of DCS. This feature of oxygen is what the EAD concept, disscussed above, is based upon. Thus it appears possible to calculate a no-stop decompression over most of the air diving range and where oxygen levels are reasonable by virtually ignoring the oxygen component and calculating the profile based on the inert gas fraction only.

To put this in perspective, the EAD concept has worked since it was first introduced many years ago (Logan 1961). One laboratory study directed at this issue failed to show that this was not valid (Weathersby et al 1986, reviewed by Vann 1989, Weathersby et al 1987). So over some range oxygen's contribution to DCS risk is minimal. However, in some contexts where large amounts of oxygen are breathed during decompression, some decompression models provide a better fit to actual dive data when some contribution to DCS risk from oxygen is included (Parker et al 1998).

SURFACE INTERVAL OXYGEN

In-water oxygen decompression and surface decompression with oxygen extend bottom time significantly but introduce the risk of oxygen toxicity. An alternative use of oxygen which achieves some bottom time extension with less risk is to breathe oxygen during the surface intervals between repetitive dives. Surface interval oxygen (SIO_2) repetitive diving procedures are published in the French Navy Air Tables (Meliet 1990), and SIO_2 has been used to reduce preflight surface intervals (Edel 1970) and in an attempt to reduce the risk of DCS after caisson work (Nashimoto 1989). In chamber and field trials of repetitive nitrogen–oxygen diving (Fawcett et al 1992), 30 min of SIO_2 increased

Table 10.2.1 USN limits for oxygen diving. The table shows single-depth oxygen exposure limits and time limits for a single downward excursion that can be made by a diver within the 25 fsw/240 min limit.

Single-depth oxygen limits		Single excursion limits from 25 fsw/240 min	
Depth (fsw)	Maximum oxygen time (min)	Depth (fsw)	Maximum time (min)
25	240	26–40	15
30	80	41–50	5
35	25		
40	15		
50	10		

no-stop dive times by 34 to 120% over diving with air breathing surface intervals (Dinsmore 1989).

OXYGEN DIVING

As mentioned above, 100% oxygen is a useful diving gas only for very shallow dives, for practical purposes to a depth of 7 msw (23 fsw), although brief excursions to as deep as 15 msw (50 fsw) are possible. This is useful for military purposes because divers can breathe using relatively simple closed circuit rebreathers that give off no bubbles, yet the depths are deep enough to conceal the divers. Oxygen divers usually wear full-face masks. Because of its toxicity, exposure times are limited for pure oxygen dives; the deeper the depth down to a maximum of 15 msw (50 fsw), the shorter the allowable exposure time (US Department of the Navy 1999). The USN limits have been refined by laboratory and field exposure tests (Butler 1986, Butler & Thalmann 1984, 1986). These oxygen limits allow somewhat longer exposures than those for diving with mixed gases. The theoretical reason is that the greater depths attained in mixed gas diving lead to gas densities that result in some CO_2 retention due to increased breathing resistance. Two sets of operational oxygen diving limits are used by the USN, one where the diver spends the whole dive at one depth, and the other in which the diver makes a transit for most of the dive but can make an excursion. These are shown in Table 10.2.1.

Because oxygen is breathed with a closed circuit rebreather, several problems can occur, some of which are not likely with open circuit diving, such as hypoxia, carbon dioxide build-up, caustic cocktail from the absorbent material, and middle ear oxygen absorption syndrome. This last phenomenon occurs when a diver goes to sleep when the gas in the middle ear is predominately oxygen. The oxygen will be absorbed in a few hours and if the diver does not 'clear' the ears (as during sleep) a painful ear block can result. Navy procedures include dealing with a convulsion in an oxygen diver.

MANAGING EXPOSURE TO OXYGEN

Oxygen is used extensively in diving, and divers must deal with its toxicity. The physiologic effects of oxygen under pressure are well covered in Chapter 9.4. From a practical perspective we are concerned with two main 'types' or overt manifestations of oxygen toxicity. The first of these is the classical central nervous system (CNS) toxicity, and the other is a more slowly developing 'pulmonary' oxygen toxicity although other organ systems can be affected in a variety of ways (Ch. 9.4) (Clark, 1993, Clark & Lambertsen 1971, Sterk & Schrier 1985).

The main concern of CNS toxicity is that it may lead to a generalized tonic–clonic convulsion, not dangerous in itself but which in a diver can easily result in drowing or physical injury. The pulmonary toxicity may be a problem in situations that involve long or repeated exposures to elevated oxygen levels that are below the range needed to invoke CNS toxicity. Practical methods for dealing with both of these manifestations have been developed for different types of diving operations.

MANAGING CNS OXYGEN TOXICITY

Signs and Symptoms

CNS toxicity acts at higher $P\text{O}_2$ levels – above about 1.8 atm – after short exposures of a few to many minutes. It is random and unpredictable, even in the same subject on the same dive profile, and may come without warning (Donald 1992). Other manifestations are justification to stop an exposure, abort a dive, or reduce the oxygen level. A seizure may occur up to several minutes after the exposure to high oxygen has been stopped, the so-called 'off effect.'

Table 10.2.2 NOAA oxygen exposure limits. The table gives limits in min for a single P_{O_2} exposure level, and for each day (24 h). (NOAA Diving Manual 2001, Tables 15.2, 16.5)

P_{O_2} (atm)	Maximum single exposure (min)	Maximum min/24 h
1.60	45	150
1.55	83	165
1.50	120	180
1.45	135	180
1.40	150	180
1.35	165	195
1.30	180	210
1.25	195	225
1.20	210	240
1.10	240	270
1.00	300	300
0.90	360	360
0.80	450	450
0.70	570	570
0.60	720	720

Depth/time Limits

The main tactic used by most diving organizations to avoid CNS toxicity is by means of empirically determined dose or exposure limits. These 'dose' limits are usually implemented by restricting exposure duration for specific oxygen partial pressures.

A set of oxygen exposure limits was used by the USN from 1970 to 1993 (e.g. see the *USN Diving Manual* 1981, Fig. 9–20 and Sec. 15.2.1). These are different from the values in Table 10.2.1, which apply only to diving with 100% oxygen. Although widely observed and even adopted into national standards, these limits were largely arbitrary, only partly based on experience, and not physiologically consistent. NOAA, with the help of Lambertsen and colleagues, produced a more appropriate chart that first appeared in the 1991 edition of the *NOAA Diving Manual*. This was modified in the 2001 edition, which includes limits interpolated at 0.05 atm P_{O_2} levels, and omits a set of ineffective 'exceptional' limits that were uncertain in both applicability and risk. The values from this chart – Tables 15.2 and 16.5 in the 2001 edition of the *NOAA Diving Manual* – are given in Table 10.2.2. Since 1993 the USN has replaced its historic limits with a single limit of 1.3 atm P_{O_2} with unlimited exposure time.

It should go on the record that these limits do not necessarily separate certain toxicity from absolute safety, they simply minimize the probability of symptoms. Some of the values in Table 10.2.2 are not consistent with other limits given below.

Operational management of oxygen exposure consists of monitoring the approach to the tolerance limit and planning the exposure so as to avoid reaching it, possibly with interpolation. This monitoring is often referred to as the 'oxygen clock,' which is 'running' during the exposure to high oxygen (Rutkowski 1989), or as the 'O_2 limit fraction.' None of the sets of limits deal specifically with exposures to more than one level or for less than the limit duration. Linear interpolation between limit values in the chart (both pressure and time) was suggested by Kenyon & Hamilton (1989), and some technical diving training organizations arrived at the same procedure independently; as just mentioned NOAA has included interpolated limits in its limit charts. There is no objective experimental evidence that this interpolation procedure is physiologically correct, but it seems to work and there have been no reported incidents suggesting that the interpolation itself has caused problems. For that matter the chart values themselves are a compilation of experience and have not been tested precisely under laboratory conditions.

Intermittent Exposures: Cycles

A well established technique for reducing or postponing CNS oxygen poisoning is the method of intermittent exposure (covered extensively in Ch. 9.4). If 'breaks' of a period of low oxygen are taken during oxygen breathing the tolerance is greatly improved. This has been demonstrated to avoid oxygen convulsions in all but rare cases, and also to postpone pulmonary toxicity at high P_{O_2}.

In diving practice, oxygen or high-oxygen mixtures are usually breathed in *cycles*. A 'cycle' is a period breathing an oxygen-rich mix or oxygen followed by a period off oxygen, breathing air or the chamber atmosphere. A typical cycle is 20 or 25 min on O_2 followed by 5 min off. Exposures far above the limits in the charts have been tolerated by using cycles during the exposure. Breathing in cycles is used in surface decompression and in treatment for DCS.

A related question is how long it takes a diver to recover after a hyperoxic exposure. Few studies have addressed this issue specifically. USN rules (from 1993) consider that a 2 h break in a normoxic environment is enough to recover, and a new oxygen procedure can begin. Others may use an exponential decay; one such approach uses a highly arbitrary 90 min half-time (Bohrer & Hamilton 1993, Mount 1998) that at least provides a quantitative recovery pattern that is believed to be quite conservative.

Countermeasures

Susceptibility to CNS toxicity is exacerbated by other factors that might modify sensitivity to oxygen, particularly those that cause an increase in internal $P\mathrm{CO_2}$. Among these are immersion, excessively hot or cold water exposure, exercise, breathing dense gas or breathing against a resistance, prolonged immersion, and shivering. Divers relying on these limits should have low resistance breathing equipment, and should avoid any unnecessary heavy exercise, any build-up of CO_2, or extremes of temperature. Divers pushing the oxygen limits are wise to wear a full-face mask and make provision for dealing with a convulsion should it occur since a convulsion will almost certainly cause the mouthpiece to be spat out.

MANAGING PULMONARY AND OTHER SLOWLY DEVELOPING OXYGEN TOXICITIES

Pulmonary toxicity is the most prominent and most easily monitored of the non-CNS, slowly developing oxygen toxicity symptoms. A more general term, albeit awkward, is 'whole body' toxicity, which encompasses pulmonary symptoms as well as paresthesias (especially numbness in fingertips and toes), headache, dizziness, nausea, noticeable effects on the eyes, and a dramatic reduction of aerobic capacity. This syndrome has been described in detail by Sterk (1986, 1987, Sterk & Schrier 1985) and it is mentioned in part in Chapter 9.4. A more severe exposure has been described by Crosbie et al (1982).

Traditional Pulmonary Toxicity Units (UPTD) and (CPTD)

Oxygen poisoning is the effect of a drug, and the degree of exposure is a 'dose.' Methods of measuring or estimating the dose of oxygen exposure are needed. A simple but meaningful method of measuring exposure to oxygen is to consider the $P\mathrm{O_2}$ (the oxygen partial pressure) and the duration of the exposure. In this approach the dose is the integral of the $P\mathrm{O_2}$ over time. Limits are expressed as the time limit that a given integrated $P\mathrm{O_2}$ level may be tolerated. As mentioned above, this is also the method usually used to manage CNS toxicity, for example when using the NOAA limits.

With regard to pulmonary oxygen toxicity, an empirical method of computing the dose of an exposure was developed some years ago at the University of Pennsylvania, the unit pulmonary toxicity dose or UPTD (when 'cumulative' it is called CPTD). A 'unit' dose is the effect of 1 min of exposure at 1 atm $P\mathrm{O_2}$, manifested as a reduction in lung vital capacity. Vital capacity was chosen as the parameter to measure the response to a dose because it is one of the most prominent objective symptoms, and because it can be measured non-invasively with some training. The method uses a curve fitted to the available vital capacity data and described by an exponential equation (Bardin & Lambertsen 1970, Wright 1972). For several years now divers have been using a practical derivative of the UPTD/CPTD method for keeping track of oxygen exposures.

The Repex Approach: Whole-body Units (OTU)

The Pennsylvania unit (UPTD or CPTD) has served well and is still widely used. Another approach using the same method of calculation but with a different name is being used mostly by the recreational and scientific diving communities. This approach is derived from a NOAA sponsored project to manage oxygen tolerance in *rep*etitive air *ex*cursions from a seafloor habitat and defined as 'Repex,' so it is called the Repex method (Hamilton 1989, Hamilton et al 1988a).

Repex uses the same basic UPTD unit, but it has been renamed to, 'OTU' or 'oxygen tolerance unit.' This was done because 'tolerance' seems more friendly than 'toxicity' and because there had been some confusion between the UPTD and CPTD, although there is really only one 'unit.' Also, it does not relate only to pulmonary problems.

The OTU and its predecessors are calculated by the following expression:

$$\mathrm{OTU} = t \times \left(\frac{P\mathrm{O_2} - 0.5}{0.5}\right)^{0.83} \tag{3}$$

where t is the duration of the exposure in minutes and $P\mathrm{O_2}$ is the oxygen partial pressure in atm or bars. The 0.5 atm is the 'threshold' below which no significant symptoms develop (Bardin & Lambertsen 1970, Wright 1972); even oxygen-injured lungs can recover at

Exposure (days)	Daily dose	Total OTU
1	850	850
2	700	1400
3	620	1860
4	525	2100
5	460	2300
6	420	2520
7	380	2660
8	350	2800
9	330	2970
10	310	3100
11	300	3300
12	300	3600
13	300	3900
14	300	4200
15–30	300	as reqd

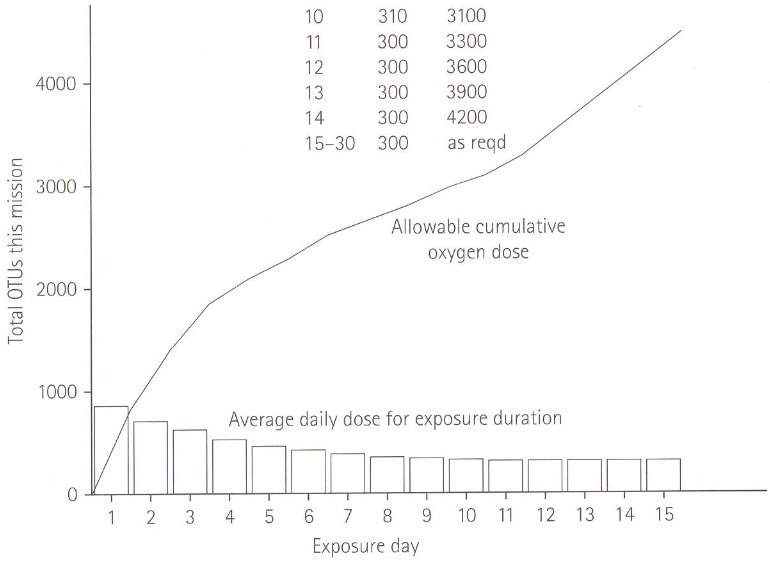

Fig. 10.2.6 Repex whole-body operational exposure limits. OTUs are calculated like UPTDs. For a diver starting fresh, the daily exposures in OTU are totaled and compared with the curve (Hamilton 1989). Divers staying below the curve normally avoid any but mild, operationally acceptable symptoms. Recovery when exposed to a $P\text{O}_2$ of less than 0.5 atm seems to be equivalent to about 300 OTUs per day.

exposures below this level (Eckenhoff et al 1987) (for a review and look-up charts see Shilling et al 1976).

The equation gave the best fit to the available data on reduction of vital capacity as a function of oxygen exposure; it gives added effect to doses above a $P\text{O}_2$ of 1.0 and less to those lower than 1.0. The resulting units are additive, and the net result of multiple short exposures can be totaled. It should be noted that because of improvements in the data set on which this is based this equation is not given in Chapter 9.4 (Lambertsen et al 1999); it is included here because it still works well to estimate the effect of operational exposures.

The Pennsylvania UPTD-CPTD dose measure did not specify limits for different situations, and it lacked an algorithm for dealing with recovery and multiday exposures. One guideline 'limit' is that 615 units accumulated in a relatively short time (hours) predicts a vital capacity reduction of 4%, a value considered to be operationally tolerable. On a continuous multiday basis 615 units/day is far too much oxygen, yet for a single first day of exposure a higher dose of about 850 units has been found to be operationally acceptable.

The Repex oxygen algorithm was developed to control daily high oxygen doses on a multiday basis. The algorithm shows that on a daily basis the total tolerable exposure limit (in OTUs) is a function of the duration, in days, of the total period of exposure to elevated oxygen, along with the daily dose. The multiday approach thus indirectly takes recovery into account. Purely empirical, Repex uses experience with accumulated doses from a variety of laboratory and operational exposures to elevated oxygen integrated into a single set of limits as shown in Fig. 10.2.6. The figure shows a total dose as a function of 'mission duration' (days of exposure) with the individual daily totals. The daily limits are intended to be operational limits, such that at any time a diver should be able to tolerate additional exposure equivalent to a standard USN Table 6 treatment (about 600 units) with only mild lung irritation and maybe other minor symptoms as acceptable side effects of the treatment.

There is an apparent discrepancy between the limits of Fig. 10.2.6 and the NOAA Limits of Table 10.2.2. Although Table 10.2.2 is intended primarily for CNS toxicity, which would apply to the PO_2 values above 1.2 atm, it also includes limits for exposures to lower levels. These were intended to address pulmonary toxicity, and are the more conservative values appropriate for long term exposure. The Repex limits allow higher PO_2 levels for the first few days of exposure.

DECOMPRESSION DOCUMENTATION

PROFILES OF INTEREST

A dominant theme throughout this section on decompression practice is that decompression is still strongly based on empirical experience. The decompression models, both deterministic and statistical, help to put this experience into usable form. Statistical models inherently require data from actual diving, i.e. empirical experience. In order for experience from a dive or set of dives to be useful it is necessary that certain parameters be recorded or otherwise documented. The most important of these is the *time-pressure-breathing gas* profile. One more factor without which the profile data is meaningless is the *outcome*, whether or not the diver experienced any symptoms of DCS following the exposure and details about that.

From the point of view of the statistical researcher (e.g. Weathersby et al 1984), dive data is primary or secondary. Only primary data is useful in developing new decompression procedures. Primary dive profiles ideally are precisely defined to within a third of an msw (or a foot of seawater) and a third of a minute, with oxygen known to within one percentage point (Weathersby & Survanshi 1991). Other essential information includes descriptions of symptoms (should they occur), their onset time, treatment, and treatment outcome, taken by a person trained in the recognition of DCS. Self-reporting of symptoms is not considered adequate for a dive profile to be considered primary data. All dives must be reported, including those that are trouble free. Primary data are usually developed in laboratory trials, which are necessarily expensive, but at-sea trials may be used if all of the above conditions can be met.

COMMERCIAL FIELD DATA

Commercial, military, and sometimes scientific diving organizations take a different approach to dive documentation, usually focussing more on the purpose, participants, and accomplishments of a dive, for example, than on the precision of the profile. However, these groups usually consider dive documentation an integral and essential part of a diving operation (Sterk & Hamilton 1991). Such dive records constitute 'field data' and are useful for some analyses. Shields and colleagues have reviewed diving company logs of many thousands of dives in the North Sea (Shields & Lee 1986, summarized in Robertson & Simpson 1997). These provide no exact depth time information but since all the dive records are included they do permit the overall incidence to be studied. In order to calculate incidences a 'denominator' is needed. That is, the number of events of interest has to apply to a specific number of dives.

When the incidence of DCS is less than 1%, tens of thousands of dives are necessary to generate enough incidents on which to base inferences concerning risk factors. An operational setting is the only environment where this level of data acquisition is possible, even though it may be without exact knowledge of dive conditions and profiles such that confident conclusions are often not possible. In the case of the sur-d/O_2 and hot-water suits (mentioned in Surface-Supplied Diving, Surface Decompression), for example, one cannot be certain whether the increased incidence of DCS was due to the procedures themselves or their use on the higher risk dives. Field data is essential to validate that a procedure is operationally acceptable, but in order to work out reasons for the observations it may be necessary to get laboratory data.

DAN FIELD DATA

Another approach to dive data is a multiyear program sponsored by the Diver's Alert Network and known as Project Dive Exploration (Vann & Uguccioni 2001). PDE is collecting data on recreational dives using dive computers to record the profiles. Trained field data co-ordinators monitor the diving operations, collect the dive profiles, and perform the all-important assessment of outcome. Before PDE, DAN was able to collect reports only on the occurrence of DCS among recreational divers who have actually reported DCS, but no 'denominator' was available with which to establish incidence levels.

The PDE study has several distinct characteristics. First, it is a prospective study and relies only on dive data collected by the project. PDE uses trained field research co-ordinators to monitor the diving operations, collect the dive profiles, and perform the all-important assessment of outcome so data are collected on the entire population, irrespective of the outcome. Although not dedicated to the study of dive computers, PDE uses recording dive computers to secure accurate profiles, and rigorous follow-up to ensure that the DCS-related outcome of every dive is collected.

PDE provides something else, in that a great deal of effort has gone into the structure and methods of using the database, and the concepts and techniques are available to others (Denoble et al 1999). Dive computers themselves are discussed in Surface-Supplied Diving, above. In addition, with some assistance from DAN, the USN is instituting a program among Special Forces divers similar to PDE with an eye towards getting a better look at the types of profiles being done operationally as well as their DCS incidence.

VALIDATION OF DECOMPRESSION PROCEDURES

Once a new model or algorithm for decompression tables is created and tables are generated, it is necessary in some ways to validate that the new procedures do in fact provide reliable decompressions. This issue has been addressed in a UHMS Workshop on Validation of Decompression Tables (Schreiner & Hamilton 1989). One approach to table validation is to perform prospective laboratory trials which have the advantage of allowing precise control of dive profiles and rapid and aggressive treatment should DCS occur. Even a few tests might be helpful to rule out a really unworkable approach or an occult disaster, but even a few trials can be expensive and there is often limited statistical confidence in the results. This is troublesome even if a large test program is contemplated, because if the actual incidence (P_{DCS}) is low then a large number of trials is necessary to provide even a reasonable estimate of it.

There is another approach. The consensus of the UHMS Validation Workshop was that if new tables were close enough to existing tables on which there is an experience base or if they are close to a proven algorithm, then new tables can be put into the field for 'operational evaluation' under special conditions without the need for specific laboratory trials. The operative word here is 'interpolative' rather than extrapolative – the new tables or their key parameters should fall within known limits by interpolation instead of extrapolation.

The operational evaluation process is intended to be beyond the laboratory phase of development. In laboratory operations the divers are volunteers who have given their informed consent; the trial exposures are by intent research and are under medical control. In operational evaluation the divers are using provisional tables as part of their normal job description. Operational evaluation in this context also involves special care when using the provisional tables, with adequate medical back-up and the ability to treat DCS promptly and adequately, management cognizance, special training and supervision, rigorous documentation of dive and outcome, and a mechanism for feedback. The developing organization is responsible.

The Workshop recommended a mechanism for dealing with the matters of judgment that might come up. The developing organization charges a 'decompression decision board' or the equivalent with responsibility for making the judgment calls, such as deciding when there have been enough evaluation dives, or when can the tables be called operationally ready. The DDB also passes on additional interpolative changes that might be needed as development proceeds, and makes the decision when such changes are extrapolative and need to go through formal laboratory research procedures involving informed consent.

Some real world programs have used these principles. The work of Imbert and colleagues in developing the COMEX 1986 and the French Ministry of Labor Tables is mentioned above, and in fact that program was incorporated into the Validation Workshop. A university archaeological diving project adapted traditional technical diving tables and operational procedures (Hamilton et al 1990). Another extensive nautical archaeology project that ended up doing thousands of dives used the Validation Workshop guidelines to get started (Vann et al 1999). A German tunneling project moved to higher pressure and added oxygen breathing to the procedures, and although the Workshop was not mentioned specifically the principles were followed (Faesecke et al 1990). It has been suggested that dive computer manufacturers, who seem reluctant to perform or sponsor actual field tests, might use Validation Workshop guidelines to reduce their liability and improve product acceptance (Hamilton 1995).

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