DECOMPRESSION PRACTICE

Divers generally fall into communities defined by a common purpose such as military, commercial, scientific, recreational or cave diving. A new community develops when a critical mass of divers finds a purpose not shared by others. The equipment, modes of diving and decompression procedures of the various communities often have supplemental risks which may be more significant than the risks of decompression illness.

No-Stop Air Diving

The simplest and most common form of compressed gas diving, *no-stop* or *no-decompression*, does not require decompression stops during ascent to the surface. The 18 m/min (60 ft/min) ascent rate chosen by the US Navy for the 1958 USN Air Tables has become a *de facto* standard (Lanphier 1990). More recently, a 10 m/min (33 ft/min) ascent rate was recommended (Boni *et al.* 1976), and some dive computers require rates as slow as 6 m/min (20 ft/min; Lang & Egstrom 1990). Another recent development in no-stop diving is the 3–5 min 'safety stop' at 3–5 m (10–15 ft; Lang & Egstrom 1990). A safety stop may achieve the same effect as a slow ascent by reducing the risk of decompression illness due to barotrauma or arterialized venous gas emboli (see 'Neurological Decompression Illness' and 'Pressure Profile'), but this hypothesis remains to be verified empirically.

Over time, the no-stop dive exposure limits have become more conservative. After caring for caisson workers affected by decompression illness at the St Louis bridge, Jaminet (1871) proposed limits for compressed air exposure of 120 min at 24 m (80 ft) and 60 min at 36 m (120 ft). The US Navy limits are 40 min at 24 m (80 ft) and 15 min at 36 m (120 ft). Newer tables and dive computers have even more conservative limits (Lewis & Shreeves 1990; Lewis 1992). Figure 14.31a shows the range of no-stop air limits for the 1958 USN, the 1983 DCIEM and 1986 Comex Tables. Overlayed on these limits are curves representing 0.5, 2.2 and 5% risk estimates for no-stop diving by a current US Navy model (Weathersby *et al.* 1992). According to these estimates, attaining a risk of 0.5% or less as desired by some diving communities will severely curtail useful bottom time.

In-Water Decompression with Air

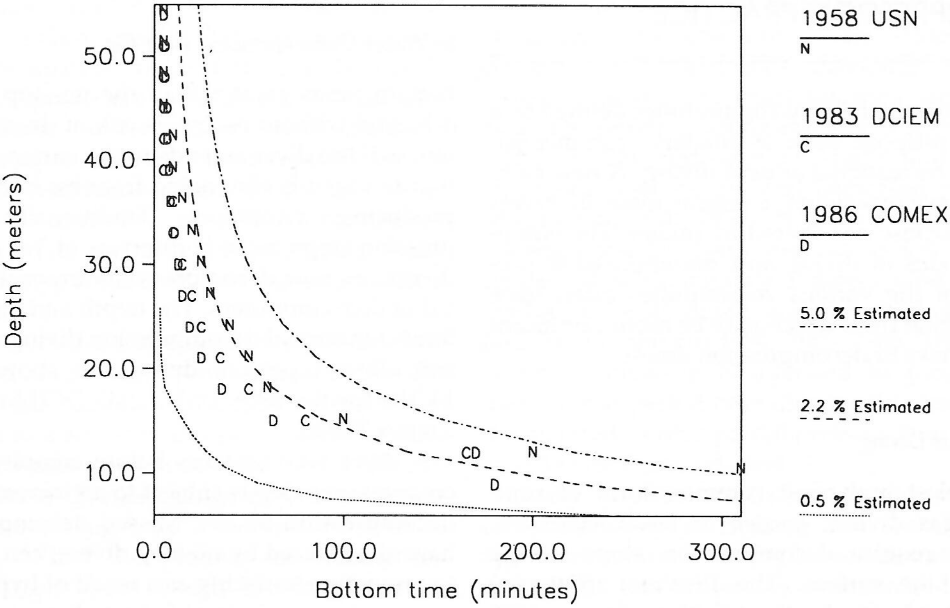
Bottom times greater than the no-stop limits are achieved without excessive risk of decompression illness if the diver ascends to the surface slowly so that nitrogen is eliminated from his body without producing symptoms. Traditionally, decompression stops occur at intervals of 3 m (10 ft), but divers can now decompress continuously with the aid of dive computers. The depth and bottom time limits for normal decompression diving which will still allow repetitive diving are shown in Fig. 14.31b for the 1958 USN, 1983 DCIEM and 1986 Comex Tables.

A diver who surfaces before completing a decompression stop is subject to an increased risk of decompression illness. Missed decompression, a hazard not faced by no-stop divers, can occur due to premature surfacing as a result of hypothermia, wave action, equipment failure, dangerous marine life, or running out of air. Running out of air is more common with scuba equipment than in surface-supplied diving. Many diving organizations require an on-site recompression chamber before allowing decompression diving, not only to treat possible missed decompression but also because of the uncertain risk of decompression illness using some decompression schedules.

This uncertainty has led to several major decompression development programmes with increasing emphasis on testing, documentation and field evaluation. The 1958 USN Standard Air Decompression Table, developed in one of the earlier programmes, tested 88 schedules in some 500–600 trials with an incidence of decompression illness of about 5% (Des Granges 1957a). The acceptance criteria were four incident-free trials per schedule. The supersaturation ratios of the Haldane decompression model used for profile calculation were adjusted three times and schedules recomputed as a result of decompression illness. The trials were insufficiently documented to be useful as primary data. Operational records report an overall incidence of decompression illness for the USN Air Tables of 1.25% (Berghage & Durman 1980).

The 1984 DCIEM Air Table was tested in 1371 trials of nearly 100 profiles with a 3% incidence of decompression illness (Nishi *et al.* 1980, 1981, 1982, 1984; Lauckner *et al.* 1984a,b, 1985). There

(a) No–Stop Exposure Limits



(b) Limits for Normal Decompression

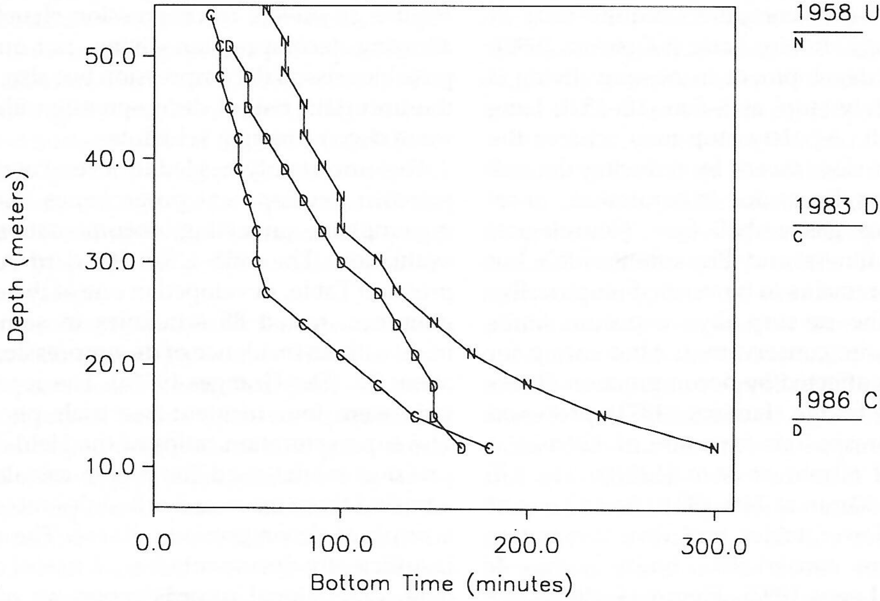


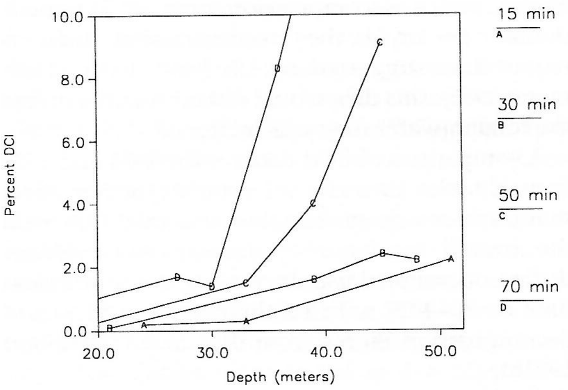
FIG. 14.31. (a) No-stop exposure limits for diving with the 1958 USN, 1983 DCIEM and 1986 Comex Air Tables. Curves representing estimated no-stop risks of 0.5, 2.2 and 5% are shown (Weathersby *et al.* 1992). (b) Depth–time limits for decompression diving with allowable repetitive diving for the 1958 USN, 1983 DCIEM and 1986 Comex Air Tables

were approximately 11 trials per profile, and profiles were recorded in real-time making them suitable as primary data. The trials included no-stop dives, in-water air and oxygen decompression, repetitive dives, and surface decompression. When decompression illness occurred, it was usually at the limits of the diving range. The series compartment Kidd–Stubbs decompression model used to compute the tested profiles was modified once in response to a perception that schedules for short and long dives were too long, while schedules for medium length dives were too short (Nishi & Lauckner 1984). There are no reports of field use to date.

The 1986 Comex Air Table was developed from the field records of 57 000 commercial dives using the 1974 French Air Table which had an overall 0.22% incidence of decompression illness (Imbert & Bontoux 1987). The incidence increased with dive severity in depth–time zones having incidences of <0.5%, 0.5–2% and 2–3% (Imbert 1991a). A three-parameter model with a single M-value and an unlimited number of Haldane tissues was fit to the field data by maximum likelihood (Imbert *et al.* 1992). The new table was found to have an incidence of 0.1% decompression illness in 32 000 dives and became part of the French regulations in 1991 (Imbert 1991b).

Figure 14.32 shows the field incidences of the 1974 French Air Table (Imbert & Bontoux 1987) and the risk estimates of a recent US Navy model (Weathersby *et al.* 1992). Both indicate increasing risk of decompression illness with depth and bottom time. In agreement with laboratory trials, however, the field incidences are lower than the risk estimates. Thalmann (1985) found that a 180 min dive at 20 m (60 ft) required triple the USN Standard Air stop time, while dives of 40 min at 45 m (150 ft) and 30 min at 63 m (190 ft) required double the USN stop times. For dives of 60 min at 45 m (150 ft) and 40 min at 57 m (190 ft), triple the stop time was inadequate to prevent decompression illness. Thus, while field data provide important indications of operational performance, they are not good estimators of risk for schedules tested under severe conditions to their maximum limits.

(a) Field Incidence



(b) Estimated Incidence

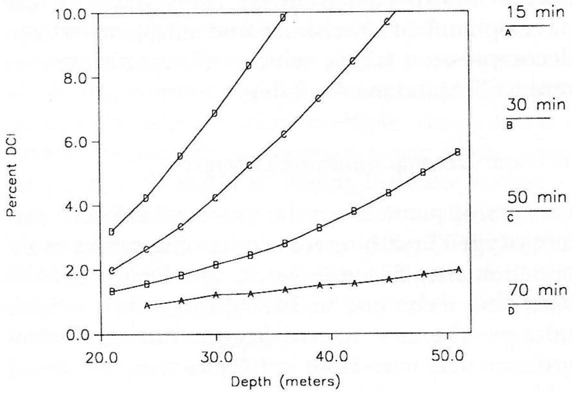


FIG. 14.32. (a) Field incidence of decompression illness taken from company records for the 1974 French Air Table (Imbert & Bontoux 1987). (b) Estimated risk of decompression illness for the 1974 French Air Table

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 Table, for example, requires 8 min of decompression after an 80 min dive at 20 m (60 ft). This dive has an estimated risk of 2.8% by a current USN model (Weathersby *et al.* 1992). 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 shorter than the current limits shown in Fig. 14.31b.

The depth–time limits of a table are determined by the decompression time and the total time allowed in the water. The DCIEM Table, for example, allows total in-water times of 100–130 min depending on depth. A dive to 30 m

(100 ft) has a maximum allowable bottom time of 55 min and a decompression time of 51 min. If double or triple the decompression time is required as suggested by US Navy trials (Thalmann 1985), this dive would not be possible unless the total in-water time was increased.

A comparison of field data for the 1974 and 1986 French tables provides an estimate of the effect that increased decompression time might have on the overall incidence of decompression illness during operational use. Increasing decompression time by 30–40% reduced the overall incidence of decompression illness from 0.22 to 0.1% (Imbert 1991b).

Field data inherently underestimate true risk, and the issue is far from settled. Further clarification is expected from US Navy trials for the development of iso-risk air and nitrogen–oxygen decompression tables, which will replace the current USN Standard Air Table.

In-Water Decompression with Oxygen

Bert (1878) pointed out the potential value of surface oxygen breathing for accelerating nitrogen elimination after decompression, and Damant (1926) used this technique in 1917 during the *Laurentic* salvage. 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 20 m (60 ft; Davis 1962). Since that time, oxygen decompression has become an integral part of deep and long-duration diving.

Oxygen can be used as a substitute for air during in-water decompression to reduce the risk of decompression illness and long decompression times. The 1986 Comex Tables have an option which offers oxygen breathing during in-water decompression at 6 m (20 ft). Compared with the corresponding air table, the oxygen table reduces the decompression time by 50% for 15 m (50 ft) dives and by 30% for 60 m (200 ft) dives. Breathing oxygen underwater, however, introduces the risk of central nervous system oxygen toxicity, and convulsions have been reported as shallow as 7.6 m (25 ft; Butler & Thalmann 1984). In-water oxygen decompression is not recommended deeper than 6 m (20 ft) and then only with careful attention to depth control. Air must be available as a back-up breathing medium in the event of oxygen toxicity symptoms, there should be an emergency plan for convulsions, and there should be a back-up decompression plan if in-water oxygen cannot be used.

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, for example, 7500 air dives were conducted at depths of 50–60 m (150–180 ft) with in-water oxygen decompression at 3 and 6 m (10 and 20 ft; Fife *et al.* 1992). There were three incidents of decompression illness and no symptoms of oxygen toxicity.

When the 1974 French Air Tables were used with oxygen decompression at 3 and 6 m (10 and 20 ft), over 11 000 dives were conducted with a 0.7% incidence of decompression illness. The incidence of decompression illness with oxygen decompression was 2–3 times lower than with air decompression for dives of the same depth and bottom time (Imbert & Bontoux 1987). No oxygen toxicity incidents were reported.

Surface Decompression with Oxygen

During salvage of silver from the *Empress of Ireland* in 1914 and gold from the *Laurentic* in 1917–24, the weather or military situation sometimes forced Royal Navy divers to surface before completing decompression and be recompressed in a shipboard pressure chamber (Damant 1926; Davis 1962). Salvage of the US Navy submarines S-51 in 1925 and S-4 in 1927 were also conducted with surface decompression (Van Der Aue *et al.* 1951).

Subsequent work by Hawkins and Shilling (1936) and Van Der Aue *et al.* (1945) 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). Van Der Aue's surface decompression table was published in the *USN Diving Manual* and is unchanged to this day.

There is less risk of central nervous system oxygen toxicity in a dry environment than underwater (Yarborough *et al.* 1947), but episodes of oxygen toxicity occurred at 50 and 60 ft (15 and 18 m) during surface decompression from helium–oxygen dives (Molumphy 1950a). Van Der Aue limited his use of oxygen to 40 ft (12 m) but still noted a 1% incidence of mild central nervous system symptoms. Fire is a further hazard of oxygen use. Oxygen equipment must be oil-free and exhaled oxygen exhausted outside the chamber. Diver selection and training must emphasize the avoidance of ignition sources and flammables (Nashimoto 1967).

The USN Surface Decompression Table Using Oxygen (Sur-D O_2) enables 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 (Arntzen & Eidsvik 1980). Some reports, however, suggest that Sur-D O_2 is associated with a higher incidence of neurological symptoms than in-water decompression and that hot-water suits (as opposed to dry suits) may be a contributing factor (Shields & Lee 1986; Imbert 1991b; Imbert *et al.* 1992). Other reports take issue with this conclusion and argue that the procedures, not the mode of diving, is the problem (Beyerstein 1992; Mills 1992; Overland 1992).

The Sur-D O_2/hot-water suit issue reinforces the importance and limitations of operational dive records (secondary data) aside from their roles in business management and occupational safety. When the incidence of decompression illness 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 is possible, but without exact knowledge of dive conditions and profiles, confident conclusions are not possible. In the case of Sur-D O_2 and hot-water suits, for example, it cannot be certain whether the increased incidence of decompression illness was due to their use on higher risk dives. Further data are required to answer this question.

Repetitive and Multi-Level 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 a previous dive. The simplest scheme for determining repetitive dive decompression requirements takes the sum of the bottom times at the greatest depth, but this is restrictive for long surface intervals. Of the many methods for determining repetitive dive bottom times, that of the US Navy is the most flexible if somewhat complex.

The USN Tables were computed with a multi-tissue Haldane decompression model (Chapter 13), but during surface intervals between repetitive dives, nitrogen elimination from all tissues was calculated with a single tissue having a 120 min half-time (Des Granges 1957b). This half-time theoretically clears all tissues 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 tables are: 6 h for Rogers (1988), 8 h for 1974 French, 12 h for 1986 Comex and 18 h for DCIEM. The US Navy Repetitive Tables were tested in 4–6 trials of 61 two-dive profiles (Des Granges 1957b). All trials were of decompression dives, and decompression illness occurred in three subjects on profiles with maximum depths of 220 and 260 ft (67 and 79 m).

Repetitive and multi-day diving are common in all diving communities. Recreational diving accident data suggest that multiple dives have a greater incidence of decompression illness than single dives (Vann *et al.* 1989b), but 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 neurological) in 5400 two-dive profiles including both no-stop and decompression exposures (Imbert *et al.* 1992).

Dive trials by the US Navy indicated that the USN no-stop repetitive dive procedures may be overly conservative (Thalmann 1985). Rogers (1988) computed recreational diving tables with shorter surface intervals using a 60 min rather than a 120 min Haldane tissue half-time to clear residual nitrogen in 6 h rather than 12 h surface intervals. These commercially developed tables were subjected to one of the most extensive repetitive dive trials ever conducted outside the military (Powell *et al.* 1988). There were 1400 man-dives of 40 profiles including single-day, multi-level dives and multi-day dives with four and six dives per day for six consecutive days. Except for 228 open-water dives, however, all were dry chamber trials. There was only one incident of decompression illness, which occurred on the second day during chamber trials of six dives per day for 6 days. Open-water evaluation of these procedures is continuing.

Multi-level diving is a variant of repetitive diving in which a diver does not return to the surface. Commercial, recreational and military diving is frequently multi-level. 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). Other repet-up or multi-level dive procedures have been developed (Gernhardt *et al.* 1992; Rogers 1988; Imbert *et al.* 1992; Lewis 1992). The US Navy has modified the USN Repetitive Dive Tables to allow long multi-level dives where the deep and shallow stages can be in any order (Thalmann & Butler 1983).

Surface Interval Oxygen

In-water oxygen decompression and surface decompression extend bottom time significantly but introduce the risk of oxygen toxicity and require complex equipment. An alternative use of oxygen which achieves some bottom time extension with less risk and equipment overhead is to breathe oxygen during the surface intervals between repetitive dives. Surface interval oxygen ($\mathrm{SIO_2}$) repetitive diving procedures are published in the French Navy Air Tables (Meliet 1990), and $\mathrm{SIO_2}$ has been used to reduce pre-flight surface intervals (Edel 1970) and the risk of decompression illness after caisson work (Nashimoto 1989). In chamber and field trials of repetitive nitrogen–oxygen diving (Fawcett *et al.* 1992; Vann *et al.* 1992a), 30 min of $\mathrm{SIO_2}$ increased no-stop dive times by 34–120% over EAD (Equivalent Air Depth) diving with air breathing surface intervals (Dinsmore 1989).

Dive Computers and Recorders

Early pneumatic and analog computers were not widely accepted as they were undependable and deviated from USN Air Table performance (Huggins 1987). Improvements in pressure transducer and digital technology coupled with the growing popularity of recreational diving have made mass-produced dive computers possible at reasonable cost and reliability.

The first commercially successful digital dive computer was tested without incident in 1983 during 110 dry chamber dives (Huggins 1992). Many mass-produced dive computers are now available, all using variants of the Haldane decompression algorithm, but no futher decompression trials have been conducted (Lewis 1992). The decompression 'safety' of computer and table diving is debated vigorously (Lang & Hamilton 1989), but accident reports do not offer compelling evidence for a higher incidence of decompression illness with computers (Vann *et al.* 1989b). Accident data compiled by the Divers Alert Network (DAN) indicate that decompression illness occurs after deeper dives and after more multi-level and decompression dives with computers (Vann *et al.* 1989b). The only direct comparison between computer and table incidence is from recreational diving aboard the *Ocean Spirit* where there were no incidents of decompression illness in 44 277 computer dives and seven incidents in 33 403 table dives (0.02%; Gilliam 1992). Large studies of this nature are important, but additional information is necessary for these studies to be useful in quantifying the decompression risks of table and computer diving. Rather than rely on self-reported symptoms, the absence of symptoms must be actively verified to minimize denial or lack of recognition. Dive profiles also must be verified to avoid errors in computer application or table selection.

Computers minimize errors in table selection by accurately tracking depth–time profiles. Indeed, one of the most significant contributions the dive computer can make to decompression safety will be to record these profiles in real-time. A number of special-purpose dive recorders are available (Peterson 1992; Gotoh 1992; Henderson *et al.* 1992; Heinmiller 1992), and several mass-produced dive computers can store depth–time data. These instruments allow recorded profiles to be downloaded to personal computers for storage and analysis. Dive computers/recorders will make accurate open-water dive trials possible and, when linked to diving accident reports, may enable large primary databases to be developed which could be analysed for decompression risk by probabilistic methods. All divers enrolled in such projects, however, must be evaluated by trained personnel to achieve reasonable certainty that no incidents of decompression illness are missed. Self-reporting is unreliable as minor symptoms are often not revealed.

Nitrogen–Oxygen Diving

There are two kinds of non-saturation nitrogen–oxygen diving: fixed percentage and fixed partial pressure. Fixed percentage nitrox, also known as *oxygen enriched air* or *enriched air nitrox* (EAN), uses a breathing gas with greater than 21% oxygen. The advantages of fixed percentage nitrox are reduced nitrogen absorption at depth and accelerated nitrogen elimination during decompression (see 'Oxygen Window'). The disadvantages are the need for oxygen-clean equipment to reduce fire hazard, the complexity of gas mixing, the requirement for accurate gas analysis, and the importance of depth control to stay within the mixed-gas oxygen exposure limits to minimize the risk of central nervous system oxygen toxicity (*NOAA Diving Manual* 1979).

The most widespread application of fixed percentage nitrox diving is NOAA's adaptation of the US Navy Air Tables using 32% oxygen with the Equivalent Air Depth (EAD) principle (Eq. 2; *NOAA Diving Manual* 1979). The no-stop exposure limit at 15 m (50 ft) is 200 min with 32% nitrox, for example, while the limit is only 100 min with air. Nitrox is not suitable for deep diving, however, because of the increased risk for central nervous system oxygen toxicity. NOAA's upper limit for oxygen partial pressure exposure is 1.6 ata (162 kPa), which makes 39 m (130 ft) the greatest allowable depth with 32% oxygen. The NOAA National Undersea Research Program has extended EAD diving for use with mixes of any oxygen percentage (Dinsmore 1989).

A military application of fixed percentage nitrox diving uses semi-closed circuit scuba which injects a fixed oxygen percentage gas (frequently 32.5, 40 or 60% oxygen) into a recirculating breathing system that absorbs carbon dioxide (Morrison & Reimers 1982; *US Navy Diving Manual* 1982). The oxygen partial pressure in the breathing loop is several per cent lower than in the injected gas due to oxygen consumed by the diver. Decompression is conducted according to specially computed tables or EAD corrections to standard air tables (see 'Equivalent Air Depth'). Semi-closed circuit scuba uses less gas than open circuit scuba but is technically complex and expensive to purchase and maintain.

Closed circuit, mixed-gas scuba, which controls the oxygen partial pressure to a predetermined set-point, uses even less gas than semi-closed scuba and is even more complex and expensive (Morrison & Reimers 1982; *US Navy Diving Manual* 1982). An electronic control system adds oxygen to the breathing loop when oxygen sensors detect a partial pressure below the set-point. In theory, only metabolically consumed oxygen need be provided, but a diluent gas is also needed during descent to inflate the breathing bags. Closed circuit, mixed-gas scuba is impractical for all but the military and a few specialized civilian diving organizations. Two versions, the Mk 15 and Mk 16 UBAs (Underwater Breathing Apparatus), are currently used by the US Navy (*US Navy Diving Manual* 1982).

The oxygen set-point for the Mk 15 and Mk 16 UBAs is 0.7 ata (71 kPa), which results in oxygen percentages above 21% at depths shallower than 23.3 m (77 ft) and percentages lower than 21% deeper than 23.3 m. Decompression requirements can be reduced with higher set-points, but the maximum set-point is limited by central nervous system oxygen toxicity. Oxygen convulsions occurred at a set-point of 1.6 ata (162 kPa), but a 1.4 ata (141 kPa) set-point was used without symptoms of oxygen toxicity in 110 wet, working dives at 30 and 45 m (100 and 150 ft) with 60 min bottom time (Vann 1982b). Trials comparing 0.7 and 1.4 ata (71 and 141 kPa) for 60 min dives at 30 and 45 m (100 and 150 ft) indicated a 2–3 fold reduction in decompression time with the higher set-point (Vann 1982a,b). A civilian version of the Mk 15 UBA has also used 1.4 ata (141 kPa; Hamilton *et al.* 1988a).

The development of 0.7 ata (71 kPa) decompression procedures by the US Navy for the Mk 15 UBA was the first verification of a decompression algorithm rather than validation of a table (Thalmann 1984, 1985, 1986; Thalmann *et al.* 1980). Decompression was controlled in real-time by a computer algorithm to allow for variations from planned dive profiles due to problems with the equipment or subjects (Thalmann 1984). Air decompression schedules computed from the final algorithm after 673 man-dives were up to three times longer the USN Standard Air schedules. This was confirmed in 837 man-dives (Thalmann 1985). The results of the 1510 man-dives will serve as primary data in the development of a probabilistic model for computing air and nitrogen–oxygen tables.

Helium–Oxygen Diving

Helium–oxygen is generally used below 50–72 m (165–240 ft) to avoid the nitrogen narcosis which occurs during air diving. The first helium dive trials, conducted in the 1920s by the US and Royal Navies, assumed that the helium and nitrogen partial pressures acted independently in decompression calculations (Momsen 1942). The resulting incidents of decompression illness lead to the conclusion that helium might be unsuitable for diving.

Experiments resumed in the 1930s when End (1937, 1938) demonstrated the practicality of helium–oxygen diving to 120 m (400 ft), and the US Navy developed the USN Partial Pressure Table (Momsen 1942) which was used, while still under trial, for the salvage of the *USS Squalus* in 1939 (Behnke & Willmon 1939). Further testing was not altogether successful (Molumphy 1950a,b; Alexander *et al.* 1970; Summitt & Crowley 1970), and there is little other documentation on short, deep helium–oxygen 'bounce' diving by the Navy. US Navy helium–oxygen experience is better documented for shallow water diving with the semi-closed Mk 6 UBA (Workman & Reynolds 1965) and the closed circuit Mk 16 UBA (Thalmann 1986). The Canadian Forces have recently developed helium–oxygen decompression tables (Nishi 1990).

The commercial diving industry modified the USN Helium Partial Pressure Table for its own use in the 1960s and continued active development throughout the 1970s. The resulting tables are unpublished with largely undocumented history and performance. The development of helium decompression procedures for 30–60 min dives at 120–180 m (400–600 ft) proved to be a significant challenge (Hamilton 1976). 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.* 1992).

Because helium is less soluble than nitrogen, helium dives might be expected to permit faster decompression than nitrogen dives. This appears true for saturation decompression (see 'Saturation Diving') and perhaps also for dives shallower than 18 m (60 ft), but differences for deeper dives are small at best and difficult to demonstrate with statistical significance (Duffner & Snider 1959; Hempleman 1967; Thalmann 1985; Thalmann *et al.* 1989).

Helium is not only less soluble than nitrogen but appears to be exchanged more rapidly (see 'Inert Gas Exchange'). Rapid elimination might explain faster decompression from helium saturation dives while rapid absorption might make helium and nitrogen decompressions more nearly equal for short, deep dives. 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.

Decompression after helium diving usually occurs with air or oxygen to save helium and/or decompression time and, consequently, there is little data on which to base a direct comparison of helium and nitrogen decompression illness. Such information is available, however, from recent Mk 15 and Mk 16 UBA studies for similar dives with no gas changes during decompression (Thalmann *et al.* 1980; Vann 1982b; Thalmann 1984, 1985, 1986). The overall incidences of decompression illness 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; $P < 0.001$).

Another troublesome aspect of helium is an apparently greater propensity than nitrogen to cause adaptation (see 'Adaptation to Decompression'). This might explain the inconsistency of helium trials and would argue for infrequent use of the experimental subjects to avoid developing helium decompression procedures suitable only for adapted or worked-up divers.

The use of helium and nitrogen in the same dive produces interesting effects because of their different exchange rates. Consider a diver saturated with nitrogen who is isobarically placed in helium. Cutaneous counterdiffusion (see 'Skin Bends and Counterdiffusion') is transient rather than steady-state as the diver is breathing, as well as immersed, in helium. Counterdiffusion also takes place internally where perfusion and diffusion transport helium into tissue faster than nitrogen can be eliminated. A transient supersaturation occurs, the magnitude of which increases with depth (D'Aoust & Lambertsen 1982). When three divers switched from nitrogen to helium at 30 m (99 ft), all developed severe itching within 1 h and joint pain within 5–7 h suggestive of bubble growth. Similar experiments at 20 m (66 ft) caused less itching and no pain (Hamilton *et al.* 1982).

An opposite effect occurs when the switch is from helium to nitrogen. Consider a diver who 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. This technique was used in record-setting dives to 303 m (1000 ft; Keller & Bühlmann 1965; Bühlmann 1975) and is standard for most deep helium–oxygen bounce diving (Hamilton 1976). Despite standard operational practice, however, Thalmann (1986) found no difference in the incidence of decompression illness after helium–oxygen dives when air or helium–oxygen was breathed during decompression. Momsen (1942), moreover, reported unspecified adverse effects in divers shifting to air deeper than 165 ft (49.5 m), and subsequent experiments which used rapid shifts deeper than 33 m (110 ft) noted vertigo and nausea suggestive of vestibular or inner ear decompression illness (Hamilton 1976).

Compressed Air or Caisson Decompression

Decompression after diving has received more attention by the medical and research communities than decompression after caisson work (McCallum 1967). Compressed air exposures are generally longer (4–8 h) and at lower pressures (9–30 m) than dives but allow less decompression time than the high DCI incidence USN Exceptional Exposure Table (Workman 1957; Kindwall 1989). Official caisson decompression regulations are frequently untested extrapolations of procedures for shorter duration diving exposures, and workers were often decompressed for a lunchtime surface interval (split-shift) which doubles their decompression stress (Paton 1967). Decompression illness is statistically associated with aseptic osteonecrosis (Davidson 1976; Ohta & Matsunaga 1974; Cross 1987; Zhang *et al.* 1991), but fear of job loss can make the reported incidence (1.4%) less than the incidence noted by anonymous survey (26%; Kindwall 1989).

A recent experimental study of caisson decompression procedures indicated that air schedules which might be of adequate length were too long to allow sufficient work in an 8 h day (Kindwall *et al.* 1983). A 4 h exposure at 20 m (66 ft), for example, required nearly 5 h of decompression. For compressed air work to be practical and reasonably safe, the only alternatives may be daily exposures with oxygen decompression or long-duration saturation exposures. Preliminary tests by Kindwall *et al.* (1983) suggested a 4 h exposure at 20 m might require only 2 h of oxygen decompression. Oxygen has been used in Germany during decompression from pressures in excess of 30 m (100 ft; Faesecke *et al.* 1990). The incidence of decompression illness was 0.6% in 3400 exposures.

Saturation Diving

During an exposure of 24–48 h at constant pressure, a diver's tissues become saturated with his inspired inert gases, and 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 desirable. The inspired oxygen partial pressure is generally limited to 0.3–0.5 ata (30–51 kPa) to avoid pulmonary oxygen toxicity while in saturation (Chapter 6), but raised to 0.4–0.6 ata (40–61 kPa) during decompression. Most saturation diving occurs at depths below 61 m (200 ft) with helium as the inert gas. At depths of 300 m (990 ft) and deeper, nitrogen or hydrogen is added to the helium to ameliorate the high pressure nervous syndrome (Chapter 8). Nitrogen narcosis limits nitrogen–oxygen saturation diving to depths shallower than 36 m (120 ft).

During working saturation dives, divers live or are 'stored' in a habitat or deck chamber and commute to the work site by swimming or in a submersible decompression chamber. Such *excursion dives* can be ascending or descending. Oxygen partial pressures during excursions range from 0.4 to 1.4 ata (40 to 141 kPa) with air as the excursion gas from nitrogen–oxygen saturation. No-stop air excursions which permit direct return to nitrogen–oxygen storage without decompression have been tested and published with complete operational procedures (Hamilton *et al.* 1988b,c; Hamilton & Schane 1990).

The size of an excursion increases with the storage depth, and excursions of unlimited duration are allowed within a restricted depth range above and below storage. Unlimited duration excursions from helium–oxygen saturation were tested by the US Navy during the development of saturation decompression procedures (Larsen & Mazzone 1967; Summitt *et al.* 1970a,b,c,d). Operational

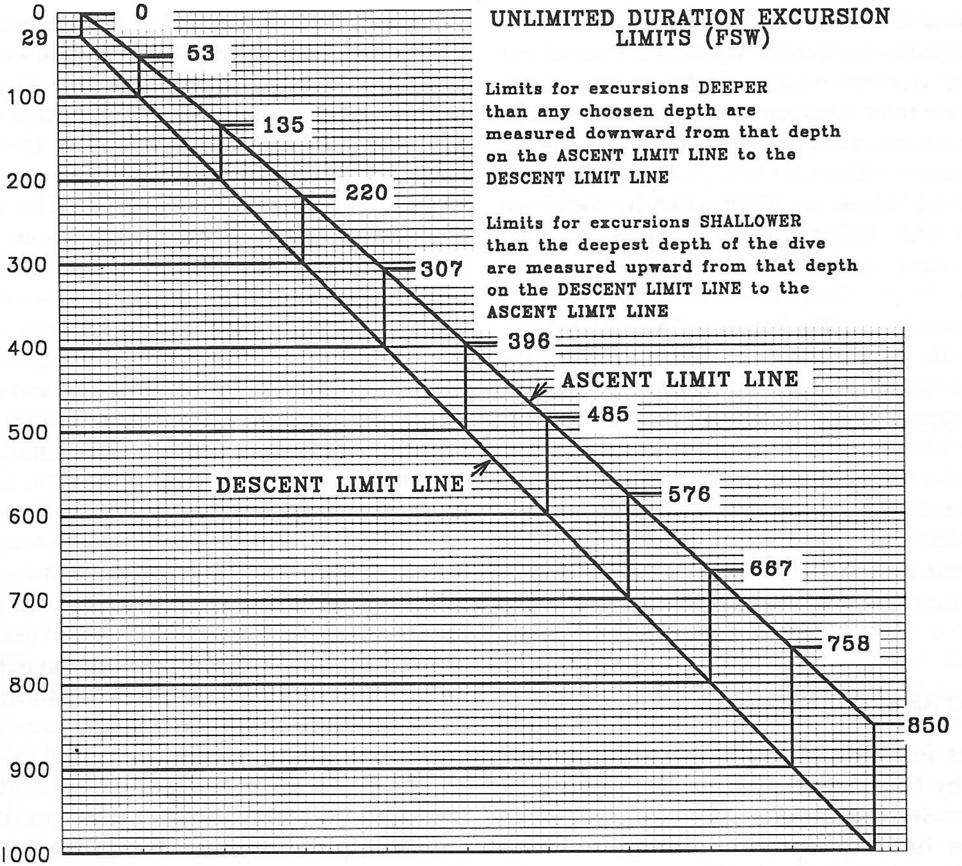


FIG. 14.33. US Navy unlimited duration helium–oxygen saturation excursion limits. Upward excursion limits in 100 ft increments are shown. Breathing gas is at least 0.42 bar PO_2 in helium (see Thalmann 1989b)

limits were published in 1978) Spaur *et al.* 1978), but made more conservative in 1989 after reports of decompression illness from the field (Thalmann 1989b). The use of unlimited helium–oxygen excursions is illustrated in Fig. 14.33, 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. If a descending excursion on nitrogen–oxygen occurs within 36 h of beginning decompression to the surface during nitrogen–oxygen saturation, Hamilton *et al.* (1988b) compress up to 11 m (35 ft) deeper than the storage depth and decompress back to storage over as long as 6 h.

For helium–oxygen, the US Navy allows an immediate upward 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. 14.33). Comex begins final decompression from storage without upward excursion and normally allows excursion dives of not more than 10 m (33 ft; Imbert & Bontoux 1988). Procedures developed during the Atlantis dive series at Duke University also begin without upward excursion (Vann 1984; Bennett *et al.* 1987a,b).

As saturation decompression schedules evolved during the 1960s, 1970s and 1980s, the ascent rate, inspired oxygen partial pressure, inert gas species and saturation depth emerged as factors which might influence the risk of decompression illness. During decompression from helium–oxygen saturation dives, Vorosmarti *et al.* (1978) found that raising the inspired oxygen partial pressure from 0.22 ata (22 kPa) to 0.4 ata (40 kPa) reduced the incidence of decompression illness from 52% (14 incidents in 27 dives) to zero (no incidents in 42 dives; $P < 0.0001$).

A simple model relating inspired oxygen partial pressure ($P\text{I}O_2$) to the rate of ascent from a saturation dive assumes that ascent rate is a linear function of oxygen partial pressure (Hennessy 1978; Vann 1984, 1986; Eckenhoff & Vann 1985; Hamilton *et al.* 1988c; Imbert & Bontoux 1988)

$$\text{rate} = k \times P\text{I}O_2 \qquad (13)$$

To develop a saturation decompression procedure, the value of k in equation (13) is adjusted in successive dives until the incidence of decompression illness becomes acceptably low.

The effect of saturation depth was suggested by a comparison of decompression illness incidences for air or nitrogen–oxygen dives deeper and shallower than 30 m (100 ft; Barry *et al.* 1984). The incidence for the shallower dives was 13% (14 incidents in 107 dives) and for the deeper dives 31% (14 incidents in 45 dives; $P < 0.01$). The value of k in equation (13) was estimated empirically for both nitrogen and helium (Vann 1984) and subsequently derived as a decreasing function of depth using a bubble model and likelihood analysis of 233 man-decompressions (Vann 1986).

The empirical estimates of k (Eq. 13) indicated that ascent rates for helium could be 2–3 times faster than ascent rates for nitrogen at the same saturation depth (Vann 1984). The ascent rates were approximately equal for helium–oxygen saturation at 600 m (1968 ft) and nitrogen–oxygen saturation at 30 m (99 ft).

CONCLUSION

Decompression illness is an interesting disease covering a range of fields within physics, physiology and medicine. Beyond this academic interest, however, is the practical problem of conducting safe decompression in diving, aerospace and caisson work. A quantum improvement in decompression safety is possible because of recently introduced statistical methods and computer technology. The greatest obstacle to progress is the lack of reliable exposure and epidemiological data from the laboratory and field. Cooperation between interested organizations is essential if needed data are to be forthcoming.

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