Chapter 17

MILITARY DIVING OPERATIONS

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INTRODUCTION

Divers breathe gases and experience pressure changes that can cause different injuries from those encountered by most military personnel. This chapter discusses the operational hazards, equipment, and procedures of military diving. The pathophysiology, diagnosis, and treatment of diving-related disorders, including decompression sickness, are discussed in a later chapter. The US Navy has responsibility for all diving by US forces, and most US military divers are in the Navy. All diving operations by US forces must be conducted in accordance with the *US Navy Diving Manual* and related directives. US Navy diving and salvage forces include T-ARS-50 Safeguard-class salvage ships, explosive ordnance disposal (EOD) units, mobile diving and salvage units, underwater construction teams, and teams assigned to submarine tenders and shore-based ship repair facilities. The diving and salvage forces conduct salvage, search and recovery, underwater mine clearance, underwater construction, security inspections, and ship's husbandry tasks such as hull cleaning and maintenance.

Salvage divers receive basic training at the Naval Diving and Salvage Training Center (NDSTC) in Panama City, Florida, and qualify in the Mark (Mk) 21 Mod 1/ Kirby Morgan (KM) 37 NS mixed-gas diving helmet (Figure 17-1) to a depth of 300 feet of seawater (fsw; equivalent to 90 meters of seawater [msw]). EOD technicians undergo dive training at NDSTC as well and qualify in the Mk 16 Underwater Breathing Apparatus (UBA), which is used for mine clearance. About 100 US Navy divers are specialized in saturation diving using personnel transfer capsules (PTCs) and deck decompression chambers (DDCs).

Naval special warfare combat divers, known as SEALs (sea, air, land) are trained for reconnaissance and direct action missions at rivers, harbors, shipping, and coastal facilities in restricted or denied waters. SEAL divers operate from surface craft, submerged submarines, and miniature wet submersibles known as SEAL delivery vehicles (SDVs). Insertion by fixed- or rotary-wing aircraft is also possible. SEALs qualify in open-circuit and closed-circuit oxygen scuba (self-contained underwater breathing apparatus), with some receiving additional training in the Mk 16 closed-circuit, mixed-gas scuba rig.

SEALs are part of the Special Operations Forces, which include US Army, Air Force, and Marine Corps divers; divers from these services have narrower training and missions and dive less frequently. SEALs train at the Naval Special Warfare Center in Coronado, California, while divers from other services train at NDSTC or at the US Army Special Forces Underwater Operations School in Key West, Florida. Other military divers include US Air Force Pararescuemen and combat controllers, US Army port facility maintenance divers, and US Coast Guard divers for rescue and pollution response. The military also employs civil service divers and contracts with commercial diving companies for specific projects.

Training in diving medicine for military physicians is conducted by the US Navy for all US forces and occasionally for foreign militaries. Instruction includes 6 weeks of practical diving training and 3 weeks of diving medicine at NDSTC. Navy undersea medical officers receive 12 weeks of additional training in submarine-specific issues at the Naval Undersea Medicine Institute in Groton, Connecticut.

The unique medical support requirements for diving are a result of the physiological, engineering, and environmental challenges present underwater. Military diving physicians require broad training for the wide range of missions they may support, but military physicians may also be consulted concerning civilian diving casualties, because many military personnel or their dependents are recreational divers. In addition to physiological hazards, divers must cope with threats posed by various forms of marine life. Medical officers need to be mindful of all the problems, not just the respiratory ones that military divers and swimmers may encounter in the marine environment.

Figure 17-1. Both divers are wearing the KM 37 NS helmet with an attached divers underwater color television system.

CENTRAL NERVOUS SYSTEM OXYGEN TOXICITY IN DIVERS

Cerebral oxygen toxicity occurs with inspiration of high partial pressures of oxygen and is a serious concern during certain diving or chamber operations. A seizure is the most spectacular and objective sign of central nervous system (CNS) oxygen toxicity, but there is no evidence that seizures lead to permanent damage if the oxygen exposure is promptly discontinued. Other symptoms of CNS oxygen toxicity include irritability, twitching, dizziness, incoordination, and visual or auditory disturbances. These symptoms do not necessarily precede convulsions.

Factors that elevate cerebral blood flow also augment oxygen delivery to the brain, which appears to increase susceptibility to oxygen toxicity. These factors include immersion, exercise, and hypercapnia.[1] Carbon dioxide may be present in the inspired gas or may be retained in the body owing to inadequate ventilation caused by high gas density or external breathing resistance. The primary treatment for all forms of oxygen toxicity is to reduce the partial pressure of inspired oxygen to a nontoxic level.

Oxygen exposure limits have been established to reduce the risk of convulsions for divers breathing pure oxygen or the oxygen in nitrogen-oxygen gas mixes. Chamber trials and experience in open water indicate that convulsions occasionally occur near or within the accepted oxygen exposure limits. Oxygen exposure limits are more conservative for nitrogen-oxygen mixes than for pure oxygen. Nitrogen-oxygen mixes are used at greater depths and have higher gas densities. The higher gas densities are believed to cause greater carbon dioxide retention within the body, which increases susceptibility to oxygen toxicity.

UNDERWATER BREATHING APPARATUSES

A UBA provides the diver with a continuous and reliable supply of physiologically safe breathing gas. There are two broad categories of UBAs, surface supplied (or tethered) and self-contained. Each type has a number of subcategories with advantages and disadvantages that lend themselves to a particular operational utility.

Open-Circuit, Self-Contained Underwater Breathing Apparatus

The most familiar and common UBA currently in use is the open-circuit, compressed-air scuba. Open-circuit scuba consists of one or more tanks of gas compressed to a pressure of 137 to 341 ata (absolute atmospheres) or 2,000 to 5,000 psi gauge (psig). A first-stage pressure regulator attached to the tanks reduces their high pressure to an intermediate pressure of about 7 ata (100 psig) over the ambient water pressure. During inhalation, a second-stage regulator, held in the diver's mouth, reduces the intermediate pressure to ambient. The system is described as "demand" and "open-circuit" because air flow is available for inhalation on demand and the exhaled gases are vented directly to the surrounding water.

Based on Dalton's law of partial pressures, the partial pressures of oxygen and nitrogen change with depth for divers breathing air or 100% oxygen (Figure 17-2). With pure oxygen, there is a significant risk of CNS oxygen toxicity at 33 fsw (10 msw), while with compressed air, which is only 21% oxygen, CNS oxygen toxicity does not usually appear until depths greater than 190 fsw (57 msw).[2]

Surface-Supplied Diving

UBAs became possible with the invention of the air compressor in the 18th century during the Industrial Revolution, but the first practical equipment did not appear until about 1828, when the Deane brothers in England developed an open helmet that rested on the diver's shoulders.[3] Hand-driven pumps on the surface supplied the helmet with air through a hose, and ex-

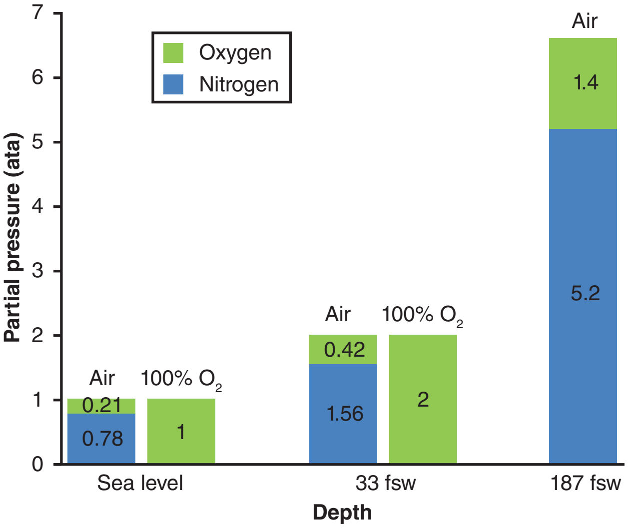

Figure 17-2. Nitrogen and oxygen partial pressures for air and 100% oxygen at various depths.
O_2: oxygen
ata: absolute atmosphere
fsw: feet of seawater

cess air escaped around the shoulders, but the helmet would flood if the diver leaned over too far. Further developments by the Siebe Gorman diving company of England in the mid-19th century added a closed suit to the helmet, which prevented flooding and improved thermal protection. This became the traditional "hard-hat" deep-sea diving dress, which remained the primary equipment for military and commercial diving until the 1970s. The US Navy diving helmet, the Mk V (Figure 17-3), was introduced in 1905, with improvements in 1916 and 1927, and was the system of choice until 1980.

The current diving helmets in use by the US Navy are the Mk 21 Mod 1 and KM 37 NS (see Figure 17-1). These masks are nearly identical and incorporate a demand regulator from open-circuit scuba, but use an oronasal mask that allows spoken communications instead of a mouthpiece. The oronasal mask is a significant improvement and has much less respiratory dead space than previous diving helmets. This permits lower gas-supply flow rates while limiting carbon dioxide retention. The Mk 21 Mod 1 helmet has a depth limit of 190 fsw (57 msw) when used for air diving. Its principal applications are search, salvage, inspection, ship's husbandry, and enclosed-space diving. The Mk 21 Mod 1 can also be used to a depth of 300 fsw (90 msw) with helium-oxygen mixtures.

Figure 17-3. The US Navy Mk V Mod 1 diving helmet.

Figure 17-4. The US Navy Mk 20 Mod 0 surface-supplied, open-circuit, lightweight system with full facemask is limited to a depth of 60 fsw (18 msw) for applications such as diving in mud tanks and enclosed spaces.

Another tethered diving system in the US Navy inventory is the lightweight Mk 20 Mod 0 (Figure 17-4), which is used to a maximum depth of 60 fsw (18 msw) for diving in mud tanks or enclosed spaces. For saturation diving, the Navy uses the Mk 21 Mod 1 helmet and Mk 22 Mod 0 band mask (Figure 17-5) with a hot water suit and hot water shroud for heating breathing gas.

Closed-Circuit Oxygen Scuba

The term "closed-circuit" describes a UBA in which 100% of the breathing gases remain within the unit, as opposed to escaping into the aquatic environment around the diver. The gas exhaled is carried via an exhalation hose to a canister containing a chemical absorbent that removes the exhaled carbon dioxide. The gas then travels to a breathing bag, where it is available again to the diver. Metabolically consumed oxygen is then replaced by an oxygen addition system.

Figure 17-5. The US Navy Mk 21 Mod 0 helmet with hot water suit, hot water shroud, and come-home bottle (left) and Mk 22 Mod 0 with hot water suit, hot water shroud, and come-home bottle (right) for heating breathing gases. These are the primary underwater breathing apparatuses for saturation diving. Reprinted from: US Department of the Navy. *US Navy Diving Manual*. Rev 6. Washington, DC: Naval Sea Systems Command; 2011: 15-2, 15-3. NAVSEA 0994-LP-100-3199.

Closed-circuit UBAs have no escaping bubbles (except during ascent or inadvertent gas release), making them ideal for Naval special warfare and EOD operations. They also offer extended dive duration and weight advantages over open-circuit scuba. Closed-circuit UBAs are significantly more complex than open-circuit scuba, and malfunctions are more frequent. Among the disadvantages are a generally greater breathing resistance, additional training requirements for divers and maintenance personnel, and costs of initial purchase and subsequent maintenance. The Mk 25 Mod 2 (Figure 17-6) is the closed-circuit UBA used by most US Navy combat swimmers. It uses 100% oxygen without any inert gas diluent. Figure 17-7 shows the gas flow path.

By using 100% oxygen at shallow depths, there is no need for decompression, and if proper procedures are followed, the risk of decompression sickness is theoretically zero. However, there are several potential serious hazards associated with closed-circuit oxygen scuba:

- dilutional hypoxia from failure to initially purge nitrogen from the lungs and the breathing loop;
- increased risk of CNS oxygen toxicity at depths greater than 25 fsw (7.5 msw);
- carbon dioxide poisoning caused by overexertion, skip-breathing, increased breathing resistance, or exhaustion of the carbon dioxide absorbent; and

Figure 17-6. The Mk 25 Underwater Breathing Apparatus. May 18, 2006 - A US Navy SEAL (Sea, Air, Land) hangs on to a pier during a Combat Swimmer Training dive. US Navy photo by Senior Chief Mass Communication Specialist Andrew McKaskle (Released).
Reproduced from: http://www.navy.mil/view_image.asp?id=37909.

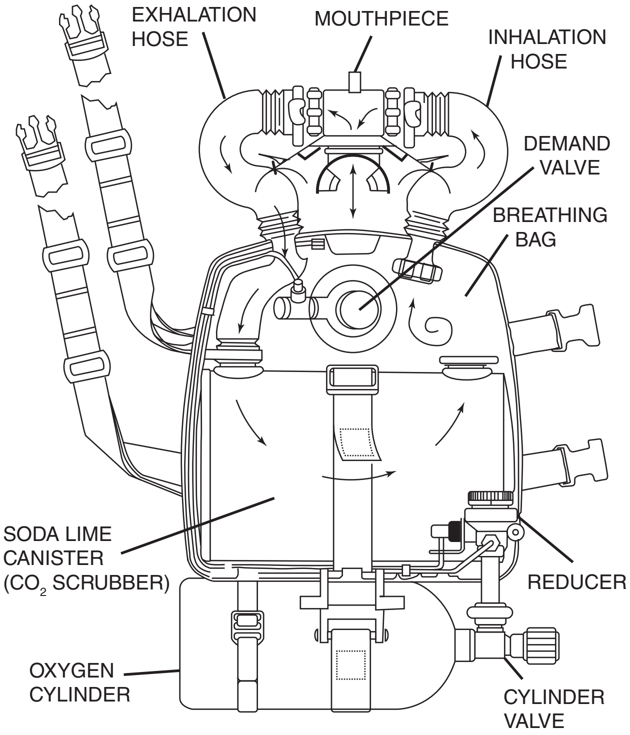

Figure 17-7. Gas flow path of the Mk 25.
Reprinted from US Department of the Navy. *US Navy Diving Manual*. Rev 6. Washington, DC: Naval Sea Systems Command; 2011: 19-10. NAVSEA 0994-LP-100-3199.

- flooding of the breathing loop, leading to both loss of buoyancy and chemical burns from wet absorbent (known as a "caustic cocktail").

Furthermore, the location of the breathing bag or bags relative to the lungs can cause carbon dioxide retention and reduce the diver's exercise capacity. When the diver is in a prone swimming position, a back-mounted bag is at a lower pressure than the lungs. This imposes a negative static lung load (as when breathing through a snorkel) and requires extra work during inspiration but less work during expiration. A chest-mounted bag imposes a positive static lung load, which assists inhalation but imposes extra work during exhalation. Of the two types of lung load, a small positive load causes less carbon dioxide retention and is preferable to a negative load.

Due to the very serious risk of CNS oxygen toxicity, strict operational limits are placed on depths and durations of closed-circuit oxygen dives. Further information on Mk 25 diving operations and procedures can be found in Chapter 19 of the *US Navy Diving Manual*.[2]

Closed-Circuit, Mixed-Gas Scuba

Closed-circuit, mixed-gas scuba affords the mobility of a free-swimming diver with the depth advantage of mixed gas. Figure 17-8 shows the US Navy Mk 16 UBA, which has a back-mounted breathing bag. Closed-circuit, mixed-gas rebreathers have one or more oxygen sensors (the Mk 16 has three) that measure the inspired oxygen partial pressure. This partial pressure is compared to the desired oxygen set point by a digital computer, which adds oxygen to the breathing bag when the partial pressure falls below the set point. For the Mk 16 Mod 1, the oxygen set point is 0.75 ata at depths shallower than 33 fsw (10 msw), and 1.3 ata deeper than 33 fsw (10 msw).

Perhaps the greatest advantage of a closed-circuit mixed-gas rebreather is gas conservation. At a fixed depth, the gas consumption of a closed-circuit rebreather equals the diver's metabolic rate (between 0.5 L/min for rest and 3.0 L/min for work), which a small oxygen supply can support for hours. The purpose of the diluent supply (Figure 17-9) is to fill the counterlung during descent, but the diluent can be quickly exhausted by multiple vertical excursions. The diluent can be air for depths shallower than 150 fsw (45 msw), and 12% oxygen in helium (He_2O_2 88/12) to prevent nitrogen narcosis for depths up to 300 fsw (90 msw). Both air and 12% oxygen (but not a smaller percentage of oxygen) can be breathed in an open-circuit mode at the surface in the event of equipment malfunction.

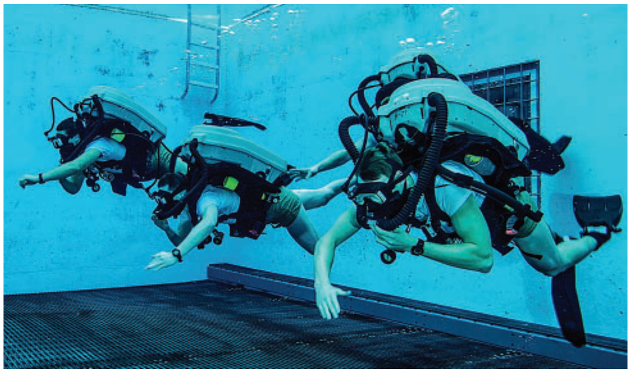

Figure 17-8. Students at the Naval Diving and Salvage Training Center conduct training with the US Navy Mk 16 Mod 1 UBA.
Photo courtesy of the US Navy.

Closed-circuit mixed-gas rebreathers are significantly more complex than closed-circuit oxygen rebreathers, and malfunctions are more frequent. Divers who make emergency ascents to the surface are at risk for arterial gas embolism (AGE) or decompression sickness (DCS), and those who lose consciousness underwater are at risk of drowning. Loss of consciousness usually occurs during descent or ascent, usually due to CNS oxygen toxicity or hypoxia, respectively. Closed-circuit mixed-gas scuba is still evolving and will remain a specialty most appropriate for divers who are highly trained, well-funded, and willing to assume risks beyond those encountered with open-circuit scuba.

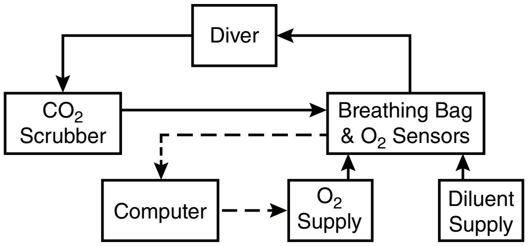

Figure 17-9. Schematic diagram of the Mk 16. This mixed-gas rebreather has a single, back-mounted bag, which contains three sensors that measure the oxygen partial pressure. The dotted lines represent electrical signals to and from the computer. If the mean partial pressure falls below the set point (0.75 ata shallower than 33 fsw [10 msw] and 1.3 ata deeper than 33 fsw [10 msw] for the Mk 16 Mod 1), the computer adds oxygen to the breathing loop.

THE ROLE OF RESPIRATION IN DIVING INJURIES

Risk of injury in diving can be mitigated in several ways, primarily through proper planning before the dive. However, there are several factors challenging divers, some of which are within their control (experience, practice, gear, team, etc), and some which are not (innate physiology, laws of physics). Also, a diver's ability to consciously influence fundamental physiological processes such as respiration adds complexity to the diving environment.

Divers who make emergency ascents to the surface are at risk for AGE or DCS, and those who lose consciousness underwater are at risk of drowning. Loss of consciousness when breathing air or nitrogen-oxygen has been called "deep-water blackout," as opposed to shallow-water blackout. The causes of these events can be difficult to determine, but nonfatal occurrences and unplanned laboratory incidents indicate that respiration plays an important role, as Edward H. Lanphier, MD, describes in Case Study 17-1.

Case Study 17-1. Carbon Dioxide Retention and Dyspnea. We were testing a new bicycle ergometer at 7.8 ata (224 fsw, 67 msw) in the dry chamber. Nitrogen narcosis is very evident on air at that pressure, but we were doing OK until we started breathing on the measuring circuit that gave us only about half the air we needed. Herb stopped pedaling after about three minutes, out cold with his eyes rolled back. I took the bike. I knew I wasn't getting nearly enough air, but I was too narc'd to think straight and was determined to finish the test. I pedaled myself right into oblivion and coming around slowly afterwards with a horrible feeling of suffocation was the worst experience of my entire life. Both of us surely would have drowned if such a thing had happened when we were underwater.[4]

Carbon Dioxide Retention and Dyspnea

Respiration is designed to maintain physiologically acceptable levels of oxygen and carbon dioxide in the blood and tissues, and healthy people breathing free air at sea level adjust their ventilation unconsciously to match their exertion. This is not always so during diving, where the effects of nonphysiological levels of oxygen, nitrogen, and carbon dioxide can interact and are exacerbated with increasing depth by work, breathing resistance, and gas density.[5,6]

Exercise capacity at sea level is limited by the cardiovascular system, whereas the respiratory system is usually the limiting factor during diving. Immersion shifts blood from the legs to the thorax, which reduces vital capacity and maximum ventilatory capacity. A regulator decreases the ventilatory capacity still further by increasing the work of breathing. Work of breathing is caused, in part, by resistance to gas flow in the airways and the breathing apparatus, and may be exacerbated by wasted work due to overbreathing the regulator. Resistance increases with depth as the gas density increases, but this effect is also dependent on the gas mixture used (helium is less dense than nitrogen). Ultimately, regardless of the cause, carbon dioxide is retained when ventilation is inadequate.[6]

Carbon dioxide is the primary ventilatory stimulus in diving. The hypoxic ventilatory drive is generally absent, because most diving gases are hyperoxic. Blood is designed to carry oxygen and carbon dioxide at normoxic pressures, not at elevated oxygen partial pressures. At sea level pressure, where venous oxygen is low, carbon dioxide is tightly bound to hemoglobin. At high oxygen partial pressures during diving, carbon dioxide is more loosely bound to hemoglobin, causing its tension in the blood and tissues to rise (known as the Haldane effect). However, the actual effect on increasing the carbon dioxide tension at depth has been disputed.[7]

Dyspnea generally results if increased ventilation does not reduce the elevated carbon dioxide tension. However, because dyspnea has a perceived component, it may not be solely due to retained carbon dioxide. There may be an additional neurologically mediated effect at higher pressures, over 1,000 fsw (305 msw), similar to the effects of high pressure nervous syndrome (HPNS).[6]

Multiple factors (see Case Study 17-1) may contribute to inhibited ventilation, and divers sometimes consciously override the hypercapnic ventilatory stimulus and hypoventilate (skip-breathe) to conserve air. Besides the risk of pulmonary barotrauma from breath-holding while breathing compressed gas, skip-breathing can contribute to hypercapnia, which, among other problems, can be responsible for headaches after diving.[8]

The importance of adequate respiration may not be adequately stressed during diver training, and a diver who expects the same respiratory performance at depth as on land may be surprised by the breathlessness that can occur if sudden exertion is required in an emergency. As Case Study 17-1 indicates, dyspnea is a frightening experience, and panic is a common response. Newly trained divers are particularly susceptible to making emergency ascents when dyspnea occurs. A diver overcome by a desire to surface and breathe free air may ascend too rapidly and risk AGE, DCS, or both.

An episode of respiratory insufficiency underwater can be a learning experience, but it is not an ideal lesson (Case Study 17-2). Because the normal unconscious regulation of respiration at sea level may be compromised during diving, divers should beware of incipient dyspnea, ventilate adequately, and minimize exertion. Sufficient ventilatory reserve should be maintained so that sudden, unexpected activity does not cause breathlessness and panic. If breathlessness occurs, the best way to avoid becoming in extremis is to stop all activity and let breathing return to normal.

Case Study 17-2: Deep-Water Blackout. During a dive to 180 fsw (54 msw) in a water-filled pressure chamber, a diver performed moderate exercise while swimming against a trapeze at an oxygen consumption of 2 L/min. He was using an Mk 15 UBA (similar to the Mk 16; see Figure 17-8) with an oxygen partial pressure of 1.4 ata in nitrogen. Despite orders from the diving supervisor to slow down, he increased his workload until he became unconscious. He revived immediately on removal from the water.

Interactions Between Gases and Impaired Consciousness

Carbon dioxide retention is exacerbated as depth increases by increased ambient pressure and greater work of breathing. Inspired carbon dioxide partial pressures of 10% to 15% surface equivalent are narcotic and can affect a diver's consciousness.[2] When the oxygen partial pressure is elevated, hypercapnia loses its effectiveness as a warning signal of respiratory depression or impending unconsciousness. The narcotic effect of excess carbon dioxide is additive to nitrogen narcosis, and narcosis can cause the hypercapnic ventilatory drive to be overlooked (see Case Study 17-1). Elevated carbon dioxide increases cerebral blood flow and raises oxygen delivery to the brain, increasing the risk of CNS oxygen toxicity.

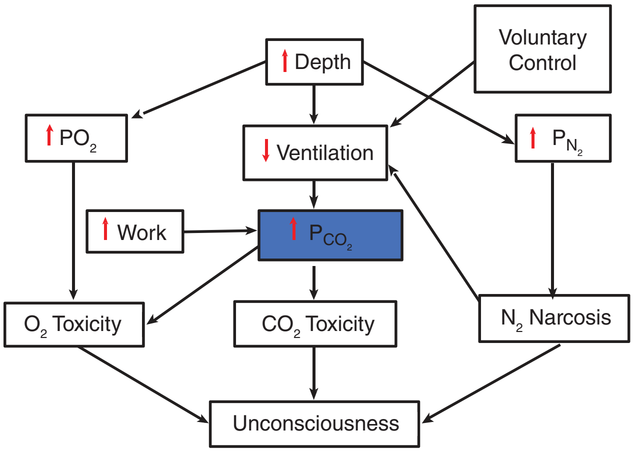

Figure 17-10. Factors affecting carbon dioxide retention and consciousness. Various factors contribute to increased P_{CO_2} in blood (center of diagram). Gas density increases as depth increases, which raises the work of breathing and decreases ventilation. Nitrogen narcosis increases with depth and can lead to altered mental status, either because it suppresses ventilation or because ventilation is altered by absolute increased pressure (dashed line).

P_{N_2}: pressure of nitrogen gas

Thus, diving can impair consciousness through the combined effects of nitrogen narcosis, carbon dioxide intoxication, and oxygen toxicity. These effects are exacerbated by exercise and gas density, which further increase carbon dioxide retention. Figure 17-10 illustrates the interactions among gases, exercise, and depth that increase the risk of unconsciousness. Deep air (as opposed to heliox) diving is dangerous because interactions of depth, work, oxygen, nitrogen, and carbon dioxide affect respiration and consciousness. Carbon dioxide is the primary factor controlling respiration during diving when the hypoxic ventilatory drive is absent in the presence of hyperoxia. Various factors contribute to increased P_{CO_2} in blood (center of Figure 17-10). Gas density increases as depth increases, which raises the work of breathing and decreases ventilation. Nitrogen narcosis increases with depth and can lead to altered mental status; however, debate exists as to whether nitrogen narcosis suppresses ventilation, or whether ventilation is altered due to absolute increased pressure.[9] Some divers reduce ventilation voluntarily to save gas, whereas others have poor ventilatory response to elevated carbon dioxide. Elevated carbon dioxide potentiates CNS oxygen toxicity, and carbon dioxide itself is narcotic.[10] Carbon dioxide is more likely additive to

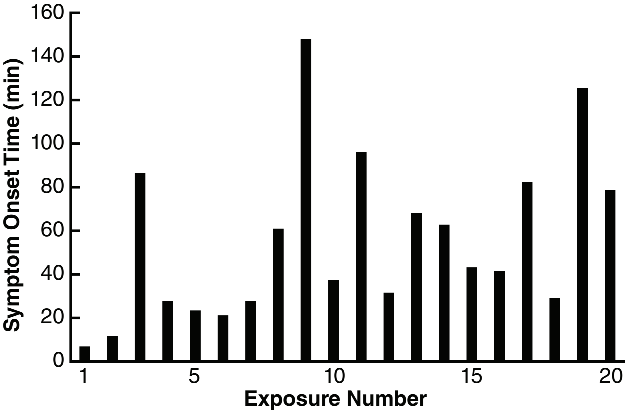

Figure 17-11. Variation in individual susceptibility to symptoms of central nervous system oxygen toxicity. The time to symptom onset is illustrated for a single individual who was exposed to 100% oxygen at 70 fsw (21 msw) on 20 days over 3 months. The average onset time was 44 minutes, with a range of 7 to 148 minutes.

Data source: Donald K. *Oxygen and the Diver*. Welshpool, Wales: SPA Ltd; 1993.

inert gas narcosis rather than synergistic, although this is still in debate.[9] In the presence of hyperoxia, dyspnea caused by carbon dioxide is less effective as a warning of altered consciousness. The risks of unconsciousness from oxygen toxicity, carbon dioxide toxicity, and nitrogen narcosis (all of which increase with depth) are exacerbated by physiological interactions among them.

Individual Susceptibility to Impaired Consciousness

Susceptibility to carbon dioxide retention, oxygen toxicity, and nitrogen narcosis vary widely from one individual to another. Some divers have poor ventilatory response to inspired carbon dioxide and are believed to be at an elevated risk of CNS oxygen toxicity due to increased cerebral oxygen delivery.[6,11] Studies also have shown wide variability of the latent period before CNS toxicity for the same individual. Experiments by the British found that the time to symptom onset varied randomly from 7 to 148 minutes for a single diver who made 20 exposures at 70 fsw (21 msw) while breathing 100% oxygen (Figure 17-11).[12]

A few individuals have made compressed air (21% oxygen) dives to depths of 300 to 500 fsw (90-150 msw) and have returned safely, despite nitrogen and oxygen stresses that would incapacitate most people. Other divers in these conditions have developed severe DCS or drowned, probably owing to loss of consciousness. There is no way to predict who is susceptible or resistant or how individual susceptibility varies from day to day.

DECOMPRESSION PROCEDURES

Other than avoiding diving altogether, the most effective way to reduce DCS risk is to employ methods that make the practice of undergoing changes in barometric pressure safer. This involves utilizing a system of techniques and procedures that are based in theory and also, ideally, proven by experimental data. One of the most often cited and commonly used sources of diving procedures is the *US Navy Diving Manual*.[2] In particular, it contains an extensive set of dive tables specific to different types of diving that guide the diver on how to safely allow the body to equilibrate to the surface after being under increased atmospheric pressure for a period of time. Several other diving authorities have developed similar tables and algorithms, all with varying allowed bottom times and ascent procedures. The discussion in this text is based on the US Navy tables, which are the most commonly used tables in military diving.

In relation to DCS, diving today is a relatively safe activity, especially when compared with the practices at the turn of the 20th century, when permanent paralysis and death were common (Case Study 17-3).

Case Study 17-3. Fatal Decompression Sickness in 1900. A Royal Navy diver descended to 150 fsw (45 msw) in 40 minutes, spent 40 minutes at depth searching for a torpedo, and ascended to the surface in 20 minutes with no apparent difficulty. Ten minutes later, he complained of abdominal pain and fainted. His breathing was labored, he was cyanotic, and he died after 7 minutes. An autopsy the next day revealed healthy organs but gas in the liver, spleen, heart, cardiac veins, venous system, subcutaneous fat, and cerebral veins and ventricles.[13]

According to the current US Navy standard air decompression tables, this diver should have had up to 532 minutes of decompression time.[2] Decompression risk is relatively low for divers who follow standard decompression tables such as those published in the *US Navy Diving Manual*, but even divers who adhere to accepted tables may develop the less serious forms of the disease and, occasionally, severe problems. Decompression tables specify rules for the time at depth, decompression stops, and surface intervals between dives. More recently, diver-worn digital computers have automated the process of decompression calculations, making them simpler and less prone to the kinds of errors divers make when working with tables. Additionally, these computers can more accurately calculate actual depth and time, thereby allowing the diver more time in the water, particularly on a multilevel dive. However, neither dive tables nor dive computers guarantee freedom from risk of DCS.

In 1993, the rate of ascent to the first decompression stop was changed in the *US Navy Diving Manual* from 60 fsw/min (18 msw/min) to 30 fsw/min (9 msw/min).[2] The safety stop, a development in recreational diving during the 1990s, interrupts ascents from no-stop dives with a 3- to 5-minute stage at 10 to 20 fsw (3-6 msw). Slower ascent rates and a safety stop may reduce the incidence of venous gas emboli, but their effect on the risk of DCS is uncertain.

No-Stop (No-Decompression) Dives

No-stop (ie, no-decompression) dives are the simplest, safest, and most common form of exposure. No-stop dives are short enough that the diver can return directly to the surface with an acceptably low risk of DCS. Although the slowest ascent rate possible conveys the least risk, an acceptable and practical alternative is the prescribed ascent rate of 30 fsw/min

(9 msw/min), per the *US Navy Diving Manual*. Table 17-1 is the US Navy table for no-stop air dives. It lists the maximum time (in minutes) allowed at a corresponding depth. The repetitive group designation letters in the table are used to determine allowed bottom time for subsequent repetitive dives.

In-Water Decompression Stops

If the bottom time at a given depth exceeds the stated no-stop limit for a decompression table or dive computer, the diver must remain at a shallower depth (a decompression stage or stop) long enough to allow inert gas to be eliminated harmlessly through the lungs. If the decompression stops are too short, excessive formation and growth of bubbles in the blood and tissues may result in DCS. In-water decompression stops are traditionally at 10-fsw (3-msw) intervals, with the shallowest stop at 10 or 20 fsw (3 or 6 msw). Decompression tables show the required stops and time at particular depths; these requirements vary depending on the decompression gas used.

Experiments and observations have found that decompression time can be reduced by 30% to 50% with about the same or a lower risk of DCS if oxygen is used instead of air during in-water decompression stops, but this benefit comes with the risk of CNS oxygen toxicity.[14] In-water oxygen decompression is not recommended deeper than 30 fsw (9 msw). A typical protocol requires the diver to breathe air at deeper stops, then switch to 100% oxygen at 30 fsw (9 msw). A backup decompression plan should be available for times when in-water oxygen cannot be used. Air should be available as a backup breathing gas in the event of CNS toxicity symptoms, and an emergency plan should be in place to manage convulsions. To reduce the risk of CNS toxicity, the US Navy tables stipulate that 5-minute air breaks be taken for every 30 minutes of oxygen breathing.

TABLE 17-1

US NAVY NO-DECOMPRESSION LIMITS AND REPETITIVE GROUP DESIGNATORS FOR NO-DECOMPRESSION AIR DIVES

		Repetitive Group Designation															
Depth (fsw)	**No-Stop Limit**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**Z**
10	Unlimited	57	101	158	245	426	•										
15	Unlimited	36	60	88	121	163	217	297	449	•							
20	Unlimited	26	43	61	82	106	133	165	205	256	330	461	•				
25	595	20	33	47	62	78	97	117	140	166	198	236	285	354	469	595	
30	371	17	27	38	50	62	76	91	107	125	145	167	193	223	260	307	371
35	232	14	23	32	42	52	63	74	87	100	115	131	148	168	190	215	232
40	163	12	20	27	36	44	53	63	73	84	95	108	121	135	151	163	
45	125	11	17	24	31	39	46	55	63	72	82	92	102	114	125		
50	92	9	15	21	28	34	41	48	56	63	71	80	89	92			
55	74	8	14	19	25	31	37	43	50	56	63	71	74				
60	60	7	12	17	22	28	33	39	45	51	57	60					
70	45	6	10	14	19	23	28	32	37	42	47	48					
80	39	5	9	12	16	20	24	28	32	36	39						
90	30	4	7	11	14	17	21	24	28	30							
100	25	4	6	9	12	15	18	21	25								
110	20	3	6	8	11	14	16	19	20								
120	15	3	5	7	10	12	15										
130	10	2	4	6	9	10											
140	10	2	4	6	8	10											
150	5	2	3	5													
160	5		3	5													
170	5			4	5												
180	5			4	5												
190	5			3	5												

•: Highest repetitive group that can be achieved at this depth regardless of bottom time.
Reproduced from: US Department of the Navy. *US Navy Diving Manual*. Rev 6. Washington, DC: Naval Sea Systems Command; 2011: 9-63. NAVSEA 0994-LP-100-3199.

Surface Decompression

During salvage of silver and gold in World War I, the weather or the military situation sometimes forced British divers to surface before completing their required in-water decompression stops.[14] Experience showed that this could be done safely if the divers were rapidly recompressed in a shipboard pressure chamber within 5 to 10 minutes of reaching the surface. Surface decompression was initially conducted with air, but subsequent studies by the US Navy found that decompression with oxygen was more effective.[14] Surface decompression with oxygen is typically conducted with recompression on 100% oxygen to a depth of 50 fsw (15 msw). It is acceptable to breathe 100% oxygen at a depth of 50 fsw (15 msw) in a dry chamber, in contrast to the 30 fsw (9 msw) depth limit for divers in the water, because dry divers are at a lower risk of oxygen toxicity.[14] As with in-water decompression, air breaks of 5 minutes are given for every 30 minutes of oxygen breathing.

Repetitive and Multilevel Diving

If two dives are made in close succession, inert gas remains in the body from the first dive. The second dive must therefore include reduced bottom time or longer decompression time to avoid increased DCS risk. The second exposure is known as a repetitive dive, and the time between the two dives is called the surface interval. The US Navy Residual Nitrogen Time Table for Repetitive Air Dives[2] indicates how to account for previous dives when planning repetitive dives. A no-stop repetitive air dive may be considered a new dive with no reduction in bottom time when the required surface interval has been met, which can range between just over 2 hours to nearly 16 hours, depending on the profile of previous dives. Repetitive diving is common among recreational divers, and four or more no-stop dives per day are not unusual over several days. Repetitive multi-day diving was once thought to increase the risk of DCS, but more recent data point to some amount of acclimatization that decreases DCS risk. The mechanism for this occurrence is poorly understood, but there has been a demonstrated decrease in venous gas bubble load after multi-day repetitive dives. However, multi-day diving also increases oxidative stress, leading to blood vessel endothelial dysfunction, which can increase DCS risk.[15–17]

Multilevel diving is a variant of repetitive diving in which the diver does not return directly to the surface but ascends in stages that take advantage of the longer no-decompression times at shallow depths (see Table 17-1) while avoiding mandatory decompression stops. Commercial, recreational, and military diving (with submersibles, in Special Operations) are frequently multilevel. There are a number of multilevel dive tables, but multilevel dives are most efficiently conducted when dive computers are used.

Dive Computers

The common term for a digital computer that a diver carries underwater for decompression guidance is a dive computer. (An alternative term sometimes used by the US Navy is a decompression computer.) The computer is usually worn on the wrist where it can be easily viewed. There are many different commercially available dive computers, but all are programmed with models, or algorithms, derived from the same or similar mathematical calculations as decompression tables. A decompression model is a mathematical representation of the kinetics of inert gas exchange in body tissues with rules to preclude ascents that might result in unsafe bubble formation or growth. Because the understanding of decompression physiology is incomplete and because there are differences among individuals, no decompression model is totally effective in preventing DCS. However, with current algorithms the incidence appears to be less than 1%.[18]

Dive computers accurately track depth-time profiles and minimize the human errors that can occur in table selection. They are most useful when conducting multilevel dives. Standard dive tables are based on maximum depth attained and total bottom time, and assume the diver spends the entire dive at that maximum depth. By using a dive computer that calculates inert gas exchange in real time, a diver may safely extend the no-decompression limit on a multilevel dive beyond the limits prescribed in the standard tables. Currently, only the Cochran Navy AIR III (Cochran Consulting Inc, Richardson, TX) decompression computer is authorized for use on military dives in lieu of standard dive tables, and only for no-decompression dives at altitudes less than 1,000 ft (305 m) above sea level. Dive computers are reasonably reliable, but hardware failures occasionally occur, so backup computers or tables are recommended. Despite their particular advantages and ease of use, dive computers are not a substitute for proper dive planning.

Nitrogen-Oxygen Diving

Many breathing devices can be used with gases other than air. The most common mixtures are of nitrogen and oxygen (called NITROX), in which the oxygen percentage is greater than the 21% in air. Such mixes are also known as enriched air NITROX. NITROX can be used with open and closed-circuit UBAs, but the oxygen fraction varies with the depth. NITROX mixes that contain less nitrogen than air reduce the risk of DCS if used with standard decompression procedures; however, the bottom time is often extended instead, which negates the reduction in decompression risk. The advantages of fixed percentage NITROX are as follows:

- extended bottom times for no-decompression diving,
- reduced decompression time,
- reduced residual nitrogen in the body after a dive,
- reduced possibility of decompression sickness, and
- reduced nitrogen narcosis.

The disadvantages of using NITROX include:

- increased risk of CNS oxygen toxicity,
- decreased allowable maximum depth due to risk of CNS oxygen toxicity,
- production requires special equipment,
- equipment requires special cleaning techniques,
- long-duration dives can result in pulmonary oxygen toxicity,
- working with NITROX systems requires special training, and
- NITROX is expensive.

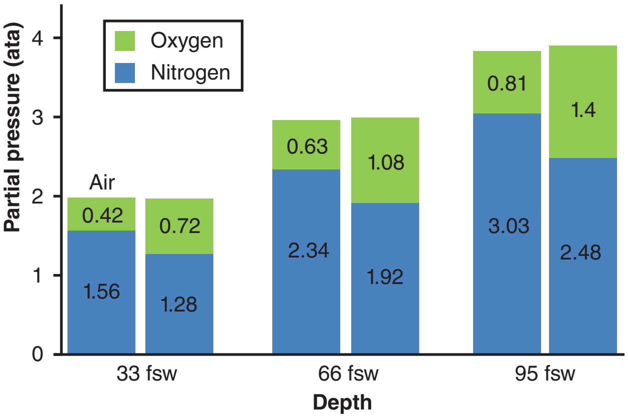

Figure 17-12. Oxygen partial pressures in air and 36% nitrogen-oxygen mixture (NITROX). The 36% NITROX provides a decompression advantage over air by reducing the nitrogen partial pressure to which a diver is exposed. Thus, 36% NITROX at 33 fsw (10 msw) has the same nitrogen partial pressure and is the decompression equivalent of breathing air at 20.5 fsw (6.2 msw). This is known as the equivalent air depth (EAD). The EAD at 66 fsw (20 msw) is 47 fsw (14.3 msw), and the EAD at 95 fsw (29 msw) is 71 fsw (21.6 msw). NOTE: the normal working limit for 36% NITROX is 95 fsw (29 msw) because at this depth the oxygen partial pressure rises to 1.4 ata; the risk of CNS oxygen toxicity increases significantly above this pressure.
ata: absolute atmospheres
CNS: central nervous system
fsw: feet of seawater
msw: meters of seawater

Figure 17-12 illustrates the oxygen and nitrogen partial pressures at various depths with air and with 36% NITROX. The 36% NITROX has a clear decompression advantage over air, owing to its lower nitrogen partial pressure, but the depth limitation due to increased risk of oxygen toxicity is also obvious. Ignoring depth limits in NITROX diving has led to fatal convulsions. NITROX diving can be conducted with reasonable safety, but additional training in physics, physiology, and gas mixing and analysis is advisable. The decompression requirement is obtained by calculating the equivalent air depth of a given NITROX mixture (Table 10-1 in the *US Navy Diving Manual*[2]) and using that depth on the standard air table. NITROX is not suitable for deep diving because of the increased risk of CNS oxygen toxicity. Per the *US Navy Diving Manual*, the normal working limit for oxygen partial pressure exposure is 1.4 ata, which makes 100 fsw (30 msw) the greatest allowable depth with 32% oxygen (including a safety factor for rounding gas percentages to the nearest whole number and potential errors in gas analysis).

Helium-Oxygen and Trimix Diving

For dives deeper than 150 fsw (45 msw), heliox (a mixture of helium and oxygen, commonly referred to as "mixed gas") or trimix (a mixture of helium, nitrogen, and oxygen) are used to eliminate or reduce nitrogen narcosis. The oxygen fraction in these mixtures is often less than 21% and is determined to keep oxygen partial pressures below 1.3 to 1.4 ata, which are potentially toxic to the CNS at deep depths. The *US Navy Diving Manual* contains helium-oxygen tables for use with surface-supplied and closed-circuit diving operations.

Omitted Decompression

A diver who surfaces before completing a required decompression stop is subject to increased risk of DCS. Decompression may be omitted as a result of water conditions, equipment failure, personal injury, uncontrolled ascent, or running out of air. Out-of-air situations are more common with scuba than with surface-supplied equipment. If omitted decompression does occur, the diver should be treated in a recompression chamber or decompressed in the water, depending upon the amount of decompression missed, presence of symptoms, and tactical situation. Due to the risk of omitted decompression, no-decompression dives are safer than planned decompression dives.

Flying After Diving and Diving at Altitude

DCS can occur independently of diving during altitude exposures above about 18,000 ft (5,500 m; a barometric pressure of 0.5 ata).[19] Nitrogen dissolved in the tissues at sea level has a tension of about 0.79 ata and leaves solution to form bubbles at altitude. Flying after diving increases the risk of DCS because additional nitrogen remains in the tissues after a dive. To reduce the DCS risk from flying too soon after diving, divers are advised to wait long enough at sea level for nitrogen dissolved in their tissues to be eliminated harmlessly through the lungs. The *US Navy Diving Manual* Table 9-6 lists preflight surface intervals required before flying is considered safe. These surface intervals range from 0 to 21 hours for a commercial flight depending on the severity of the previous diving exposure. The US Air Force requires a 24-hour wait after any diving before flight.

Diving at altitude also increases the risk of DCS. Because the bodies of sea-level residents are in equilibrium with the 0.79 ata of nitrogen in atmospheric air, rapid ascent to an altitude of 18,000 ft (5,500 m), where atmospheric nitrogen is only 0.4 ata, causes a supersaturation of 0.39 ata. The supersaturated nitrogen dissipates over about 24 hours and must be accounted for during that time. Dives conducted within 12 hours of initial ascent to altitude are considered repetitive dives. *US Navy Diving Manual* Table 9-5 lists the repetitive group designator associated with altitudes up to 10,000 ft (3,048 m).

After equilibration is complete, the no-decompression times are still shorter than normal because bubbles grow larger at reduced barometric pressure than at sea level. Therefore, a dive conducted at an altitude of 5,000 ft (1,524 m) to a depth of 60 fsw (18 msw) is equivalent to an 80-fsw (24-msw) dive at sea level. *US Navy Diving Manual* Table 9-4 lists equivalent sea level depths for air diving at altitudes up to 10,000 ft (3,048 m), as well as altitude diving procedures relevant to military diving.

Safety of Decompression Practices

The question of how safe diving is with the use of dive tables or computer algorithms is extremely difficult to answer despite significant advances in the understanding of decompression physiology. The inability to accurately predict DCS lies in the incomplete understanding of the human physiologic response to diving and the unique interactions of gas exchange, bubble dynamics, and, tissue response. Additionally, DCS has long been considered a binomial event, meaning it either does or does not happen, making it difficult to capture sub-threshold events. The true nature of DCS is more likely a spectrum that is difficult to gauge until the point of significant symptoms. In historical findings, the measured DCS incidence rates in a set of US military dives has been shown to range from 0.029% to 1.25% over a wide variation of dives.[20,21]

Much work has been done in attempting to model the complex system of human decompression by either trying to replicate the components of gas exchange and bubble dynamics coupled with empirical parameters (deterministic modeling), or by using modern statistical methods of analyzing diving databases and applying estimated parameters (probabilistic modeling).[22] At present, insufficient experimental or observational data are available to confirm the estimated probabilities of DCS, although the estimates are suspected to exceed the true values. As such data and more powerful computing techniques become available, probabilistic algorithms are expected to replace the algorithms currently used by dive tables and dive computers.

SATURATION DIVING

The term “saturation diving” refers to diving operations (dry or wet) conducted with divers remaining at a particular depth for a period of time such that their bodies become equilibrated, or saturated, to a maximum partial pressure of inert gas. After about 24 hours at any depth, the inert gas tension in the body reaches equilibrium with the inert gas partial pressure in the ambient atmosphere, and the decompression time achieves its maximum length, independent of dive duration. Although saturation dives are logistically complex, they prevent the stresses of multiple bounce dive decompressions in circumstances where long working times are desirable. The overall advantage is that the work can be completed in less time on station because the efficiency of bottom time per diver is greater.

Saturation diving is used most often in commercial diving, occasionally in scientific diving, and by the US Navy for salvage or submarine rescue.

Saturation divers usually live in a DDC at a "storage" pressure near to or shallower than the dive site depth at which they work. If the chamber is on a surface ship, the divers transfer to a PTC through a mating hatch in the DDC, and the PTC is lowered to the dive site. Figure 17-13 shows a saturation diving system with one PTC and two DDCs. The US Navy currently uses a portable system known as SAT FADS (Saturation Fly Away Diving System), which can be mounted on different types of vessels and is certified to an operating depth of 1,000 fsw (305 msw).

Saturation diving may also be conducted from sea-floor habitats, but few of these are now in use because they are expensive and difficult to maintain. The longest running sea-floor operation is the Aquarius Habitat off the coast of Key Largo, Florida. Owned by the National Oceanic and Atmospheric Administration and managed by Florida International University, Aquarius Habitat primarily conducts marine science research, but it has also been used for saturation diving training by the US Navy and for simulated astronaut training by NASA.

If a diver is stored at a given depth and the worksite is deeper than the storage depth, he or she makes a descending, or downward, excursion to the worksite. Ascending, or upward, excursions from storage depth are usually made from underwater habitats. The *US Navy Diving Manual* provides tables for excursions from various saturation depths after which divers may return to the storage pressure without decompression stops. Downward excursions are most common, with the DDC storage depth chosen as shallow as the operation of the excursion tables allow. This minimizes the pressure at which the divers must live and the length of the final decompression to the surface. Oxygen partial pressures during excursions can range from 0.4 to 1.2 ata, depending on the breathing apparatus used and the type of operation. Because helium is expensive and not readily available, and because open-circuit equipment (scuba or surface-supplied) uses large gas volumes as the depth increases, exhaled gases are sometimes returned to the PTC or the surface, where they are reconditioned for reuse by removing carbon dioxide and adding oxygen.

Atmospheric Control

A saturation chamber is a closed environment whose atmosphere must be carefully controlled to maintain diver health. As the saturation depth increases, the oxygen percentage must decrease so that the oxygen partial pressure does not exceed 0.5 ata, which is the approximate threshold for pulmonary oxygen toxicity in long-duration exposures. At a depth of 1,000 fsw (305 msw), for example, the oxygen percentage must not exceed 1.6% in order to maintain a Po_2 of 0.5 ata. The US Navy uses a goal Po_2 range of between 0.44 and 0.48 ata.

Figure 17-13. The dive bell component of the Flyaway Saturation Diving System, which is used to transport saturation divers to and from a large compression chamber on the surface and the ocean depths where they perform their work. Gulf of Mexico, May 9, 2012 - Navy Diver 1st Class Alvin Carter, right, a reserve component sailor certified to mix gases for breathing in deep-water diving, watches as a winch hoists a manned dive bell from a depth of more than 600 feet, more than 65 miles south of the coast of Panama City Beach, FL. US Navy photo by Mass Communication Specialist 2nd Class Charles E. White (Released).
Reproduced from: http://www.navy.mil/view_image.asp?id=123795/.

The balance of the pressure is made up by inert gas, which is nitrogen for dives to depths of about 120 fsw (37 msw) and helium at greater depths. Most saturation diving occurs deeper than 200 fsw (61 msw), with helium as the inert gas. At depths of 1,000 fsw (305 msw) and deeper, a trimix of helium-nitrogen-oxygen or a mix of hydrogen-helium-oxygen is sometimes used to reduce the risk of HPNS, but it is uncertain if the nitrogen ameliorates the HPNS or only relieves some of its symptoms. The Navy currently has procedures only for helium-oxygen.[2]

Accurate gas analysis is essential to maintaining safe levels of oxygen and carbon dioxide. The carbon dioxide level is typically controlled to less than 0.5% surface equivalent or a Pco_2 of 0.005 ata, by absorbent material in a closed-loop life-support system. At a depth of 1,000 fsw (305 msw), for example, the percentage of carbon dioxide must not exceed 0.016%. Chamber ventilation must be adequate to keep the atmosphere mixed. In a helium atmosphere, heavier gases such as carbon dioxide and oxygen tend to pool in low or poorly ventilated areas, and toxic levels of carbon dioxide have occurred in bunks isolated by curtains.

Toxic atmospheric contaminants such as carbon monoxide or hydrocarbons can be eliminated only by flushing the chamber and piping systems with fresh gas, but this is costly and may be impossible on a ship with limited gas supplies. Contaminants must be prevented from entering the chamber. Carbon monoxide is produced at a rate of 8 to 10 mL per person per day by the metabolism of hemoglobin and must be monitored, but unsafe levels from this source are unusual.

Hydrocarbons can be introduced from petroleum lubricants, leaks in life-support refrigeration units, or improperly cleaned piping. Petroleum lubricants are a fire hazard as well as source of pollution. Divers produce methane at a rate of 300 to 500 mL per person per day. Some chamber systems lock out human waste immediately; others hold it in a sanitary tank. Human waste allowed to sit in a sanitary tank produces ammonia, indole, skatole, sulfur dioxide, hydrogen sulfide, chlorine, and carbon dioxide; therefore, sanitary tanks should be vented externally to prevent contaminating the chamber atmosphere. Many naturally occurring contaminants can be removed by filters in the life-support loop. Mercury is prohibited, and instruments or components such as mercury thermometers and electrical mercury switches must be avoided. The basic rule for preventing contamination is "if in doubt, keep it out."

Fire

Although the concern for fire is significant in any enclosed environment used for human occupation, the chance for combustion is remote at oxygen percentages lower than 6%. This means that fire is of the greatest concern at depths less than 231 fsw (70 msw). Many of the same materials that pose a risk of atmosphere contamination are also fire concerns (petroleum products, hydrocarbons, flammable gases). Applying the same rules to saturation systems as to standard recompression chambers will provide significant safety from fire. A variety of fire suppression systems exist, typically employing the use of water under pressure either through handheld or wall-mounted devices.

Infection

Hygiene is important in a closed environment. High humidity fosters an environment that promotes the development of superficial infections. A common recommendation for preventing external otitis is to instill a solution of aluminum acetate with 2% acetic acid into each ear every morning and evening, and before and after diving. The external ear canals are filled with this solution for 5 minutes while the diver lies on one side and then the other. Bed linen should be changed every 48 hours and daily showers taken whether diving or not. Chamber surfaces require daily cleaning with a nonionic detergent solution, and the bilges should be rinsed and drained at the same time. Food spills and the like should be cleaned immediately. Divers should wear their own thermal protection suits to prevent the spread of skin infections. Suits should be rinsed with nonionic detergent and water and be hung to dry.

Hyperbaric Arthralgia

Hyperbaric arthralgia is joint discomfort or pain that occurs during compression and decreases in intensity during 24 hours or more at constant depth. Symptoms include joint cracking, a sensation of "dry and grainy" joints, and a feeling similar to sprain. In order of severity, affected joints are the shoulders, knees, wrists, hips, and back. Least affected joints are the ankles, fingers, and elbows. Hyperbaric arthralgia can occur during short bounce dives but is more common during deep saturation dives. Its frequency, severity, and duration increase with depth and compression rate, but task performance is usually not affected. The condition is less common with the slow compression rates used to alleviate HPNS. The origin of hyperbaric arthralgia is unknown, but suggested causes are changes in the nature of bubble formation with increasing pressure and changes in joint fluid osmolarity leading to dehydrated articular cartilage. There is no evidence that hyperbaric arthralgia leads to joint degeneration or aseptic bone necrosis.

High Pressure Nervous Syndrome

HPNS begins at about 300 to 600 fsw (90–180 msw) and is manifested by tremor, decreased motor and intellectual performance, dizziness, nausea, vomiting, and occasionally psychosis. Focal reflex changes sometimes occur, and balance may be affected. Deeper than 1,000 fsw (305 msw), electroencephalograms may show slow theta waves, and alpha activity may be depressed. Divers easily fall into microsleep if not continually aroused. HPNS symptoms can be reduced, but not eliminated, by slowing or interrupting compression as depth increases. Although there is considerable individual variability, HPNS imposes a limit of not much more than 2,000 fsw (610 msw) as the maximum depth that humans can tolerate under dry conditions. The maximum depth at which practical work in the water is possible is less than 2,000 fsw (610 msw) owing to excess work of breathing in the UBA, particularly during exhalation.

Temperature Control

Saturation diving using helium-oxygen mixtures poses additional problems because of heat loss from the body due to the high thermal conductivity of helium. A significant amount of heat is lost through respiration, and the loss may be too great to be overcome by metabolic compensation alone. Therefore, various thermal protection mechanisms are employed (see further discussion below).

Heating the breathing gas (raising its temperature by 16° to 28° C [30°–50° F]) mitigates respiratory heat loss. Without using a heating device, divers would succumb to respiratory symptoms and hypothermia with relatively little warning due to the rapid cooling effect of breathing cold helium mixtures.

The usual thermal protection of wetsuits and dry suits is not sufficient at saturation depth sea temperatures and helium environments. In addition to breathing gas heating, active external heating of the body is required, typically through hot water suits. Hot water is received through the diver's umbilical, circulates through the suit, and discharges to the sea.

Decompression

Saturation decompression must occur very slowly to prevent DCS. For helium-oxygen, the US Navy uses a continuous reduction of pressure according to the following scale:

- 6 fsw/h from 1,600–200 fsw (1.8 msw/h, 480 to 60 msw);
- 5 fsw/h from 200–100 fsw (1.5 msw/h, 60-30 msw);
- 4 fsw/h from 100–50 fsw (1.2 msw/h, 30-15 msw); and
- 3 fsw/h from 50–0 fsw (0.9 msw/h, 15-0 msw).[2]

To minimize decompression during sleep, the US Navy schedule stops decompression from midnight to 0600 and from 1400 to 1600, during which the oxygen partial pressure is maintained at 0.4 to 0.48 ata. Saturation divers are required to remain near a recompression chamber for at least 2 hours after decompression and within 30 minutes' travel time to a chamber for 48 hours. Flying is prohibited for 72 hours after saturation diving.

THERMAL PROTECTION AND BUOYANCY

Global water temperature is typically below body temperature, and except for short exposures, unprotected divers are at risk of hypothermia, as discussed above in relation to saturation diving. Hyperthermia, on the other hand, is an unusual hazard for divers. The *US Navy Diving Manual* gives allowable exposure durations as a function of temperature and the means of thermal protection. Buoyancy control is closely linked to thermal protection, because almost all thermal protection methods use gas for insulation.

Most heat loss occurs by convection through the skin and lungs; as a result, the ambient temperature in a saturation chamber must be 29.4° C to 32.2° C (85° F–90° F) for normal body temperature to be maintained. The range of thermal comfort narrows with increasing depth. Water vapor diffuses slowly at high pressure, and evaporation provides little cooling, which makes the skin feel wet without evidence of sensible water. The comfort range for relative humidity is 50% to 70%.

Historically, hard-hat divers wore heavy woolen underwear beneath a canvas outer suit. The suit was supposed to remain dry but frequently leaked. Because the suit was filled with air, the diver wore heavy boots and weights to achieve the negative buoyancy needed to walk on the bottom. To maintain proper buoyancy, the suit had to be inflated during descent and deflated during ascent. Hard-hat divers could suffer severe injury from suit squeeze (ie, barotrauma that occurs when a poorly fitting suit is insufficiently expanded) if the air supply was inadequate to maintain suit volume during descent. During ascent, gas was vented from the suit to avoid uncontrolled positive buoyancy (ie, blow-up), in which the diver was propelled to the surface and risked air embolism, DCS, or mechanical injury from collision.

The wetsuit is the most common form of thermal protection used today. Made of air-filled, closed-cell neoprene foam, wetsuits are satisfactory for several hours at temperatures of 10° C to 15.5° C (50° F–60° F) but provide less protection with increasing depth as the air-filled cells compress. Minor suit squeeze sometimes occurs with tight-fitting wetsuits. As a diver descends, wetsuit compression reduces buoyancy by several pounds. A buoyancy compensator to which gas can be added or removed is typically used to make adjustments from slightly positive to slightly negative buoyancy, according to whether ascent or descent is desired. With open-circuit scuba, buoyancy increases by several pounds as compressed gas is consumed from the tanks. Swimming with fins, the common mode of propulsion with scuba, helps a diver remain warm for several hours.

The next level of thermal protection, the variable-volume dry suit, is a waterproof outer garment over insulating underwear that is sufficiently warm for brief periods of ice diving. Dry suit diving requires training in buoyancy control to avoid suit squeeze or blow-up. For an untethered scuba diver in deep water wearing a dry suit, a suit squeeze could make the diver negatively buoyant, resulting in a fatal uncontrolled descent. Conversely, over-inflation of the suit can lead to an uncontrolled ascent or blow-up, resulting in serious or fatal AGE or DCS. Dry suits can be inflated from the diver's breathing gas or from a separate gas supply. Helium is a poor choice as an insulator because its thermal conductivity is 5.7 times greater than that of air, and its heat capacity 4.4 times greater than that of air.[23] These characteristics cause heat loss to increase with depth. Dry suits provide inadequate thermal protection during 6- to 8-hour exposures in -1.1° C to 4.4° C (30° F–40° F) water for inactive divers, such as the operators or passengers of SDVs. Additionally, a diaper or other urine-collection device is required if the dry suit is to remain dry during a dive of several hours' duration. Because of its greater bulk, a dry suit is more difficult to swim in than a wetsuit.

Wetsuits and dry suits provide passive insulation, which delays but does not prevent body cooling. Active heating is the most effective thermal protection. The most common active heat source is hot water (not to exceed 43° C [109° F]) supplied from the surface or a PTC to a loose-fitting wetsuit, through which the water flows before it exits at the hands and feet (see Figure 17-5). An even distribution of flow and careful temperature control are critical for adequate heating without causing hot spots or thermal burns. During deep helium-oxygen diving, the breathing gas must be heated to prevent convective heat loss through the lungs, which can cause a progressive hypothermia that may go unnoticed.

Hyperthermia can occur in special circumstances. At remote diving sites in hot climates, recompression chambers that treat diving casualties and DDCs that support saturation diving may be outdoors and exposed to the sun. Hyperthermia can occur when diving in very warm water, such as in the Arabian Gulf where water temperatures can exceed 32° C (90° F). Divers in confined waters (eg, in or around power plants) may also be exposed to temperatures that can cause hyperthermia. This is a particular problem in hazardous environments such as nuclear reactors, where special suits and breathing apparatuses are worn to prevent inward leaks of water contaminated by radioactive material. These suits may incorporate closed-circuit cooling water to prevent overheating. In addition to being leak-proof, suits used in water or other liquids that are contaminated with biological agents or toxic chemicals must be made of materials that will not degrade during exposure. Before the diver undresses, the suits must be thoroughly washed down to prevent harmful exposure to the diver or support personnel.

MEDICAL STANDARDS FOR DIVING

As with many activities, diving is associated with inherent risks. These are due to operating in a foreign environment under physical (temperature, pressure) and physiological (micro-bubble emboli, inflammatory) stress, conditions that are not normally familiar to the human body. To maximize safety, it is imperative that any alterations from a normal physiological state be assessed and determined to be compatible with safe diving practices. The guiding principle is that any abnormality that could unnecessarily be made worse by diving, which could place the diver in immediate undue risk in the diving environment (or cause the diver any detriment), should represent a contraindication to diving.

In the military, diving medical officers (DMOs) examine candidates for initial diving training, provide advice to diving officers concerning the medical aspects of diving operations, examine divers before or after dives, offer routine medical care, and treat divers for diving injuries. Some conditions (eg, epilepsy) are absolute contraindications for diving, while others (eg, upper respiratory infection) are temporarily disqualifying or disqualifying until corrected. Table 17-2 summarizes the generally accepted recommended absolute and relative contraindications for recreational and commercial diving. No list on this matter is complete, and there are exceptions to every rule, so each diver should be evaluated for his or her specific conditions by a qualified examiner. Conditions that might be allowed for recreational divers may be disqualifying for military divers. US Navy regulations outlined in the *Manual of the Medical Department*, NAVMED P-117, Chapter 15, guide the military diving medical standards for all US military services.[24]

TABLE 17-2

RECOMMENDED ABSOLUTE AND RELATIVE CONTRAINDICATIONS TO DIVING

System	Absolute Contraindications	Relative Contraindications
Ears and upper respiratory	Open tympanic perforation Inability to equalize the middle ear Tube myringotomy Inner ear surgery (eg, stapedectomy, ossicular chain) Permanent obstruction of the external canal Meniere disease or other inner ear disease Chronic mastoiditis or mastoid fistula History of vestibular barotrauma Inability to retain mouthpiece Deafness in one ear	Middle ear barotrauma Recurrent or chronic sinus, external canal, or middle ear infections Allergies of the nose and upper respiratory tract
Pulmonary	History of spontaneous pneumothorax Reactive airway disease (asthma) of any origin Chronic obstructive pulmonary disease Restrictive lung disease History or radiographic evidence of pulmonary blebs, bullae, or cysts	Childhood asthma without residual hyperactivity or air trapping Pneumothorax due to barotrauma, penetrating injury, or surgery without air trapping
Cardiovascular	Aortic or mitral stenosis History of myocardial infarction Angina or coronary artery disease Cardiac septal defects Complete or fixed second-degree heart block Wolf-Parkinson-White syndrome with paroxysmal atrial tachycardia or syncope Exercise-induced tachyarrhythmias Fixed-rate pacemaker Hypertension with evidence of end-organ damage Drugs that inhibit normal exercise Peripheral vascular disease that limits exercise	None
Neurological	Seizure disorder Brain or spinal cord tumor Cerebrovascular accident or transient ischemic attack Demyelinating disease Spinal cord trauma with neurological deficit Head injury with sequelae Intracranial surgery Central nervous system aneurysm or vascular malformation Migraine headaches with neurologic symptoms Episodic loss of consciousness	History of head trauma with loss of consciousness but no sequelae Chronic headaches History of neurological decompression sickness with residual symptoms
Hematological	Unexplained anemia Polycythemia or leukemia Sickle cell disease	Acute anemia
Endocrine	Insulin-dependent diabetes mellitus Diabetes mellitus treated by diet or oral agents with history of hypoglycemia	Non–life-threatening hormonal excess or deficiency Renal insufficiency Obesity
Reproductive	Pregnancy in any stage	None

(**Table 17-2** *continues*)

Table 17-2 *continued*

Psychiatric	Inappropriate motivation Claustrophobia or agoraphobia Active psychosis or psychosis while receiving psychotropic drugs Panic disorder Alcohol or drug abuse Suicidal ideation with or without severe depression Significant anxiety state Manic state	None
Ophthalmological	Radial keratotomy Uncorrected visual acuity inadequate to find diving buddy or boat if corrective lenses Corrected visual acuity inadequate to read instruments	None
Gastrointestinal	Uncorrected abdominal wall hernia Paraesophageal or hiatal hernia Chronic or recurrent obstruction Severe gastroesophageal reflux	Peptic ulcer disease Malabsorption Functional bowel disorders Inflammatory bowel disease
Musculoskeletal	Low back pain with neurological symptoms Disability that would hamper work in the water or with diving equipment Juxtaarticular aseptic bone necrosis	Acute sprain or strain Acute trauma

Data sources: (1) Bove AA, Davis JC, eds. *Bove and Davis' Diving Medicine.* 4th ed. Philadelphia, PA: Saunders, 2004. (2) Davis JC, Bove AA. *Medical Examination of Sports SCUBA Divers*. Flagstaff, AZ: Best; 1986. (3) Linaweaver PG, Vorosmarti J. *Fitness to Dive: 34th UHMS Workshop Report*. Kensington, MD: Undersea and Hyperbaric Medical Society; 1987.

The *US Navy Diving Manual* provides general guidelines for return to diving after DCS or AGE, but each case requires review by a DMO.[2] Current guidelines state that divers successfully treated for type I DCS may be cleared by a DMO for return to diving duty after 7 days post treatment. Divers successfully treated for AGE or type II DCS, with no residual symptoms, may be cleared by a DMO to return to diving duty 30 days after treatment. If symptoms persist, follow-on treatments may be recommended at the discretion of the DMO. Return-to-duty determination will likely require further workup and specialist review.

HYPERBARIC OXYGEN THERAPY AND RECOMPRESSION CHAMBERS

Decompression illness is a relatively rare phenomenon, and most civilian recompression facilities are used more frequently to provide hyperbaric oxygen therapy (HBOT) for other indications. HBOT is recommended for conditions caused by gas bubbles, inadequate perfusion, and metabolic poisons. The recognized expert on this subject matter is the Undersea and Hyperbaric Medical Society (UHMS), which regularly reviews current literature and publishes a peer-reviewed journal on diving and hyperbaric medicine. According to the UHMS and the Centers for Medicare and Medicaid Services, HBOT constitutes breathing oxygen in a pressurized chamber. The current recommendation is that the Po_2 should be 1.4 ata or higher. Breathing 100% oxygen at 1 ata or exposing isolated parts of the body to 100% oxygen is not considered HBOT.[25]

The field of HBOT has undergone significant changes in its lifetime, and there are numerous claims for its ability to treat many types of ailment. The UHMS has fought hard to keep the field rooted in evidence-based medicine, but many treatment centers continue to promote HBOT for unapproved indications. The Food and Drug Administration continues to monitor these practices and has issued warnings to consumers to be skeptical of overzealous claims.[26] The following indications are approved uses of HBOT as defined by the UHMS's Hyperbaric Oxygen Therapy Committee:[25]

- air or gas embolism
- carbon monoxide poisoning
- carbon monoxide poisoning complicated by cyanide poisoning

- clostridial myositis and myonecrosis (gas gangrene)
- crush injury, compartment syndrome, and other acute traumatic ischemias
- decompression sickness
- arterial insufficiencies
- central retinal artery occlusion
- enhancement of healing in selected problem wounds
- severe anemia
- intracranial abscess
- necrotizing soft tissue infections
- osteomyelitis (refractory)
- delayed radiation injury (soft tissue and bony necrosis)
- compromised grafts and flaps
- acute thermal burn injury
- idiopathic sudden sensorineural hearing loss

The above conditions, except for severe anemia, intracranial abscess, acute thermal burn injury, and idiopathic sudden sensorineural hearing loss, are covered for reimbursement by the Centers for Medicare and Medicaid Services[27] (the exceptions may be covered by third-party insurers). In light of recent military conflicts involving injury due to explosions, there is increasing interest in the possible benefits of HBOT for traumatic brain injury, and several studies are ongoing. Under certain circumstances the US Navy will treat some of the approved indications; however, most Navy chambers are designed for supporting military diving operations and lack the medical support infrastructure needed to treat more complicated medical patients.

There are two principal types of hyperbaric chambers: multiplace and monoplace. Multiplace chambers are made of steel or aluminum, can accommodate two or more people, and are usually compressed with air. Their depth capability is often greater than 60 fsw (18 msw). Multiplace chambers generally have two or more compartments, known as "locks," that allow personnel to be transferred in or out while at pressure (Figure 17-14). Typically the inner lock is larger and kept at depth, while the outer lock is smaller and available to "travel" from surface pressure to depth as required. Depending on size, an inner lock may accommodate as many as 12 patients who receive 100% oxygen by mask or hood. The lock is periodically ventilated with air to keep the carbon dioxide level below 1.5% surface equivalent and to maintain the oxygen level below 25% to limit the fire hazard.[2] Critical care nursing can be provided if mechanical ventilation or intravenous drug infusions are required.

Figure 17-14. Double-lock hyperbaric chamber.
Santa Rita, Guam, February 25, 2015 - US Naval divers monitor a patient during a demonstration for patient care due to decompression illness in the hyperbaric chamber. US Naval Base Guam is home to the only recompression chamber in the region and provides treatment to military and civilian personnel from Guam and the Micronesia Islands. US Navy photo by Mass Communication Specialist 2nd Class Chelsy Alamina (Released).
Reproduced from: http://www.navy.mil/view_image.asp?id=192715.

A monoplace chamber is generally an acrylic cylinder compressed with 100% oxygen that accommodates a single patient in the supine position. Its depth capability is often 45 to 60 fsw (13.5–18 msw). Monoplace chambers do not allow for direct patient access, although air breaks during oxygen breathing often can be given by mask for conscious patients. Monoplace chambers have been used effectively for decompression illness therapy, but depending on depth capability, they may not be able to provide therapy in accordance with the standard treatment tables. Because of their lower cost, there are many more monoplace chambers than multiplace chambers. Lightweight, inflatable monoplace chambers that can be compressed with air have proven effective but are cumbersome to use. In addition to treatment, they can be used as hyperbaric stretchers to provide transport to more robust facilities.

SUMMARY

Military diving operations have special medical requirements because of the physiological stresses imposed by barometric pressure, breathing gas composition, and immersion. Personnel at risk include several thousand divers in the US military (Navy, Marine Corps, Army, Air Force, Coast Guard) in addition to military divers from other nations. For US forces, the *US Navy Diving Manual* provides guidance on the conduct of diving operations and associated medical assistance. Diving history provides a useful context in which the interactions of mission and environment can be appreciated from a medical perspective. UBAs, which provide a reliable source of breathing gas and extend the dive time, introduce additional problems that can occur with increasing depth, including the need for thermal protection and alterations of consciousness from interactions of oxygen, carbon dioxide, and nitrogen.

Ascent from depth must become progressively slower as the surface is approached to avoid DCS from bubbles that form in the diver's body. Decompression schedules and diver-worn computers provide guidance concerning how to ascend with acceptable DCS risk. After 12 to 24 hours at depth, divers become saturated with inert gas and may remain at depth indefinitely without accruing additional decompression time. Saturation dives require special pressure chambers in which the divers live while not actively working underwater. Failure to follow the decompression prescriptions of dive schedules or computers increases the risk of DCS or AGE (which sometimes occur even if these prescriptions are followed). The pulmonary, cardiovascular, and neurological systems require close evaluation during medical examinations to determine fitness to dive for initial training or for the return to diving after DCS or AGE.

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