Chapter 26

MILITARY DIVING MEDICINE

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INTRODUCTION

All services in the Department of Defense have elements actively involved in diving operations. Historically the US military, particularly the US Navy, has been a world leader in the development of diving and undersea technology, including diving medicine.[1] Diving Medical Officers (DMOs), both physicians and physician assistants, and Diving Medical Technicians (DMTs) are specifically trained in military diving medicine and perform fitness-to-dive evaluations, prevent and treat diving-related injuries, and monitor ongoing diving operations for safety. Diving medicine, a specialized type of occupational medicine, considers the medical issues involved in working in the unique conditions of the undersea environment, much as aviation medicine is concerned with similar issues in the hypobaric realm of flight. This chapter will address the issues that military preventive medicine specialists should understand about military diving, including relevant physics and physiology associated with diving, approaches to the prevention of diving illnesses and injuries, and the epidemiology and management of diving medicine problems.

MILITARY DIVING OPERATIONS

Military diving is divided into two general missions, fleet diving (eg, underwater ship's husbandry, salvage, underwater construction) and specialized diving (eg, special operations, explosive ordnance disposal [EOD], saturation). Military diving is generally performed at depths of less than 60 ft, except for some salvage, EOD, and saturation (prolonged duration) diving operations. Fleet diving is conducted throughout the US Navy and by US Army Engineer Corps divers, while specialized diving is performed by all four services in the Department of Defense. Special Operations Forces (SOF) in the Army include Rangers and Special Forces ("Green Berets"). Combat divers in the Special Forces perform inland search and rescue and combat search and rescue, as well as coastal infiltration and exfiltration, reconnaissance, and demolitions. Army Ranger combat divers are currently used only to perform reconnaissance. The SOF elements in the Air Force—Pararescue Teams and Combat Controllers—also must be capable of conducting downed-aircraft recovery and infiltration into denied territory. Navy Sea/Air/Land (SEAL) forces conduct all aspects of SOF diving, including maritime direct-action operations (eg, ship attacks, ship boardings, harbor penetrations, hydrographic reconnaissance, clearance of beaches for amphibious assaults, shallow-water mine countermeasures). Divers in the Marine Corps Force Reconnaissance Units survey landing beaches and conduct covert underwater insertions. The Coast Guard, a Naval augmentee in time of war, uses divers for ship's husbandry, navigational buoy maintenance, and ocean search and rescue. As part of what is the most extensive diving program in the US military, the Navy operates the Naval Experimental Diving Unit, the Naval Submarine Medical Research Laboratory, and the Naval Medical Research Center. These organizations conduct manned and unmanned testing of military diving equipment, decompression algorithms, and hyperbaric physiology. The Naval Safety Center supports all diving in the Department of Defense by managing diving data, issuing safety messages, inspecting diving lockers, and investigating accidents.[2,3]

HISTORY OF DIVING

Early Diving Endeavors

The first recorded example of military diving was in the 5th century BC when a Greek diver cut the anchor lines of Persian warships to create confusion between vessels and cover his escape.[4] Salvage diving is nearly as old, traceable to the 1st century BC in the eastern Mediterranean. Over time, the use of divers in combat operations has evolved to include reconnaissance, covert infiltration, ordnance disposal, obstacle removal, and demolitions, in addition to underwater sabotage. US divers disposed of ordnance during the Civil War, investigated the sinking of the *USS Maine* in 1898, and performed submarine rescue and salvage in the early part of the 20th century. It was the period during and after the second World War, however, that saw rapid growth in military diving, including the development of all types of specialized diving and significant improvements in fleet diving.[5] All of these advances were made possible by revolutionary improvements in diving technology.

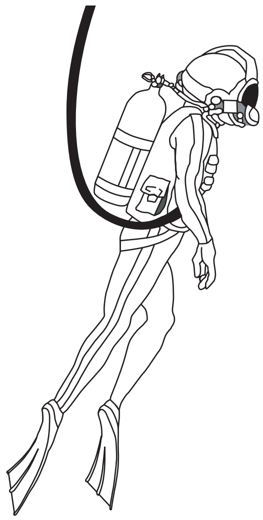
Evolution of Diving Equipment

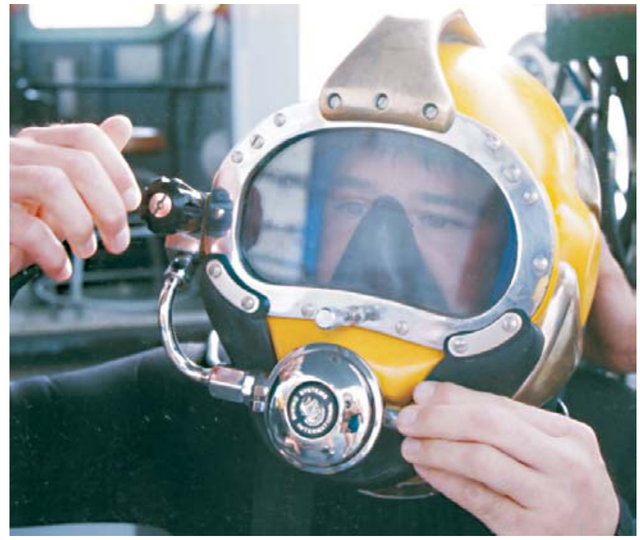
Humanity's success underwater has always depended on the ability to procure air or oxygen and to survive in the environment. Although the ancients initially relied on simple breath-hold diving, they soon recognized the need to spend greater time working at depth. One solution was the diving bell, an inverted container lowered by rope to provide air at depth and increase bottom time. Alexander the Great is reported to have used one in the 4th century BC.[4] Diving bells were improved and came into widespread use from the 16th to the 19th centuries to support the growing business of salvage diving. Then in 1840, Augustus Siebe improved on existing diving suits, designed to protect divers from temperature and pressure extremes and other hazards, with new technology that allowed air to be pumped from the surface to divers at depth (Figure 26-1). This surface-supplied diving apparatus was the prototype for deep sea diving rigs, which are still used today in situations requiring prolonged bottom time, stationary work, or other specific circumstances.[5]

Fig. 26-1. Siebe's Diving Dress and Helmet. Augustus Siebe developed the first practical diving suit. He improved on earlier attempts by attaching the helmet to the rest of the suit and adding an exhaust valve.
Source: US Department of the Navy. *US Navy Diving Manual*. Rev 4. Washington, DC: Naval Sea Systems Command; 1999: 1-5.

The next significant technological breakthrough was the development of scuba (self-contained underwater breathing apparatus). In 1878, Fleuss demonstrated the first practical scuba, which was a closed-circuit (no expired gas released into the water), 100% oxygen rebreather rig. This technology was used to develop oxygen rebreather systems for submarine escape and rescue in the early 20th century. The first scuba used to a significant degree in the US was invented in 1940 by Dr. Christian Lambertsen and was a semi-rebreather rig with steady-flow oxygen. This physician was also instrumental in military diver training during and after World War II and was an early authority in diving medicine. In World War II, scuba was used by Navy Underwater Demolition Teams and combat divers from the Office of Strategic Services, both forerunners of today's SOF divers. Finally in 1947, Frenchmen Cousteau and Gagnon developed the first successful open-circuit (releases expired gas into the water) air scuba rig, including a demand regulator, which supplied air only as the diver breathed. This Aqua-Lung rig conserved air and increased diving time, while the use of air as a breathing gas was a safer and cheaper alternative to oxygen. The Aqua-Lung not only provided more opportunities in military diving, it set the scene for the development of diving for sport and recreation.[4]

After World War II, researchers became interested in testing human endurance under the waves. Saturation diving grew out of experiments designed to test whether or not divers could survive at depth for days and weeks with their tissues "saturated" with the gases they breathed. Neither air nor pure oxygen could be used at these extreme depths because they caused nitrogen narcosis and oxygen toxicity, respectively, which are explained later in this chapter. Helium was the principal gas added to combat these conditions. In 1924, the US Navy began to experiment with helium-oxygen breathing mixtures, and this technology was successfully used in the famous salvage of the USS Squalus in 1939. The Navy continued to pioneer advances in mixed-gas diving, which was a necessary step to allow divers to dive longer and deeper. The US Navy performed its saturation diving experiments with personnel in an artificial habitat, SEALAB, which remained at depth for extended periods but required signifi-





- Principle of Operation:
  1. Self-contained, closed-circuit oxygen system
- Minimum Equipment:
  1. MK-21 Helmet
  2. Harness
  3. Weight belt (if required)
  4. Dive knife
  5. Swim fins or boots
  6. Surface umbilical
  7. EGS bottle deeper than 60 fsw
- Principal Applications:
  1. Search
  2. Salvage
  3. Inspection
  4. Underwater Ships Husbandry and enclosed spamce diving
- Advantages:
  1. Unlimited by air supply
  2. Head protection
  3. Good horizontal mobility
  4. Voice and/or line pull signal capabilities
  5. Fast deployment
- Disadvantages:
  1. Limited mobility
- Restrictions:
  1. Work limits: 190 fsw
  2. Emergency air supply (EGS) required deeper than 60 fsw or diving inside a wreck or enclosed space
  3. Current—Above 1.5 knots requires extra weights
  4. Enclosed space diving requires an Emergency Gas Supply (EGS) with 50- to 150-foot whip and second stage regulator
- Operational Considerations:
  1. Adequate air supply system required
  2. Standby diver required

Fig 26-2. General Characteristics of the MK 21 Diving System.
Source: US Department of the Navy. *US Navy Diving Manual*. Rev 4. Washington, DC: Naval Sea Systems Command; 1999: 6–54.

cant support from the surface. An improved approach, the Deep Diving System, allowed divers to operate at depth out of a tethered capsule, which was then pressurized to that depth and returned to the surface at the completion of the dive. The capsule was mated to a pressurized decompression chamber, which provided a larger living area and was mounted on the deck of a ship where the divers and capsule could be easily monitored.[5] Since the early 1980s, saturation diving in the Navy has been deemphasized and attention targeted toward missions in shallower water, particularly specialized diving.

Current fleet divers use open-circuit scuba primarily but sometimes dive with surface-supplied rigs, such as the MK 20 and the MK 21 (Figure 26-2), which provide more protection and allow communication with the surface. Combat and EOD divers

- Principle of Operation:
    1. Self-contained, closed-circuit oxygen system
- Minimum Equipment:
    1. Secumar life jacket
    2. Dive knife
    3. Swim fins
    4. Face mask
    5. Dive watch
    6. Depth gauge(0–80 fsw type and/or depth timer)
    7. Whistle
    8. Emergency flare (open water)
    9. Weight belt (as required)
- Principal Applications:
    1. Special warfare operations
    2. Shallow search and inspection
- Advantages:
    1. No surface bubbles
    2. Minimum support
    3. Long duration
    4. Portability
    5. Excellent mobility
- Disadvantages:
    1. Limited to shallow depths
    2. Central nervous system O_2 toxicity hazard
    3. No voice communications
    4. Limited physical and thermal protection
- Restrictions:
    1. Working limits: 190 fsw
    2. Normal—20 ft for 240 min
    3. Maximum—50 ft for 10 min
    4. No excursions are allowed when using Single Depth Dive Limits
- Operational Considerations:
    1. Buddy diver required if diver not tethered
    2. One safety boat required for diver recovery

Fig. 26-3. General Characteristics of the LAR V Diving System.
Source: US Department of the Navy. *US Navy Diving Manual*. Rev 3. Washington DC: Naval Sea Systems Command; 1993: 10-19.

use both open- and closed-circuit scuba. The LAR V (Figure 26-3) is often used for long, shallow, clandestine insertions, while the MK 16, which supplies oxygen at a fixed partial pressure, is used at deeper depths. Both are closed-circuit diving rigs that allow extended operating times, remove or "scrub" carbon dioxide from the exhaled gases and emit no bubbles.[5]

DIVING PHYSICS AND DECOMPRESSION THEORY

Application of Gas Laws to Diving

To function safely in the undersea environment, a diver must possess a fundamental knowledge of basic physics and how its laws predict the behavior of matter under a wide range of temperatures, pressures, and volumes. Pressure is defined as the amount of force applied per unit of area and is commonly expressed in terms of pounds per square inch (psi) or atmospheres (atm). Divers more frequently use feet of seawater (fsw), which is not a pressure measurement in the strict sense but is useful when actually working in the undersea environment. For calculations, feet of seawater can be easily converted to pounds per square inch or atmospheres because 1 fsw exerts a pressure equal to 0.445 psi, and every 33 fsw is equivalent to 1 atm[5,6] (Table 26-1).

TABLE 26-1

PRESSURE CHART

Depth (gauge pressure)	Atmospheric Pressure	Absolute Pressure
0	1 atm	1 ata (14.7 psi)
33 fsw	+ 1 atm	2 ata (29.4 psi)
66 fsw	+ 1 atm	3 ata (44.1 psi)
99 fsw	+ 1 atm	4 ata (58.8 psi)

fsw: feet of seawater
atm: atmosphere
ata: atmosphere-absolute
psi: pounds per square inch
Adapted from US Department of the Navy. *US Navy Diving Manual*. Vol 1 and 2. Rev 3. Washington, DC: Naval Sea Systems Command; 1993.

TABLE 26-2

GAS LAWS

Boyle's Law: **P(A)V(A) = P(B)V(B)**	**Dalton's Law:** **P(total) = ppA+ppB+ppC**	**Henry's Law:** **V(A) = ppA x S(A)**
P(X) = pressure of gas X	P(total) = total pressure in mixture	V(A) = volume of gas A
V(X) = volume of gas X	ppX = partial pressure of gas X	ppA = partial pressure of A
		S(A) = solubility of A

Source: US Department of the Navy. *US Navy Diving Manual*. Vol 1 and 2. Rev 3. Washington, DC: Naval Sea Systems Command; 1993.

At sea level, the absolute pressure on a diver is 1 atmosphere-absolute (ata), and so the absolute pressure exerted on a diver at depth is always equal to the weight of the water plus the weight of the atmosphere. The weight of the water acts as a force on the diver called hydrostatic pressure, which is measured as gauge pressure.

Given this overview of pressure, the basic physics definitions and gas laws attributed to Boyle, Henry, and Dalton (Table 26-2) can be used to explore the behavior of gases and liquids. Boyle's Law states that if the temperature of a fixed mass of gas is kept constant, the volume of the gas will vary inversely with the pressure, such that the product of the pressure and the volume will remain constant. Boyle's Law is important to divers because it relates changes in the volume of a gas to the change in pressure (or to changes in depth) such that when pressure doubles, volume decreases to half its original value (Figure 26-4). This law is most important in the first 33 ft of water because as the diver moves through this pressure differential of 1 ata at the surface to 2 ata at 33 fsw, the volume of gas in the diver undergoes its greatest absolute change in volume. This relationship is integral to appreciating the pathophysiology of both pulmonary over-inflation syndrome and barotrauma.

Dalton's Law, or the "law of partial pressures," dictates that the total pressure exerted by a mixture of gases is equal to the sum of the pressures of each of the different gases making up the mixture, with each gas acting as if it were alone and occupying the entire container. Divers usually use a mixture of gases rather than a single pure gas, so this law enables a diver to calculate the individual pressures exerted by component gases, to predict potential ranges for individual gas toxicity, and to prevent such diving hazards as oxygen toxicity.

Henry's Law states that the amount of any given gas that will dissolve in a liquid at a given temperature is a function of the product of the solubility coefficient for that gas and the partial pressure of the gas in

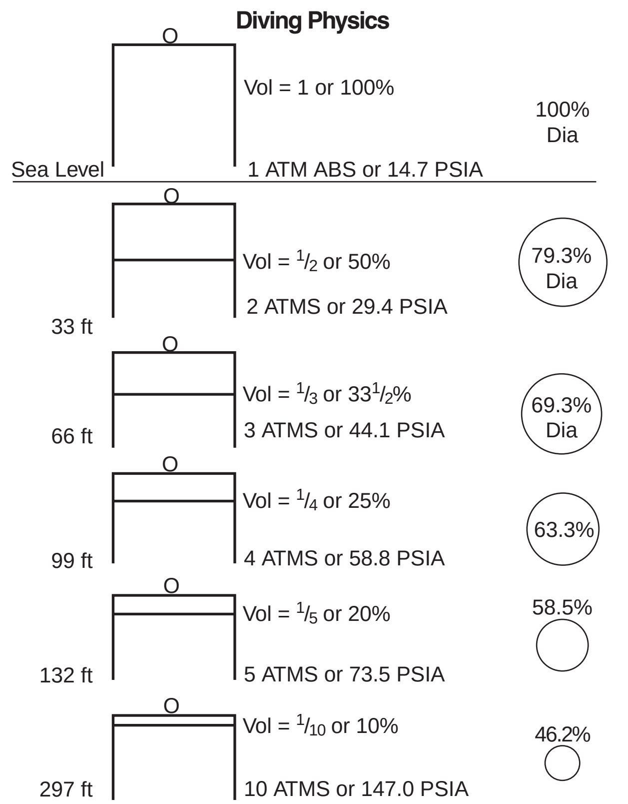


Fig. 26-4. Gas volume and bubble diameter as a function of depth—Boyle's Law.
Reprinted with permission from: Somers LH. Diving physics. In: Bove AA, Davis JC. *Diving Medicine*. 2nd ed. Philadelphia: W.B. Saunders; 1990: 13.

contact with the liquid. Furthermore, the solubility coefficient depends on both the properties of the solute (the gas) and solvent (the liquid—usually plasma) and is different for each combination. Simply stated, since water constitutes such a large portion of the human body, as a person dives deeper, more gas will dissolve in body tissues, which must then be released upon ascent. If a diver remains at depth for enough time, his or her body tissues will ultimately reach equilibrium with the ambient breathing gas such that eventually no more gas can be dissolved, a state known as saturation. When a diver whose body tissues are saturated with a dissolved gas ascends toward the surface, less ambient pressure is exerted on the diver, and there is more release (off-gassing) than acceptance (on-gassing) of the inspired gas. A simple example is removing the cap from a bottle of soda. Carbon dioxide is under pressure, and the liquid is saturated with it. When the cap is removed and the ambient pressure reduced, carbon dioxide comes out of solution as bubbles. If a diver ascends too quickly, he or she may not off-gas fast enough and may transiently enter a supersaturation state where so much gas is dissolved in the tissues that it cannot all naturally escape through exhalation, and gas molecules coalesce to form bubbles. This theory has become the dominant hypothesis in explaining the development of decompression sickness or the "bends." Determining how a diver could avoid this malady and predictably ascend safely to the surface became the impetus for the development of the US Navy Diver Decompression Tables.[5–7]

History and Development of Decompression Procedures

Diving and medicine have been closely linked through history, as is demonstrated by the crucial role physiology has played in the study of decompression sickness (DCS). Pol and Watelle first suggested in 1854 that gas bubbles might be involved in the development of what is now known as DCS and realized that there was a relationship between pressure, duration of exposure, rapidity of decompression, and onset of illness. They also noted that relief of symptoms occurred during recompression. In 1857, Seyler demonstrated that bubbles blocked the pulmonary circulation. Then in 1878, Bert demonstrated bubbles in blood and tissue after decompression and noticed that these bubbles consisted predominately of nitrogen. He recommended using recompression with oxygen as therapy for DCS and also recommended decompression with oxygen, but he did not specify decompression rates.[7,8]

In 1900, Heller, Mager, and Von Schrotter proposed the first decompression procedure, noting that partial pressures of inert gases at depth could be calculated using Dalton's Law and that nitrogen could be assumed to be inert. Using Henry's Law as a guide, they developed a gas elimination equation to describe the movement of an inert gas into and out of solution at varying partial pressures and the movement of this dissolved gas into and out of tissues. Their simple model assumed no additional tissue diffusion barrier for nitrogen but predicted that the rate of on- or off-gassing of dissolved nitrogen would depend on three factors: (1) the diffusion gradient of nitrogen into the blood, a function of partial pressure and depth, (2) tissue blood flow, and (3) the ratio of inert gas solubility in blood to its solubility in tissue. The model described tissue gas characteristics in terms of half-times and an exponential time constant, as in drug pharmacokinetics. The calculated decompression rate of 20 min/ata, when tested in occupational scenarios, proved adequate for short dives to 5 to 6 ata but not for longer dives.[7]

In 1908, Boycott, Damant, and Haldane, who were evaluating caisson workers, noticed that the incidence of DCS increased as the duration of the dive approached 5 hours, but the incidence appeared to remain constant for exposures longer than 5 hours. Their experiments with goats confirmed these observations.[9] Additionally, the researchers felt that the body should not be considered one compartment but rather a series of tissue compartments, due to the variability in tissue homogeneity and gas solubility. The time it took for half the gas to leave a saturated tissue compartment was termed a half-time. For mathematical convenience, Haldane arbitrarily selected half-times of 5, 10, 20, 40, and 75 minutes to cover the spectrum of possible exchange rates, but these rates were not assigned to specific real tissues. The gas elimination equation demonstrated that the 75-minute tissue would be almost 95% saturated at the 5-hour point.[7,10]

Haldane is also credited with the observation that men could be decompressed to 1 ata after complete saturation at 2 ata without developing symptoms but could not tolerate greater drops in pressure without developing DCS. Experimentally he found that goats could perform a 2:1 drop in ambient pressure without developing DCS and confirmed this in the hyperbaric chamber by observing decompression drops from 2 to 1 ata, from 4 to 2 ata, and from 6 to 3 ata without clinical sequelae. It appeared, therefore, that both men and goats could tolerate a 2:1 pressure drop or a 1.58:1 ratio of P_{N2}/P_B, (where P_{N2} is the partial pressure of nitrogen in tissue and P_B is the absolute pressure) at least to a depth of 3 ata. Based on these data, Haldane and his associates proposed decompression procedures designed to ensure that the ratio of P_{N2} to P_B never exceeds 1.58:1 in any tissue compartment. For convenience, however, decompression stops were proposed in increments of 10 fsw. This was the beginning of "staged decompression," which can be likened to intermittently opening and closing the cap of a shaken soda bottle to avoid the soda's bubbling over. The Royal Navy adopted the Haldane Tables in 1908, and these early tables provided adequate decompression for dives as deep as

200 fsw for as long as 30 minutes, but they were not recommended for exposures at deeper depths.[7,10]

The first tables developed for US Navy use were devised by French and Stillson in 1915 and are called the Bureau of Construction and Repair tables (C and R tables). They used the Haldanian ratio of 1.58:1, employed oxygen decompression for dives between 200 and 300 fsw, and were used successfully in 1915 to salvage the sunken submarine F-4 at a depth of 306 fsw.[11,12] Since 1915, various modifications have been made to these tables by US Navy researchers to extend bottom time while minimizing DCS. Hawkins, Shilling, and Hansen in 1935[13] and Yarborough[14] again in 1937 performed retrospective mathematical analyses of nitrogen uptake and elimination for nearly 3,000 dives. Tissues with short half-times (called fast tissues) appeared to tolerate very high ratios and off-gas quickly during ascent, allowing the decompression stops for these tissues to be deleted. Based on the longer 20-, 40-, and 75-minute half-times, Yarborough calculated new decompression tables, which were issued in 1937 and resulted in an acceptable annual incidence of DCS of only 1.1% in Navy divers.[7,10]

In 1951, while developing surface decompression tables for dives using air, Van der Aue conducted an extensive evaluation of the Yarborough tables on long working dives. For these dive profiles, he discovered that the 5- and 10-minute tissues did sometimes require deep decompression stops for off-gassing, while to achieve adequate decompression at the shallower stops, it was necessary to factor in another hypothetical tissue with a half-time of 120 minutes.[15] This work demonstrated that as dive depth or duration, or both increased, deeper decompression stops were required because of the greater saturation of tissues.

Before revising the Yarborough Tables, DesGranges, Dwyer, and Workman in 1956 analyzed inert gas uptake and elimination during 609 working dives using half-times of 5, 10, 20, 40, 80, and 120 minutes. They confirmed that the Haldanian ratio was not constant but that the ratios for slow and fast tissues differed and that they decreased exponentially with depth. The authors graphed the safe and unsafe nitrogen supersaturation ratios for each decompression stop and constructed a table of safe ratios on the basis of both tissue half-time and depth of stop.[16] Tables based on these concepts were adopted by the US Navy.

Workman in 1957 took a different approach to the decompression table, which previously had focused on time required for off-gassing at certain stops. Since the degree of allowable supersaturation differed for every tissue and every depth, he produced a table that simply stated what the maximum allowable inert gas pressure or saturation was for each tissue at each decompression stop.[17] These maximum values, called M-values, can be used to develop tables for air and mixed-gas diving. After considerable additional research, Workman eventually also added tissue half-times of 160 and 240 minutes and reduced the allowable ratios to provide for adequate decompression on long, deep exposures.[18] Despite extremely limited testing of these final additions, these tables were promulgated for emergency use.

The decompression tables currently used by the US military were developed through careful calculations and were largely verified with human testing. Berghage and Durman[19] evaluated the incidence of DCS in divers using the US Navy Tables from 1971 to 1978. During this period, 16,120 dives involving decompression were reported by the Navy, yielding 202 cases of DCS and an overall incidence rate of 1.25%. The majority of Navy dives are shallow (< 50 fsw) and do not involve decompression, so only 43 of a possible 295 depth/time combinations on the tables had more than 100 dives (data points) that could be used in analysis. On these schedules, the overall incidence of DCS was 1.1%, but it was as high as 4.8% with some schedules, particularly for those dive profiles of 100 fsw for 60 minutes and longer. Recent analysis of Naval Safety Center diving data[20] for more than 600,000 dives during the period 1990 through 1995 demonstrated identical rates for the two types of DCS at 1.3 per 10,000 dives.

Current Decompression Procedures and Tables

The US Navy Diving Decompression Tables (Figure 26-5) have been improved and modified to apply the safest decompression procedures to all types of diving. Specific populations whose dive profiles may be unpredictable (eg, special operations divers) have benefited greatly from these changes. The nature of SOF diving is to spend a considerable period of time at shallow depths with the occasional need to perform deeper excursions. For an extra margin of safety, the standard Navy decompression tables are based on the "square dive" concept, which means if the total dive time is 30 minutes, the table considers that the diver has spent the entire 30 minutes at the deepest depth, even though the diver may have been at that depth for only a few minutes.[5] Using this concept, the decompression obligation for SOF divers was unnecessarily long. So the Combat Swimmer Multilevel Dive decompression procedures were developed by Butler and Thalmann[21] for air diving in 1983 and expanded to include Mark 15 and 16 oxygen rigs in 1985. LAR V divers can also use these procedures, which consider the dive profile as multiple square dive segments and acknowledge off-gassing credit for the long intervals in shallow water, just like off-

Depth feet /meters	Bottom time (min)	Time first stop (min:secc)	Decompression stops (feet/meters) 50 15.2	40 12.1	30 9.1	20 6.0	10 3.0	Total decompression time (min:sec)	Repetitive group
80 24.3	40						0	2:40	*
	50	2:20					10	12:40	K
	60	2:20					17	19:40	L
	70	2:20					23	25:40	M
	80	2:00				2	31	35:40	N
	90	2:00				7	39	48:40	N
	100	2:00				11	46	59:40	O
	110	2:00				13	53	68:40	O
	120	2:00				17	56	75:40	Z
	130	2:00				19	63	83:40	Z
	140	2:00				26	69	97:40	Z
	150	2:00				32	77	111:40	Z

Fig. 26-5. A Portion of the US Navy Standard Air Decompression Tables.
Source: US Department of the Navy. *US Navy Diving Manual*. Rev 4. Washington, DC: Naval Sea Systems Command; 1999: 9-56.

gassing credit is awarded during a surface interval in between repetitive diving (multiple dives within 12 hours). The standard air decompression tables for repetitive diving, as developed by DesGranges, are used with the following four exceptions: (1) in place of the 10-minute surface off-gassing time required in normal repetitive diving, a 30-minute "shallow interval" at depths of less than 20 ft can be used, (2) for safety, all segments of the dive at 30 ft or less are rated on repetitive tables in decompression groups that are one group higher than the standard tables, (3) divers cannot move to lower repetitive groups over time, and (4) a diver can stay at depths of 30 ft or less indefinitely without ever exceeding repetitive group "O."[21]

Special Warfare divers currently have an additional option, the Naval Special Warfare Dive Planner, to plan dives and calculate decompression obligations.[22] The Dive Planner was developed because of the perception that the current tables were not equally safe across all depth and bottom-time (approximate duration of on-gassing) combinations, which was supported by the variable DCS rates noted earlier in those using standard decompression tables. Tissue saturation models, which previously had been the focus of decompression theory, contained too many parameters to be determined precisely and simultaneously and could not exactly predict decompression obligation. It was suspected that long, deep dives required substantially more decompression time than the standard tables indicated. Scientists at the Naval Medical Research Institute (now the Naval Medical Research Center, Silver Spring, Md) developed a probabilistic nitrox (nitrogen and oxygen mixture, with more oxygen than normal air) decompression algorithm named USN-93 that used formal statistical techniques and maximum likelihood modeling to form safe decompression tables. USN-93 is capable of calculating decompression obligations given an endless array of possible depths, bottom times, and travel rates. In addition, the model adjusts for divers who switch breathing mediums between air and constant partial pressure oxygen breathing apparatuses (ie, the MK 16) during the same dive.[23] This statistical model was developed using a large database of well-documented experimental chamber, air, and nitrox dives correlated with cases of DCS. Using the results of these "safe" chamber (or dry) dives, an algorithm for computing decompression schedules in real time was developed and was then successfully validated in a prospective trial of more than 700 "wet" dives, including multilevel dives and dives where the breathing gas was switched between air and a constant partial pressure of oxygen of 0.7 ata during different segments of the same dive. SEALS are equipped with "real-time" depth and time meters capable of recording and downloading very accurate dive profile information. Given a computer with at least a 486-level microprocessor, a math coprocessor loaded with USN-93, and the specific multilevel dive profile, a DMO can calculate a decompression table for almost any dive. This computer is an adjunct to the sources of decompression information already available, including the Combat Swimmer Multilevel Dive procedures and Standard Air Decompression Tables, which are used by the DMO to predict the best possible decompression plan given the specific operational diving scenario.[24,25]

Standard Navy decompression tables are designed for use at altitudes less than 2,300 ft (700 m) above sea level. Diving gauges may not compensate for altitude or for fresh water being less dense than seawater. These two factors contribute to inadequate decompression by divers at altitude who are unfamiliar with the unique decompression requirements there. The Navy Experimental Diving Unit maintains altitude decompression tables for US military use.[26] Civilian divers venturing into bodies of water above 700 m can consult Buhlmann's Swiss dive tables.[27]

GASES AND DIVING

Oxygen Disorders

Oxygen deficiency, or hypoxia, leads to unconsciousness and death. The majority of military diving uses air, the absence of which is easily and quickly recognized by the diver. But unlike sudden strangulation or suffocation, a gradual decrease in oxygen content may not be detected. Unconsciousness can occur without anticipated warning signals. Any diving system that utilizes either surface-supplied mixed gas or rigs that carry their own oxygen (eg, LAR V, MK 16) can produce a hypoxic state due to malfunction or incorrect gas mixing. The treatment of suspected hypoxia in the water is to shift to an alternate gas supply. Incoherent or unconscious divers should be placed on 100% oxygen, if available, from 40 fsw or shallower until the diver reaches the surface and can be monitored appropriately.[5]

Just as too little oxygen can create difficulty for divers, excessive amounts can cause oxygen toxicity, specifically in the tissues most sensitive to high levels of oxygen, including the lung, the eye, and the brain. Pulmonary oxygen toxicity is seen at oxygen partial pressures of 0.5 ata (the equivalent of breathing air at 46 fsw or deeper).[6,7] The symptoms include discomfort or a burning sensation deep in the throat or substernal area, accompanied by cough or burning on inspiration. Findings include a decrease in vital capacity as measured by pulmonary function tests. Pulmonary oxygen toxicity requires several hours or days to develop and may be seen if a stricken diver requires several iterations of recompression treatment. If repetitive treatments are needed for persistent symptoms, pulmonary function tests are required. If there is a decrement in vital capacity of more than 10%, treatment with oxygen must be interrupted and a transition to other treatments considered. After daily exposures to high levels of oxygen (eg, daily treatments for 2 to 4 weeks), ocular oxygen toxicity may produce transient myopia, which will resolve over the course of 4 to 6 weeks if there are no further exposures.[28] Central nervous system (CNS) oxygen toxicity has been observed at oxygen partial pressures above 1.3 ata (the equivalent of breathing air at 171 fsw or breathing 100% oxygen at 9 fsw or deeper).[6,7] During dives with enhanced oxygen rigs and chamber runs that use oxygen, CNS toxicity must be a constant consideration because, unlike pulmonary oxygen toxicity, CNS oxygen toxicity can strike within minutes of exposure. Sensitivity to oxygen toxicity varies between individuals and within the same individual, making it impossible to predict which divers are at increased risk. The warning symptoms associated with CNS toxicity are taught using the acronym VENTID-C, with convulsions being the most common presentation (Table 26-3). Treatment is straightforward. Since high partial pressures of oxygen created the problem, the goal in therapy is to reduce oxygen tension. This can be done by several methods, including removing the oxygen mask from a chambered diver, ascending a few feet or switching to a gas of lower oxygen content, if available. The seizures of CNS oxygen toxicity are not epilepsy and usually do not require medicinal intervention; they are simply a toxic reaction. There is no increased predisposition for further seizure disorder throughout life. The cold water immersion and hypercarbia seen on long, arduous combat swimmer missions predispose divers to oxygen seizures, which if suffered at depth, place divers at great risk for drowning and developing an arterial gas embolism.[5]

Carbon Dioxide Toxicity

Carbon dioxide is a by-product of human metabolism, and its serum concentration is maintained within

TABLE 26-3

SYMPTOMS OF CENTRAL NERVOUS SYSTEM OXYGEN TOXICITY

Vision	Vision is reported to "tunnel" or close in
Ears	Ringing and increased perception of sound
Nausea	Feeling of vague discomfort in the abdomen
Twitching	Particularly the muscles of the face (cheeks)
Irritable	Sense of agitation and uneasiness
Dizziness	Sense of lightheadedness, vertigo, or both
Convulsions	Tonic-clonic seizures, usually with no warning

Source: US Department of the Navy. *US Navy Diving Manual*. Vol 1 and 2. Rev 3. Washington, DC: Naval Sea Systems Command; 1993.

the relatively narrow range of approximately 35 to 45 mmHg by both lung and tissue functions. Despite the efficiency of these systems, excessive carbon dioxide levels can develop during diving due to overproduction (from increased duration and intensity of exercise), poor ventilation, or failure of carbon dioxide removal systems in rebreather rigs.[5,6] Inadequate ventilation results from missed breathing or breath-holding during a dive, increased breathing resistance in the equipment, or excessive dead space in the breathing system. Hypercapnia, an elevated level of carbon dioxide, can present in a variety of ways. An increased rate and depth of breathing may be noticed first, followed by a nagging frontal headache or such symptoms as nausea, confusion, or unconsciousness. Alternatively, too little carbon dioxide produces painful muscle spasm of the hands and feet (tetany), paresthesias, numbness, lightheadedness, confusion, and, again, loss of consciousness. Low levels of carbon dioxide, or hypocapnia, usually occur secondary to hyperventilation. Treatment is straightforward: efforts should be made to slow the respiratory rate, and, if necessary, abort the dive. In cases of suspected hypercapnia, the diver should stop work and allow time for adequate ventilation. If the cause of the hypercapnia is the equipment, the dive should be aborted.[5,6]

Carbon Monoxide Poisoning

Divers will encounter carbon monoxide poisoning through exposure to a contaminated air supply. Containers of breathing gas, such as scuba tanks, must be pressurized to deliver the gas underwater to divers. Compressor intakes must be distant to any exhaust sources, which typically contain carbon monoxide. A shifting breeze can create a problem if the system is not monitored carefully. Headache, nausea, confusion, and unconsciousness are symptoms of high levels of carbon monoxide, which is tasteless and odorless. If more than one diver complains of symptoms consistent with carbon monoxide poisoning, contaminated gas should be suspected. Treatment involves removal from the gas source and treatment with 100% oxygen at an elevated partial pressure.[5,6,28]

Nitrogen Narcosis

Nitrogen makes up approximately 79% of air and at 1 atm serves essentially as a diluent for oxygen. Nitrogen—as with any of the diluting gases used in diving—will become toxic if the partial pressure is excessive. Humans note an anesthetic or sedating effect associated with nitrogen as partial pressure is increased. At depths much below 50 fsw, alterations in function can be detected by psychological and motor skill testing; below 200 fsw, symptoms progress to loss of fine motor control, inattention to tasks, and poor judgment. Treatment is straightforward: the partial pressure must be decreased by ascending or surfacing.[5–7]

Helium Diving

Helium is used as a breathing gas in saturation diving to reduce breathing resistance at deep depths, as well as to prevent the occurrence of nitrogen narcosis, which otherwise limits diving depth to approximately 200 ft. Helium can present three primary problems when employed in diving operations. The first is hypothermia, because helium has a thermal conductance that is seven times that of air. Divers can become hypothermic quickly at depths, so care must be taken to heat breathing gases, as well as to provide adequate thermal protection from the surrounding water (ie, dry suit or hot water suit). The second potential problem is the distorting effect of helium on oral communication, the so-called "Donald Duck effect," which can make communicating with a diver at deep depths very difficult. Finally, high pressure nervous syndrome is a derangement of central nervous system function that occurs during deep helium-oxygen dives, particularly saturation dives. The cause is unknown, but it is thought to be an effect of depth, not a specific effect of the breathing gas. The clinical manifestations include nausea, fine tremor, imbalance, incoordination, loss of manual dexterity, and loss of alertness. In severe cases, a diver may develop vertigo, extreme indifference to his or her surroundings, and marked confusion. The nervous syndrome is first noted between 400 and 500 ft, and its severity appears to depend on both depth and compression rate. With slow compression, depths of 1,000 ft may be achieved with relative freedom from symptoms. Attempts to make the syndrome less severe have included the addition of nitrogen or hydrogen to the breathing mixture, but no method has been entirely successful below depths of 1,000 ft.[5–7] These gases may influence high pressure nervous syndrome because their narcotic properties may provide a partial anesthetic effect.

ENVIRONMENTAL HAZARDS

The aquatic environment is at once both incredibly beautiful and unforgivingly dangerous to those who do not respect it. Survival here requires an awareness of hazards, such as temperature extremes and animal life, as well as an appreciation of physics to understand the behavior of gases under pressure, the significance of light refraction, and the differences in blast effects and sound conduction in water versus air.

Thermal Dangers

Divers may be exposed to thermal extremes on the surface, in a hyperbaric chamber, and in the water. Heat loss can occur through convection, conduction, radiation, and evaporation, including significant respiratory loss in dehumidified air and in diving gases such as helium. Heat loss in still water is 25 times that in air, while heat loss in moving water increases to a factor of 200.[5,6] Heat is produced by basal metabolism and exercise (shivering) and may be absorbed from environmental sources. Hypothermia is defined as a core temperature of 35°C (95°F) or less, which requires various treatments depending on whether it is mild (35°C–32°C, 95°F–90°F), moderate (32°C–28°C, 90°F–82°F), or severe (< 28°C, < 82°F). Cardiac rhythms degrade into ventricular fibrillation very easily if divers are jostled while severely hypothermic. Unfortunately, the rhythms are also quite refractory to the usual acute cardiac life support protocols.[5,29]

At the other extreme is hyperthermia. A resting diver in a swim suit will remain euthermic in 33°C (92°F) water, but if working in water warmer than 30°C (86°F), he or she may develop hyperthermia. Types of injuries include heat cramps, heat exhaustion, and heat stroke, which may present in the absence of dry, hot skin. Even personnel riding in a chamber can be thermal casualties. The Navy Diving Manual gives guidelines for which treatment tables can be used if the ambient temperature is greater than 29°C (85°F), and the chamber is not equipped with an environmental package to cool the gas inside the chamber.[5]

Acoustic Hazards

Sound is transmitted much more efficiently in water than in air, so sound that would normally be inaudible in the air can be heard at great distance underwater. Unfortunately, this rapid conduction also makes localization of sound underwater more difficult. Humans are able to detect the small difference in the time of arrival of airborne sound (traveling at about 1,000 ft/s) reaching one ear as compared to the other, thus allowing us to localize the source. With waterborne sound (traveling at nearly 5,000 ft/s), however, it is impossible for humans to identify the direction of sound transmission.[5,6] Sonar and low frequency sound have been explored as offensive weapons by which to keep unfriendly divers away from military vessels because injuries, including vestibular disturbances, cardiac arrhythmia, and tissue destruction, occur given certain conditions of frequency and volume. Low-frequency vibration can be perceived by the submerged diver, just as vibration due to sound can be felt by the music lover when touching a stereo speaker.[30,31]

Blast Injuries

Underwater explosions are very dangerous to a submerged diver. The type of the explosive used, the size of the device, its location in the water column, the surrounding seabed topography, and the location of the diver all affect the outcome of the exposure (Figure 26-6). Damage occurs as the shock wave of blast overpressure leaves the dense water and passes through the

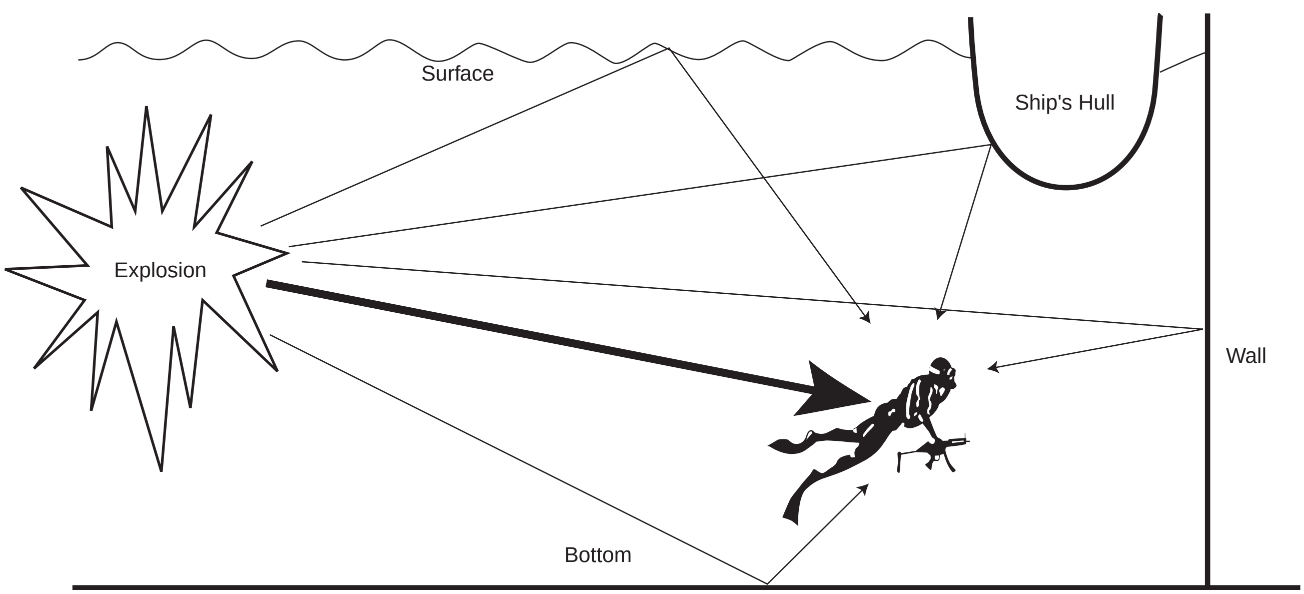


Fig. 26-6. Reflected shock waves can increase or decrease the total effect of the blast on a diver.
Source: Noonburg G. *US Army Special Forces Diving Medicine Manual*. Key West, Fla: Special Forces Underwater Operations School; 1995: SS-1.

diver's less-dense, air-filled compartments (eg, lung, intestine, sinus, middle ear). At this interface, the wave decreases in velocity and shreds the tissue, an effect referred to as "spalling." Hemorrhage, compartment rupture, air embolism, and even bone fractures have been reported in submerged blast victims.[5,32]

Electrical Hazards

Military divers are exposed to electrical hazards in their daily duties. Fleet divers, for example, are required to operate 220-volt equipment manually to cut and weld underwater. Wet divers move about the deck, and the dive station itself is in contact with wet decking, thereby enhancing the potential for inadvertent electrocution. Shipboard systems have both alternating and direct current (AC and DC), as well as high- and low-voltage sources. Dry skin offers approximately 10 times (10,000 ohms) the resistance to electricity afforded by wet skin. Once contact with a wet diver is established, alternating current levels of only about 15 mA are sufficient to produce tetany, manifested by strong and sustained muscle contraction. Direct current does not exhibit this "let go" threshold (also recognized as the inability to let go of an object) but produces heat in tissues instead. Nevertheless, a single, violent contraction may occur, throwing the diver away from the direct current source. Exposure to direct current may cause cardiac asystole, while contact with alternating current may induce ventricular fibrillation, and both may cause respiratory arrest.[5,33]

Radiation Hazards

All US Navy submarines are now nuclear powered, as are many surface ships. Potential radiation exposure is maximized near the bottom of the submarine where shielding is thinnest. Divers must often dive there, examining the submarine for various reasons. The water acts as a very good radiation shield, but divers must wear thermal luminescence dosimeters and be monitored for radiation exposure.[5]

Dangerous Marine Life

Animal Bites

Despite media attention devoted to this subject, bites are rare. Shark encounters are commonplace, but shark injuries are not. It has been stated that humans are far more likely to experience a lightning strike than a shark attack and more likely to survive a shark attack than a lightning strike. Moray eels are found in most tropical and subtropical oceans and are commonly encountered by military divers. Divers fear eels because they move like snakes, bare their many sharp teeth, and appear threatening. In actuality, the eel is a shy and very near-sighted animal. A military diver must go out of his way to provoke an encounter. Eels do not have fangs and do not envenomate.[5,6,27,34] Barracuda bites likewise are rare for divers, although surface swimmers and boaters with arms dangling in the water may attract undue attention, particularly if they are wearing shiny objects. Barracuda are found in most tropical waters of the world.[5]

Envenomation

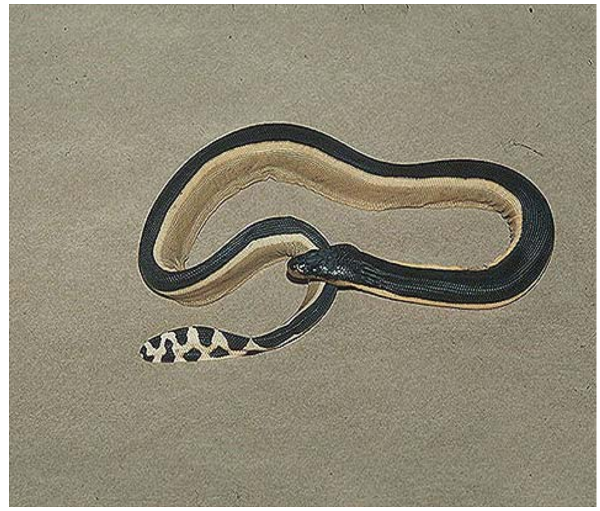
Envenomation, in contrast to bites, is commonplace. Numerous creatures capable of inflicting discomfort on humans exist in the sea (Figure 26-7). The majority of these encounters are nonfatal. All are avoidable. The following is a short list of the more notable hazards.

The sea wasp, a member of the Coelenterate family, which includes jelly fish, hydroids, sea anemones, and coral, has a very fatal venom in the thousands of nematocysts aligned on its meter-long tentacles. Reaction is swift, with shock and death possible within 4 to 6 minutes of the encounter. Antivenin is available but often administered too late. These hydroids are found around Australia and the Great Barrier Reef.[27,34]

Sea snakes provoke the same primitive, exaggerated, and unnecessary fear response as their land-bound cousins. Sea snakes are most commonly found in the warm waters of the Pacific and Indian Oceans. One member of the family, *Pelamis platurus*, is found in unusual areas, such as the cooler waters along the west coast of Latin America to just south of California and from southern Siberia to the cold waters off Tasmania. It is doubtful that any venomous snake has yet crossed into the Caribbean waters, though many banded Caribbean eels, often mistaken for sea snakes, offer divers an opportunity to swear to the contrary. Sea snakes are air breathers and are often seen in shallow water or within the protection of a rocky section of beach. They move moderately well on dry beach. They do not hiss but rather create a snoring or gurgling sound. They are often seen as "curious," not aggressive, and are not afraid to approach an unusual object for closer observation. A diver must generally go out of the way to provoke a negative encounter. The sea snake is more venomous than a cobra, but the sea snake's fixed fangs make envenomation more difficult because of the shallower penetration associated with the bite. Antivenin is available.[27,34]

Stone fish are widely distributed, including in cold coastal waters of the United States. Aside from the beautiful, feathered-looking fish found in warm waters and referred to as lionfish, turkeyfish, or zebrafish, the members of this family are really quite ugly. They

a


b


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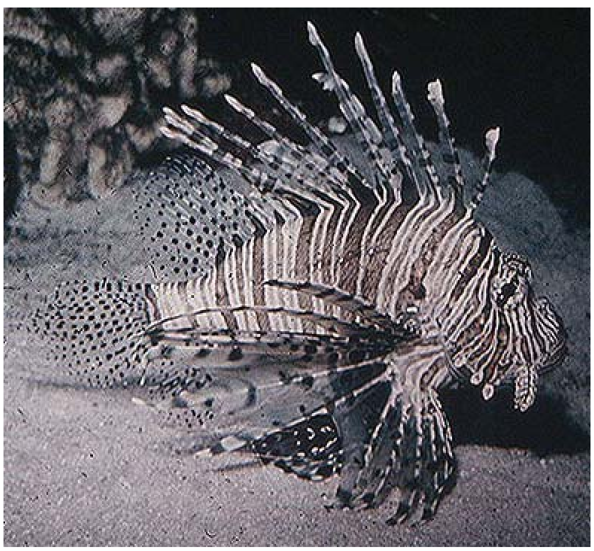

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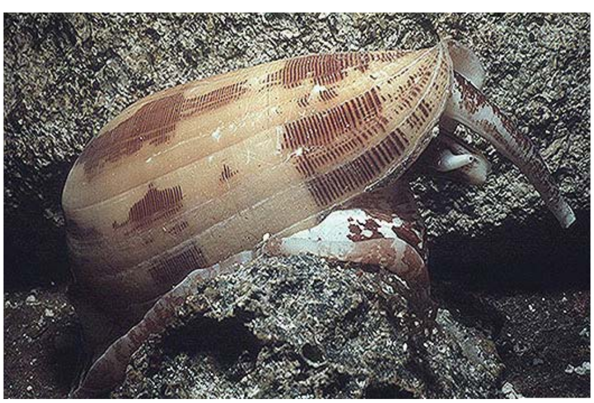

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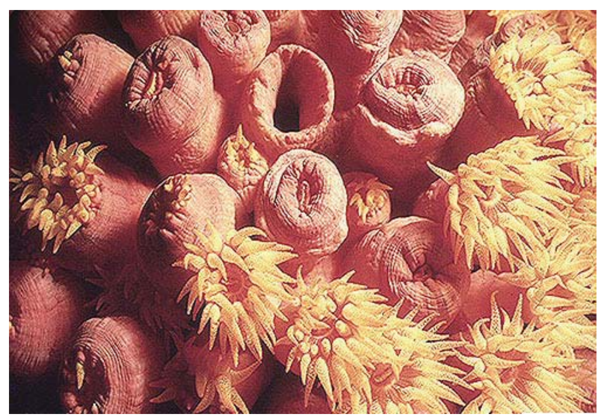

Fig. 26-7. Marine life that can be dangerous to divers includes (***a***) the sea wasp, (***b***) the sea snake, (***c***) the zebrafish, (***d***) the blue-ringed octopus, (***e***) the cone shell, and (***f***) the anemone.
Images from *Envenomations and Poisonings Reference*. Bethesda, Md: Naval School of Health Sciences; 2000. CD-ROM.

are masters of camouflage and are easily stepped on. The dorsal spines can puncture normally protective footwear and inject venom into the wound. In addition to severe pain, tissue destruction can be impressive and death is not uncommon. Antivenin is available.[6,27,34]

The blue-ringed octopus, found in the warm waters of Australia, is unique within the family of octopi. As with its cousins, it will attempt to defend itself if mishandled by biting with its beak-like mouth. But unlike its larger cousins (this one spans only about 6 inches), the blue-ringed octopus secretes a venom into the usually painless bite. Death can occur.[6,27,34]

Cone shells have a very wide distribution, from US waters off California and Hawaii to the warm waters of the world. Cone shells usually lie buried in the sandy bottom during the day and hunt during the night, crawling about like a garden snail. Cone shells are often beautifully marked and colorful, making them a tempting target for the aesthetically inclined military diver. Unfortunately, they can kill. They extend a proboscis until they touch fingers or skin and then quickly impale the contacted tissue with a small, harpoon-shaped radicular tooth that injects the venom.[5,6,27,34]

Stingrays are found in a wide range of oceans and in a moderate variety of colors, but all are described as flat, disc-shaped animals with "whip" tails, which appear to fly through the water. Military divers encounter them most often while exercising, such as jogging, in the shallow water along sandy beaches. The ray, buried in the warm sand and protected by the few inches of sun-warmed water, feels the force of a human foot landing on its back. In a rapid reflex, the tail strikes the offending human ankle and implants a formidable barb, which tears and envenomates the leg. The diver immediately steps off of the ray's back, and the ray swims away. The human, on the other hand, requires pain medication and surgical debridement of the wound to remove the barb and other foreign material. These envenomations are not lethal, but death has been attributed to freak accidents in which the chest or abdomen, usually of a child, was penetrated by a barb from a large ray. Rays are not aggressive and will do anything they can to avoid a diver. A cousin of the stingray, the torpedo ray, along with the South American eel and the African catfish, produces a nonlethal electric current. The torpedo ray does not frighten away as easily as the stingray, is stockier, and has a more fin-shaped tail.[5,6,27,34]

Sea urchins, the porcupines of the sea, are found in many colors and sizes, are very slow moving, and will not swim into a diver. To effect an injury, the diver must step or kneel on the urchin or grab at an object without noticing the urchin. The spine of an urchin can then penetrate rubber soles, gloves, neoprene, and skin. Because the pain associated with a penetrating spine is greater than can be explained by simple mechanical tissue damage, the discomfort is attributed to a venom. Experts disagree as to whether or not all urchins possess venom, as well as the mechanism of envenomation. The removal of a spine is tedious because the spines, or pedicellariae, crumble like sand. Deaths do not occur.[6,34]

Fire coral, a hard coral, is a ubiquitous organism and a problem for divers. Its appearance varies with locale but generally is brownish with very short, white, hair-like fuzz on the surface. That fuzz penetrates the skin as invisibly as does fiberglass insulation but contains thousands of microscopic nematocysts, which are miniature envenomators. Stinging hydroids are similar to fire coral in effect but appear more like a feather or plume.[5,6,27,34]

Sea anemones are giant versions of the microscopic coral animal itself, but unlike coral, which builds a rock-like calcareous skeleton, the anemone remains soft. Some reach 3 ft across, undulating in the water surge like a huge flower in a breeze. Their colors can vary from pure white to pinks to violet to deep scarlet reds. The sea anemone's tentacles are home to nematocyts, which can sting the careless diver who touches them with bare skin.[34] Divers must maintain respect for the reef as the home of abundant marine life, including anemones. Hundreds of years of work are required for the coral animals to group together and create the stone-like skeletons that remain after their death, forming the base for the next generation of the colony to attach and deposit their own calcareous skeletons. Nature teaches the careless diver to avoid coral contact by way of lacerations and abrasions, which are slow-healing and easily infected wounds.[5,6,34]

Puffer or porcupine fish are rather bulky, awkwardly moving animals, but they are considered delicacies in some Asian countries. When disturbed (a favorite pastime of night divers), they will inflate or puff up, erecting normally flat-lying spines. In this state, the fish has little control over its own movement but is suspended in the water like a huge prickly burr, making it a hazard for its tormentors to handle any further. Puncture wounds result from slow learning.

Bristle worms are underwater caterpillars, amazingly similar in appearance to their cousins on land. The bristle worm's small tufts of fuzz can cause a contact dermatitis reaction in some divers.[6,34]

Sponges are commonplace in warmer waters and are found in several varieties, from huge barrel sponges to iridescent tube sponges. After touching the mucous surface of a marine sponge, some divers develop a contact dermatitis.[5,6,34]

DYSBARIC ILLNESS

Various diving-related maladies are associated with alterations in pressure. These dysbaric illnesses include DCS and barotrauma. In 1991, Francis and Smith[35] advocated altering the classification of dysbaric illness including DCS, to emphasize symptoms rather than assumed phsysiology of injury. The system is not widely accepted, so this chapter will focus on the traditional categorization of dysbaric illness.

Decompression Sickness

DCS probably results from the formation of bubbles in tissues and blood vessels, with resultant ischemia and tissue injury.[36,37] This occurs when a diver ascends from higher to lower pressure at a rate that exceeds the body's ability to eliminate the gas, and the partial pressure of dissolved gas in tissue overcomes the pressure to keep it in solution. Despite the existence of decompression schedules for varying depths and bottom times that describe the limits of "no-decompression" dives, NO dive is risk-free. Tissue responses to pressure vary between divers and even daily within the same diver and are not understood well enough to eliminate all risk. A wide range of signs and symptoms may accompany the initial episode of DCS. Some of these may be so pronounced that there will be little doubt as to the cause, while others may be subtle and easily overlooked in a cursory examination.[5–7] Classifying DCS into Type I or Type II (Table 26-4) permits the treating facility to recognize or anticipate serious, even life-threatening, consequences. Divers at risk for DCS often delay reporting symptoms and wait for them to resolve. While the body is very forgiving, the consequences of misjudging a diving incident can be permanent and costly, so all divers must be advised to report any symptoms. If DCS cannot be eliminated as a potential diagnosis, treatment with recompression is recommended.[5]

Type I Decompression Sickness

Symptoms of Type I, also called "pain-only" or "simple," DCS include skin marbling, lymph node swelling, joint pain, and muscle pain. The most frequent symptom of Type I DCS is joint pain, usually seen in the shoulder, elbow, wrist, hand, hip, knee, or ankle. Type I pain may be excruciating but is usually mild when first noticed and becomes more intense as time passes. It may be located in a muscle group and is usually described as a progressive, deep, dull ache that is often very difficult to localize and unchanged by movement. In contrast, typical mechanical injuries, such as a strain or bruise, are often more painful with movement. Several methods of differentiating DCS pain from mechanical injury have been described, such as applying pressure to the site manually or with a blood pressure cuff (DCS pain reportedly diminishes) or warming the area (DCS pain increases), but none is reliable.[5–7] Medical history is the best way to distinguish DCS Type I pain from trauma, but if confusion exists and circumstances permit, the casualty should be treated presumptively for DCS. Another area of confusion arises when evaluating truncal pain. There is always the possibility that shoulder or hip pain does not originate in that specific joint and may be referred from the CNS. It is important to differentiate the origin of the pain because Type I problems may be treated with a shorter recompression table than Type II DCS.[5] Divers with Type I DCS symptoms, which are not considered life threatening, must be monitored carefully because they may progress to Type II DCS.

Cutis marmorata, a mottling or raised marbling of the skin, is a presentation of Type I DCS, which begins as itching but quickly progresses to redness and then a patchy, bluish discoloration of the skin (Figure 26-8). The condition is uncommon but should be differentiated from simple pruritus, which may be seen in dry (chamber) dives and is not DCS. Cutis marmorata

TABLE 26-4

COMPARISON OF SYMPTOMS IN DECOMPRESSION SICKNESS TYPES I AND II

DCS Type I	DCS Type II
Joint and/or muscle pain ("bends")	Pain in bilateral or multiple joints or muscle groups
Skin itch and rash	Pulmonary symptoms ("chokes")
Cutis marmorata	Inner ear symptoms ("staggers")
Lymph node swelling	Central nervous system symptoms
	Cardiac symptoms
	Pain under pressure

Fig. 26-8. A 27-year-old male with cutis marmorata on his abdomen.
Photograph by permission of the Center for Hyperbaric Medicine and Environmental Physiology, Duke University Medical Center, Durham, NC.

sometimes precedes evidence of neurological deficits. A rare presentation of Type I DCS involves localized pain and swelling of lymphoid tissue. Though recompression may provide symptomatic pain relief, resolution of the swelling may require several days or weeks of watchful waiting after recompression.[5–7]

Type II Decompression Sickness

Type II or "serious" DCS is potentially life threatening and includes symptoms involving the inner ear, the lungs, multiple joints, the brain, and the spinal cord. Inner ear DCS, or the "staggers," results from bubble production in the inner ear (seen almost exclusively when switching breathing gases during saturation or deep mixed-gas diving) and involves symptoms of vertigo, tinnitus, and hearing loss.[6,7] Staggers can sometimes be difficult to distinguish from inner ear barotrauma, which is typically preceded by middle ear barotrauma and a forceful attempt to equalize the pressure in the middle ear (Valsalva maneuver) against a closed Eustachian tube during descent. Inner ear barotrauma is discussed in detail later in this chapter. In addition to neurological symptoms, divers with severe DCS may suffer cardiovascular collapse or other symptoms from profuse venous bubbling, which is analogous to shaking a soda bottle then suddenly removing the cap. Large volumes of intravenous gas disrupt the pulmonary vasculature, causing diffuse pulmonary injury. This pulmonary DCS, referred to as the "chokes," starts as chest pain followed by increasing respiratory rate, dyspnea, and hemoptysis. There is rapid progression to complete circulatory collapse, loss of consciousness, and death. Immediate onsite recompression therapy is the diver's only hope. Finally, divers with Type I symptoms located bilaterally or in more than one joint or muscle group may represent the beginning of serious DCS and therefore should be treated as if they had Type II DCS. Similarly, pain in the chest, spine, or hip requires special evaluation. If a DMO is not immediately available, these symptoms should be regarded as Type II and the afflicted diver should be recompressed accordingly. Additionally, any DCS symptom that occurs during the ascent phase of a dive is considered "pain under pressure," and should be treated as Type II DCS.[5]

In the early stages, CNS symptoms of Type II DCS may not be obvious, and the stricken diver may consider them inconsequential. The diver may feel fatigued or weak and attribute the condition to overexertion. Even as weakness becomes more severe, the diver may not seek treatment until walking, hearing, or urinating becomes difficult. Symptoms must be anticipated during the period after the dive and treated before they become too severe. Many other findings can be attributed to the effects of DCS on the neurological system, including numbness, tingling, feelings of "pins and needles," weakness, frank paralysis, loss of bladder or bowel control, mental status changes, motor performance decrement, ringing in the ears, vertigo, dizziness, hearing loss, vision disturbance, tremors, personality changes, and amnesia. Attempting to differentiate such findings with nondive etiologies from those that are dive-related can be problematic. A diver with a headache has an extensive list of differential diagnoses other than DCS, and fatigue in a diver may reflect only a lack of sleep the previous evening. Divers with unexplained focal neurological symptoms following a dive must be treated with recompression therapy. Expedient delivery of recompression therapy is mandatory for Type II DCS, unless otherwise directed by a DMO.[5]

Aviators and flight crews exposed to the hypobaric environment at altitude may experience symptoms of DCS also, but symptoms usually resolve as they descend (see Chapter 25, Aviation Medicine). To avoid DCS, divers are prohibited from flying above 2,300 ft (commercial airliners are pressurized to 6,000 ft) for a minimum of 12 hours after a dive that requires decompression stops. Patients who are treated for DCS Type I must not fly for 24 hours. Both of these limitations will be extended for more complicated situations, such as aviators who dive (must wait 24 hours to fly) or patients treated on Treatment Table 4 (must wait 72 hours).[32] Treatment tables are reviewed toward the end of this chapter.

Pulmonary Over-Inflation Syndrome

Pulmonary over-inflation syndrome (POIS) is explained by Boyle's Law and can result when gas trapped in the lung expands with decreasing pressure during ascent and forces its way out into the interstitial tissues. This syndrome can be life threatening, depending on where the escaping air travels. POIS can be the most dangerous form of barotrauma because of the possibility of gas embolism. It is separated into four distinct entities for diagnosis and treatment:

1. pneumothorax;
2. mediastinal emphysema;
3. subcutaneous emphysema; and, the most serious,
4. arterial gas embolism (AGE).

A pneumothorax results when air escapes from the ruptured alveoli into the pleural space. If it is severe enough, the lung will be compressed and displaced by the air. The patient may describe sudden chest pain and may experience shortness of breath, rapid, shallow breathing, or a cough. The examination may reveal an absence or diminution of breath sounds. A simple pneumothorax may be transformed into a tension pneumothorax, particularly during the ascent phase of recompression chamber treatments, and medical personnel should be prepared for these emergencies. If a diver complains of sudden chest pain during the ascent phase of the chamber run, the ascent should be stopped and the diver should descend to a depth where he or she has relief of symptoms as a temporary measure. A chest tube should be placed to provide permanent relief.[5] A spontaneous pneumothorax, one that occurs without obvious reason, is permanently disqualifying for dive duty because of its potential for recurrence. Asthma is also disqualifying, since a plug of mucus may create an area of trapped gas distal to it. A traumatic pneumothorax, one associated with rib fracture, gun shot wound, or other trauma, is temporarily disqualifying.[38]

Mediastinal emphysema is caused by gas dissecting into in the tissues behind the sternum. Patients may report a dull ache or tight feeling in the front of the chest, with pain made worse by deep breathing, coughing, or swallowing. The pain may radiate to the shoulder, jaw, or back. Subcutaneous emphysema results when air leaks from lung tissue and accumulates between tissue planes of the upper chest and neck. These patients seldom complain of pain but often note a change in voice, may have a full or bloated look about the neck, and feel a popping or crepitus when the neck is palpated. Recompression is not the recommended treatment for mediastinal emphysema, subcutaneous emphysema, or pneumothorax. Definitive treatments are the same as for injuries not related to diving, except that a diver should have a detailed neurological examination to ensure an AGE is not also present.

An AGE is a bubble that has forced its way out of the alveoli and into the pulmonary venous circulation via an alveolar capillary. It then travels to the heart and is pumped through the arterial system until it reaches a capillary that is too small to accommodate its size. The AGE occludes further blood flow and the necessary delivery of oxygen to the tissues beyond the occlusion, creating an area of ischemia. In divers, AGE may occur while they hold their breath during ascent, following trauma such as blast injury, as a result of occluded airways due to allergies or infections, or in those with venous DCS bubbles that pass through occult or congenital cardiac shunts. AGE is generally dramatic in presentation with obvious, possibly severe, neurological symptoms occurring within seconds to minutes of the injury. Any organ system can be involved, but the most striking are the CNS and the cardiovascular system, where presentations mimic, respectively, classic stroke and myocardial infarction. Treatment requires immediate recompression in an attempt to diminish the size of the bubble and deliver oxygen to ischemic tissues. If recompression is accomplished before hypoxic damage, hemorrhage, or edema develops, a rapid and complete recovery is likely.[5–7]

Barotrauma

The most common diving-related injury is barotrauma, which results when pressure within a body cavity and the ambient pressure do not equilibrate. To be subject to barotrauma, a cavity must usually meet several criteria: (*a*) be gas filled, (*b*) have relatively rigid walls, (*c*) be enclosed, and (*d*) be subjected to change in the ambient or surrounding pressure. Ambient increases in pressure will cause the gas trapped within a cavity to compress and attempt to occupy less space. This creates a relative vacuum, which draws in the tissue forming the walls of the cavity to equalize pressure and fill the space created by the compressed gas. If the pressure difference continues, vessels in the tissue will engorge and eventually rupture, filling the space with blood and equalizing the vacuum. When this phenomenon occurs in conjunction with descent during a dive, it is termed a "squeeze." A "reverse squeeze" results from tissue damage caused by overpressurization of a cavity during ascent, as with POIS. This pathophysiological model can be applied to any gas-filled cavity, and Table 26-5 is a listing of common forms of squeezes. Prevention of

TABLE 26-5

EXAMPLES OF NEGATIVE PRESSURE BAROTRAUMA ("SQUEEZE") AND CAUSES

Squeeze	Cause
Middle ear	Eustachian tube dysfunction
External ear	Hood or piece of equipment covering the external ear passage
Sinus	Blockage of the duct that normally vents a sinus
Face mask	Failure to equalize air in the mask by nasal exhalation
Tooth	Faulty filling with trapped air beneath
Suit	Pocket of air in a dry suit that becomes trapped under a fold or fitting and pinches the skin
Lung	Extremely rare but seen with deep breath-hold diving
Whole body	Failure of the air supply in a dry suit to balance water pressure

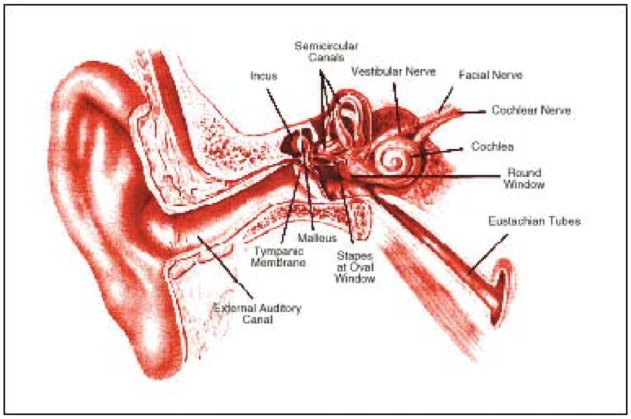

Fig. 26-9. The anatomy of the ear in frontal section. Source: US Department of the Navy. *US Navy Diving Manual*. Rev 4. Washington, DC: Naval Sea Systems Command; 1999: 3-22.

barotrauma is relatively simple and includes not diving with a cold or during a flare-up of allergies, using proper-fitting equipment, and not creating air-filled cavities that cannot be vented, as when using goggles or ear plugs.

The most common site for barotrauma of descent is the middle ear (Figure 26-9). Normally, the only connection between the ambient air and the air inside the middle ear is the Eustachian tube. This tube may not be patent due to inflammation from allergies or an infection or due to compression during the dive from a large pressure gradient that has already developed between the middle ear space and the upper pharynx. As a diver descends, he or she must perform a Valsalva maneuver to equalize the pressure in the middle ear space. If the Eustachian tube is not operating properly, middle ear pressure cannot be increased and there will be a pressure differential across the tympanic membrane, drawing it inward and causing pain. With continued descent, the middle ear may fill with blood from surrounding tissues in an attempt to equalize pressure or the tympanic membrane may rupture. As the largest pressure-volume change occurs within the first additional atmosphere (33 fsw) of descent, once a diver clears that distance, barotrauma of descent becomes uncommon. Symptoms of middle ear squeeze include pain (caused by the extreme tympanic membrane stretch), temporary vertigo, decreased hearing, or tinnitus.

Inner ear barotrauma, although relatively uncommon, usually presents in the context of concomitant middle ear barotrauma and requires medical attention. The majority of these injuries are produced during descent by an excessive Valsalva against a blocked Eustachian tube. When the pressure differential from the middle ear to the environment exceeds 90 mmHg or at a mere 4 fsw, the Eustachian tube will not open regardless of the force of the Valsalva. The relative vacuum in the middle ear will draw the eardrum, and the round and oval windows into the middle ear space. A Valsalva maneuver may raise the intracranial pressure several hundred millimeters of mercury, which is transmitted through the cochlear duct, exploding the round window into the middle ear. This force may cause tears in any of the membranous windows or vestibular apparati or cause inner ear hemorrhage. The trauma often produces a severe vertigo, with sensorineural hearing loss and tinnitus, and may be confused with other ear conditions.[6,7] All persistent symptoms of vertigo or hearing loss in a diver should be meticulously evaluated. If a diagnosis of inner ear barotrauma is suspected, the diver should be placed in a semi-sitting position and kept as still as possible; intravenous diazepam (Valium) may be useful to control vomiting. The patient should be evaluated expeditiously by an otolaryngologist.[5–7]

Sinus squeezes are less common than middle ear barotrauma. The frontal sinuses are the ones most frequently involved, but any air-filled sinus may be injured. Pain in the face over the affected sinus is the most common presentation, but there is sometimes a bloody nasal discharge in the mask. A blocked sinus ostium prevents normal venting of the sinus to release air.

Middle ear oxygen absorption syndrome can present as a middle ear squeeze, but its pathophysiology is different. Ear pain may follow long oxygen dives (as with a LAR V rig) after gas with a very high oxygen percentage enters the middle ear cavity and the oxygen is absorbed through the mucosa of surrounding tissues. If the middle ear space is not actively vented to replace the oxygen with air, a negative pressure relative to ambient may result from the oxygen being absorbed. Without an inert gas such as nitrogen in the middle ear, there will be insufficient volume support to the tympanic membrane. The diver may notice ear fullness the morning after a long oxygen exposure, which may be accompanied by sharp pain with ear-clearing maneuvers and transient hearing loss. Equalizing the pressure will eventually relieve the symptoms, although sometimes a serous effusion persists.[5]

Treatment of barotrauma of descent is straightforward—stop the descent. The diver should be brought up a few feet; if this does not relieve the symptoms, the dive should be terminated. Once on the surface, the patient should be seen by medical personnel to evaluate the degree of trauma. If the diagnosis of a squeeze is confirmed by examination, the diver should be kept out of the hyperbaric environment until the tissue damage heals. This period of time is variable depending on the extent of injury; a ruptured tympanic membrane may require weeks to heal but blood in the middle ear may require only days to resolve. A mild squeeze may not stop a diver from diving the next day, yet a severe squeeze may keep the diver out of the water for weeks. Each case of barotrauma of descent must be individually evaluated, but no form of barotrauma is treated by recompression except AGE.

Dysbaric Osteonecrosis

Dysbaric osteonecrosis is not a diagnosis that is made in the acute setting; it is primarily a chronic disease of career divers and is strongly associated with saturation diving. The pathogenesis for the disease is unknown, but it is suspected to be a result of extreme pressures causing direct damage to bone (ie, gas osmosis) or multiple microinfarctions from asymptomatic DCS.[6,7] The bone lesions present as aseptic necrosis, which can manifest as deep bone pain or be entirely asymptomatic, depending on the location of the lesion. Juxta-articular lesions are most painful, but midshaft lesions are mild and most commonly discovered on routine radiographs. Treatment is nonspecific, and nonsteroidal anti-inflammatory drugs and, for debilitating conditions, joint arthroplasty are effective. Personnel with juxta-articular lesions are permanently disqualified from diving, while those with asymptomatic lesions are considered on a case-by-case basis.[38]

EPIDEMIOLOGY OF DIVING CASUALTIES AND DECOMPRESSION ILLNESS

AGE and DCS may be difficult to distinguish clinically, due to the similarity of their signs and symptoms. Decompression Illness (DCI) is now used to describe cases which have characteristics of both AGE and DCS. Military diving, when compared with civilian sport diving and commercial diving, is relatively safe, but comparisons are difficult because accurate population-based data on DCI and diving fatalities are difficult to obtain. Military diving medical personnel can gain valuable insights by reviewing underwater accident information from both sport and commercial diving. The Naval Safety Center (NSC) collects diving accident and mishap data for the Department of Defense, which has a known and quantified population at risk.[2,20,39] All mishaps, cases of DCI, and fatalities must be reported. In addition, the computerized Dive Reporting System provides excellent data for population-based analysis of military diving accidents.[2,3]

Civilian Experiences

Sources of Data

Various organizations, including the National Underwater Accident Data Center, Diver Alert Network (DAN), and the Australian Diving Medicine Center, have compiled diving accident statistics since the early 1980s for sport, open-circuit, and air scuba diving.[7] DAN, a nonprofit diving safety association affiliated with Duke University Medical Center, Durham, NC, depends on a network of 247 hyperbaric chambers in the United States and around the world to report DCI and diving fatalities.[7,40] DAN annually solicits participation from hyperbaric facilities and requests standardized DAN forms for each DCI case or diving fatality. All cases must meet strict inclusion criteria to be used in DAN's annual "Report on Diving Accidents and Fatalities."[38] These data are excellent for their characterization of factors leading to recreational scuba fatalities and cases of DCI, but they are not adequate to compute accurate diving accident rates because there is no precise count of either the total number of dives or divers to be used as denominators. In addition, civilian DCI cases are notoriously underreported, and there is no autopsy protocol for diving fatalities that is widely accepted and practiced throughout the United States.

Risk Factors

Most fatalities and DCI cases involve multiple factors that interact as confounders, yet understanding these factors is crucial to the development of risk management strategies. The DAN data suggest a very crude fatality rate of 2 to 4 deaths per 100,000 sport divers annually from 1989 to 1994.[40] Older divers (older than 50 years) and younger divers (younger than 24 years) have higher-than-expected fatality rates. Cardiovascular disease has been a leading cause of death in DAN fatality case reports, especially among older divers. Fatigue as the result of poor physical fitness is an aggravating factor. Inexperience, risk taking, and alcohol use within 12 hours of their fatal dive often are contributing factors in all divers but particularly those younger than 24 years of age. DCI rates were increased in divers doing repetitive daily dives and dives deeper than 80 fsw. Interestingly, over 80% of the 566 cases of DCI reported to DAN for 1994 developed neurological symptoms. This high percentage of more serious decompression sickness may be due to underreporting of pain-only DCS, to more liberal decompression procedures, or to time delays in initiating recompression treatment. Only two thirds of the reported 55 cases of AGE and less than 40% of the 513 cases of DCS were treated with hyperbaric oxygen within 12 hours of surfacing. This represents a significant delay to recompression therapy and adversely affected clinical outcomes. Causes for treatment delays include patient denial of symptoms, failure to recognize the signs and symptoms of DCI, long transportation times from remote diving locations to a chamber, and failure of symptoms to spontaneously resolve with other therapies.[40] Decompression computers and decompression tables increase awareness of the need for slow ascent rates and decompression, but sometimes divers assume that since they follow tables or their computer, DCS will not occur. To the contrary, many DCI cases follow no-decompression dives or those which are not expected to require decompression.[39,40]

Accident Rates

Commercial diving accident rates are more unreliable than sport diving rates. No central data collection organization exists, and commercial diving accident information is often sketchy. There are no accurate estimates of the number of commercial divers at risk, let alone the total number of dives made. Rough estimates from the United Kingdom Department of Energy suggest diving mortality rates in the North Sea are similar to, or better than, the mortality rates in the construction industry.[7] While many sport divers follow US Navy no-decompression limits, commercial divers often do deeper dives, including mixed-gas or saturation dives, and do not follow military decompression tables when they complete their underwater work. Nevertheless, more attention is given to dive planning, equipment selection, and medical screening of divers by industry than by sport divers. The emphasis on safety in industry is driven somewhat by financial considerations because accidents delay completion of work, increase personnel and material costs, and increase insurance premiums. The military has similar concerns.

Military Data

US military diving operations are conducted in a disciplined manner by well-trained divers. The NSC studies all military diving mishaps in the continuing interest of accident prevention and emphasizes investigation procedures, reporting requirements and lines of responsibility for diving mishap and diving fatality inquiries. Unlike sport diving and commercial diving, "near misses" and nonfatal accidents are also evaluated for risk management and corrective action. NSC accident data can be regarded as reasonably accurate but not applicable to diving outside operational military dives.[2,7,39,41]

Table 26-6 shows a comparison of the use of various diving rigs in the US Navy from 1991 through

TABLE 26-6

TOTAL NAVY DIVES BY DIVING APPARATUS, 1991–1995

RIG	1991	1992	1993	1994	1995
SCUBA	55,499	57,133	53,605	44,990	26,324
MK 20	8,488	9,388	13,204	12,420	8,705
MK 21	10,923	13,793	13,865	11,489	9,972
LAR V	16,912	17,458	15,802	15,169	11,474
MK 16	4,862	3,607	4,154	3,450	2,674
CHAMBER	5,625	6,099	5,222	4,913	4,668
OTHERS	12,729	10,152	1,648	730	334
TOTALS	115,038	117,630	107,500	93,161	64,151

Data sources: (a) US Naval Safety Center. *Naval Safety Center Diving Database*. Norfolk, Va: US Department of the Navy; 1997. (b) Butler FK, Thalmann ED. *A Procedure for Doing Multiple Level Dives on Air Using Repetitive Groups*. Panama City, Fla: US Naval Experimental Diving Unit; 1983. NEDU Report 13-83.

1995.[20,42] During this period, 84% of Navy dives were shallow (between 10 and 50 fsw). An even greater percentage of dive profiles in the Army, Air Force, and Marine Corps, where Special Operations diving constitutes a larger share of the total dives, are in this range. Most EOD and Special Operations dives use closed-circuit scuba, either the LAR V or the MK 16 closed-circuit oxygen rebreather rigs. For the 5-year period mentioned, 25% of diving missions were Special Operations, 25% were ship's husbandry, and 20% were EOD. Inspections, searches, and underwater construction each made up 5% of the total number of dives. Salvage operations, which are often at 50 fsw or deeper, constituted only 1.8% of dives during this period, although there was an increase in the total percentage of deeper dives (> 50 fsw) in years when there were deeper salvage jobs or research protocols with deeper dives. These data are representative of the evolution of US military diving away from deeper, mixed-gas, bounce diving, or saturation diving to shallower, open- and closed-circuit scuba diving.[20,39]

The NSC Dive Reporting System maintains a database for epidemiologic studies of military diving. Mandatory reporting requirements, regular safety inspections of diving units, and computerized local data entry were established to collect a reasonably complete set of data.[2,3,39,41] The NSC diving database has logged more than 2.3 million military dives from 1985 through 1995, but good quality injury data were not collected until 1990.[2,3,20,41] During the period 1 January 1990 to 31 December 1995, there were 382 cases of DCI reported to the NSC in divers from the US Naval Services.[39,41] Independent analysis of these reports by DMOs from the Naval Medical Research Center and the Naval Diving and Salvage Training Center report an annual misdiagnosis rate of 23% to 39%.[39,42] Since most recompression treatments in the military are initiated by nonmedical providers, who may be disciplined if they miss a case of DCI or inadequately treat a fellow diver, many nonspecific symptoms are treated and overreporting of DCI is common.[39,41] Supervisors are taught that risk-benefit analyses favor hyperbaric treatment in almost all cases when a diver feels abnormal following a dive.[5] Even given these limitations, reasonably accurate mishap rates can be computed and tracked.[41] All of the 382 DCI cases in Navy or Marine Corps divers from the NSC database were reviewed by DMOs from the Naval Diving and Salvage Training Center for medical merit, resulting in identical adjusted DCI rates of 1.3 per 10,000 dives for AGE, 1.3 per 10,000 dives for DCS Type I, and 1.3 per 10,000 dives for DCS Type II.[39]

During this same 6-year period (1 January 1990 to 31 December 1995), there were 11 diving fatalities in the US Naval Services. The Marine Corps had five fatalities, all of which were off-duty. The Navy's six fatalities were all on duty. The fatality rate for Naval Service operational diving for this period was 0.9 per 100,000 dives. Most operational deaths were primarily from drowning secondary to poor operational planning, underwater hazards, or poor diver judgement. Some fatalities, especially the off-duty ones, were attributable to risk-taking. Five of the six operational fatalities were diving scuba and their final dive was shallower than 50 fsw. In a minority of these, improper use of underwater tools initiated the fatal event.[20,39] A surprisingly high 43% of diving fatalities since 1985 occurred in sailors and Marines while off-duty, and diving ranked 10th for overall cause of death for Naval Service personnel during this period.[43] Considering mortality only, though, military diving is relatively safe as a hazardous duty, and compares well to parachuting. An analysis of data supplied by the Army Safety Center revealed a fatality rate of 1.8 per 100,000 parachutes deployed in fiscal years 1994 through 1996 for static line operations, and a rate of 5 per 100,000 freefall parachutes deployed. There is likely significant underreporting of denominator data (parachutes deployed), and these rates may be closer to 1 in 100,000.[44]

Operational diving involves risks to which the typical service member is not exposed, and it definitely deserves its special duty designation. Good medical screening, diver training, and operational planning are important to avoid underwater accidents. Although data demonstrate that most military diving is conducted in shallow water, there is still a very significant risk of serious injury and death. There is little room for error, and a healthy respect for the hazards of the underwater environment, as well as attention to detail, rigorous continual training, and dedication to preventing accidents, will serve all divers well.

PREVENTION OF DIVING-RELATED ILLNESSES AND INJURIES

Prevention of diving accidents is the single most important task of diving medical personnel. Safety is the primary objective; it is addressed through conscientious and deliberate dive planning, which considers diving equipment, environmental conditions, medical fitness, physical fitness, and training. A safety-conscious organization with a comprehensive program, from the senior leaders down to the newly qualified diver, is essential. Officers and noncommissioned officers must ensure fitness-to-dive evaluations are current, diver training is of high quality, and an active diving research program is supported that provides working divers the best possible equipment and decompression procedures.

The Fit Diver

Fitness-to-dive evaluations in the military are done in several settings. The diver candidate is evaluated with medical standards that are more restrictive than for other service members. Selecting not only the most physically fit divers but also those without preexisting medical conditions minimizes time-consuming evaluations for borderline medical conditions, lessens the administrative burden of waivers, and provides unit commanders medically ready divers to complete mission requirements. Women who meet the medical and fitness standards for military diving are eligible for all diving duty except combat diving. Once the military has invested the time and expense to train divers, decisions regarding fitness to dive must focus on the ability of the divers to dive safely, without undo risk to themselves or their fellow divers, and to complete the mission successfully.[45] Medical conditions may be temporary and require that diving be briefly suspended (eg, upper respiratory infections, nonpulmonary barotrauma, musculoskeletal injuries), they may be chronic and require medications but not significantly affect diving duty (eg, hypertension, hypercholesterolemia, low back pain), or they may be serious and result in permanent disqualification as a diver (eg, DCI with residual symptoms, psychiatric illness, substance abuse, significant trauma with head injury). The same principles and medical insight applied to assessing fitness to dive must be used to determine when a temporarily disqualified diver can return to duty. Women are temporarily disqualified during pregnancy because diving has been associated with an increase in the incidence of birth defects (even in the first trimester) and because DCS can result in stillbirth and other complications.[27] Finally, the immediate predive check by the diving supervisor, asking whether divers are physically and mentally prepared to make a dive, is vital in preventing injury.[5,46] Military divers, however, are typically stoic, confidant, motivated, and, by nature, risk takers. Diving medical personnel, particularly the enlisted DMTs, should be quickly accessible on the dive station and easily approachable on a personal level. It is critical that medical personnel supporting diving operations be divers themselves or be familiar with the hyperbaric environment. Experience and insight are infinitely better than sympathy in assessing diving casualties, and divers tend to trust and confide in one of their own.

Many dysbaric illnesses can be prevented when divers, leaders, and medical personnel understand the general concepts of diving medicine, including recompression therapy. Training for entry-level divers should stress prevention of injuries and avoidance of risk factors for DCS and POIS. The single most important rule to teach is to avoid diving with either lower or upper respiratory congestion. Smoking increases the risk of developing these conditions and is a particularly bad habit for divers. Entry-level divers are taught safe ear clearing techniques to avoid injury from a forceful Valsalva maneuver, prophylaxis for otitis externa, and the basic signs and symptoms of decompression illness. A basic understanding of vertigo and its causes is essential because it is common and a potential cause of disorientation at depth.

Personnel and Their Roles in Prevention

Diving supervisor candidates, typically noncommissioned officers, receive advanced diving medicine training that builds on their initial knowledge base and significant diving experience. Dive operations planning is a crucial part of supervisor training, emphasizing the consideration of environmental conditions, rig selection, diver selection, protective garments selection, and proper scheduling of dives to complete the task safely.[5] Diving supervisors are the most important resource for continuous unit training, and they set the standard for safe practices on all dive stations. When accidents do occur, the supervisor and the team are the first responders and may be the only responders. They initiate the majority of recompression treatments for DCI in the operational setting and sometimes complete the entire treatment without direct physician supervision.[5,20,46] DMTs are corpsmen or medics with advanced diving medicine training, who usually are also divers. They help the diving supervisor make medical decisions and tend patients inside the chamber during most hyperbaric treatments. The DMTs are extremely valuable resources who function as on-site extensions of the DMO, administering neurological examinations and rendering care directed by the DMO during hyperbaric treatments. DMTs are also teachers, assisting the supervisors with unit medical training and monitoring dive station safety. In planning a dive, DMTs help coordinate support from DMOs, evacuation services, and recompression chambers,

EXHIBIT 26-1

PRIMARY EMERGENCY KIT FOR DIVERS

Diagnostic Equipment

- Flashlight
- Stethoscope
- Otoscope (Ophthalmoscope)
- Sphygmomanometer (Aneroid type only, case vented for hyperbaric use)
- Reflex hammer
- Tuning fork (128 cps)
- Sterile safety pins or swab sticks which can be broken for sensory testing
- Tongue depressors

Emergency Treatment Equipment and Medications

- Oropharyngeal airways (#4 and #5 Geudel)
- Self-inflating bag-mask ventilator with medium adult mask NOTE: Some of these units do not have sufficient bag volume to provide adequate ventilation. Use a Laerdal Resusci folding bag II (adult) or equivalent.
- Foot-powered or battery-powered suction unit
- Nonflexible plastic suction tips (Yankauer suction tip)
- Large-bore needle and catheter (12 and 14 gauge) for cricothyroidotomy or relief of tension pneumothorax
- Trocar thoracic suction catheter (10F and 24F) or McSwain dart
- Small penrose drain, Heimlich valve, or other device to provide one-way flow of gas out of the chest
- Christmas tree adapter (to connect one-way valve to chest tube)
- Adhesive tape (2-inch waterproof)
- Elastic-wrap bandage for a tourniquet (2 and 4 inch)
- Penrose drain tourniquet
- Bandage scissors
- #11 knife blade and handle
- Curved Kelly forceps
- 10% povidone-iodine swabs or wipes
- 1% lidocaine solution
- #21 ga. 1-1/2" needles on 5 cc syringes
- Cravats
- 200 cc syringe

as needed. Additionally, they prepare a medical kit with equipment required to evaluate and treat diving casualties (Exhibit 26-1). DMOs receive graduate-level diving medicine instruction, and they must qualify as military divers. Their schooling emphasizes accident prevention, safety, and current concepts in hyperbaric physiology and treatment. DMOs are the local diving medicine authorities; they advise commanders, supervise and train DMTs, review diving duty examinations, and treat diving-related illnesses and injuries.[5,46]

Diver Training

In addition to medical topics, diver training must emphasize equipment knowledge, proficiency in emergency and operating procedures, physical endurance and strength, and good judgment. The military diver must be prepared to operate in adverse conditions, such as low or no visibility, cold water, enclosed spaces, contaminated water, high seas, strong currents, and even under ice, if the mission requires it. Unlike the sport diver, the military diver must repeatedly train and perform certain critical skills, such as emergency procedures, because the mission often dictates diving in relatively hazardous conditions where these skills might be needed. The military diver must be able to control anxiety and manage many potential stressors underwater, to include fatigue, equipment failures, unfavorable environmental conditions, and weapons fire.[5] Simple tasks such as clearing a face mask may cause panic in a novice. The most important prophylaxis to panic is ample training and confidence in the diving equipment and procedures. All military divers endure intensive "confidence training" during their initial in-water scuba instruction. Under controlled conditions, they are forced to solve problems with equipment malfunctions, loss of air, loss of equipment, and disorientation in a calm, deliberate manner. Candidates who exhibit panic under these situations are deemed unsuitable for military diving and dropped from training. Candidates are taught equipment preventive maintenance procedures, while diving supervisors receive hyperbaric systems instruction and formal quality assurance training to ensure all diving systems remain reliable. Military divers have ongoing training requirements to maintain their diving qualifications.[5] Divers whose qualifications have lapsed must requalify, which may include a medical fitness-to-dive evaluation, physical fitness screening, demonstrated proficiency in diving medicine and physics, and successful completion of a requisite number of dives.[45] Inexperience, panic, and human error cause many diving accidents, so there can be no substitute for quality diver training.[20,39,40]

Research

Finally, an active, well-conceived diving research program helps prevent diving injuries by selecting the safest diving equipment, developing reliable decompression procedures, and understanding the psychological, physical, and physiological factors affecting divers. Ideally, researchers are constantly searching and testing new equipment and decompression procedures to improve diving safety continually; they should not merely react to mishaps as they occur. Investigating the basic mechanisms of hyperbaric oxygen, the physiological consequences of water immersion, and the psychological effects of operating in the underwater environment provides precious insights for medical officers, equipment designers, and military commanders, all of whom want to give their divers every chance to be successful. The Navy Experimental Diving Unit, Panama City, Fla; the Naval Submarine Medical Research Laboratory, Groton, Conn; and the Naval Medical Research Center, Silver Spring, Md, carry on the fine tradition of US Navy diving and undersea research, which is among the best in the world.[5]

INJURED DIVER ASSESSMENT

Establishing the differential diagnosis of a diver's complaint requires keen insight. The average military diver is young, male, exceptionally fit, and often given to avoiding physicians. Although trained to report any unusual physical or mental condition, the military diver will often minimize complaints and symptoms. Therefore, the health care provider must not be lulled into a state of complacency. Divers can present with almost any of the complaints of a nondiving patient, so when evaluating the military diver, the medical provider must augment years of medical training with knowledge of diving physiology and the unique conditions associated with the hyperbaric environment to ensure that diving-unique diagnoses are included in the differential diagnosis. For example, a military diver presenting with chest pain would be approached slightly differently than a civilian counterpart. Chest pain of cardiac origin would not be an overwhelming initial concern unless the diver had multiple risk factors for coronary artery disease. Trauma would be a priority consideration, as would evaluation of possible POIS and pulmonary oxygen toxicity. Even DCS can present with chest pain. Another example is vertigo, which may be viral or be related to a tumor but in a diver is more likely to be occupationally related. Vertigo on descent is seen when the ear is exposed to changing temperatures (caloric vertigo) or barotrauma, while vertigo on ascent is most commonly due to unequal clearing of Eustachian tubes, leading to a pressure difference between middle ear spaces (alternobaric vertigo). Vertigo that worsens after surfacing and was associated with difficulty clearing on descent is probably caused by inner ear barotrauma. Fluctuating or severe vertigo that persists is often associated with inner ear barotrauma and must be evaluated.

The most common injury seen in military divers is barotrauma, particularly barotrauma of the middle ear. Unlike civilian sport divers, a military diver may use various military diving rigs (eg, hard hat, surface-supplied, full face mask) that limit access and make it difficult to perform ear clearing maneuvers that relieve pressure in the middle ear. The diver may be unable to stop or slow the rate of descent to perform a Valsalva maneuver while being lowered on a diving stage. Barotrauma will generally present with ear pain, decreased hearing, vertigo, or any combination of these.

The next most common complaint in military divers is musculoskeletal injuries. Military divers are working divers, risking injury by manually moving hundreds of pounds of equipment each day. Salvage divers must dive using rigs or systems that are very heavy and require great strength and stamina to operate. Fleet divers make underwater repairs, moving heavy objects for extended hours, working in nearly zero visibility and in thermal extremes. Additionally, they handle potentially dangerous hydraulic and electrical equipment.[33] To perform these duties, military divers must maintain a high level of physical readiness through daily physical training, which, ironically, is associated with an increased chance of injury. Overuse injuries are particularly common.[5,46]

Finally, skin injuries, skin infections, and otitis externa are associated with prolonged water and environmental exposure. Treatment is the same as for nondivers.[5,6,46]

The Evaluation

In examining a military diver, as with any patient, the history of the complaint is paramount. The more chronologically distant the diver's complaint is from a dive or hyperbaric exposure, the more unlikely the association. Although exceptions exist, most diving-related illnesses and injuries present within the first few hours following a dive. Since DCS and AGE are the most acutely dangerous nontrauma diving injuries, the DMO or DMT must examine the patient for these conditions quickly and efficiently, emphasizing the thorax and the neurological system, to establish whether AGE and DCS can be eliminated from the differential diagnosis. Radiographic studies can be valuable in confirming diagnoses of POIS, except for AGE, but should never delay recompression in patients with obvious neurological deficits. Since the primary source of injury in POIS is in the lung, a chest roentgenogram should be taken at some point. Laboratory tests are seldom useful in identifying or confirming diving conditions. Clinicians should use these tests to evaluate the differential diagnosis as appropriate. For example, a diver with sharp unilateral chest pain should be evaluated for a pneumothorax. The diver should be treated with the insertion of a chest tube and with other supportive therapy, just as a nondiver with pneumothorax would be treated, but the diver must also receive a thorough neurological exam. Additionally, the dive profile (ie, a detailed description of the dive that includes the depths, time submerged, time at each depth, and decompression steps) is beneficial in establishing a record of the dive's depths and the times spent at each depth. A shallow dive for only few minutes tends to minimize the possibility of DCS but does not eliminate it entirely. Dives of long duration to significant depth are more commonly associated with DCS, particularly if the dives require decompression stops or if they are repetitive dives. Finally, specific diving equipment is associated with specific injuries (Table 26-7). For example, oxygen toxicity is not seen when diving on air scuba, if the dive depth is restricted to shallower than 190 fsw, as is required by Navy regulations. Caustic cocktail occurs only with closed-circuit rigs, which use hydroxide compounds as carbon dioxide absorbents. When

TABLE 26-7

COMMON US MILITARY DIVING RIGS, THEIR USES, AND THE POTENTIAL MEDICAL PROBLEMS ASSOCIATED WITH THEIR USE

Military Diving Rigs	Principal Uses	Potential Medical Problems
Open-circuit scuba	Inspections, searches, ship's husbandry, shallow salvage, insertions	DCS, POIS, nitrogen narcosis, contaminated gas exposure
Closed-circuit scuba (eg, LAR V, MK 16)	Explosive ordnance disposal, combat diver operations, searches	Oxygen toxicity, POIS, hypoxia, hypercarbia, carbon dioxide scrubber failure, caustic cocktail
Surface-supply systems (eg, MK 20, MK 21)	Ship's husbandry, inspections, enclosed-space diving, salvage	DCS, contaminated gas, nitrogen narcosis, POIS, trauma from underwater tools

DCS: decompression sickness
POIS: pulmonary over-inflation syndrome

TABLE 26-8

RELATIONSHIP BETWEEN DIVING INJURIES AND ILLNESSES AND DIVE PHASES

Condition	Predive	Phase I Descent	Phase II Bottom	Phase III Ascent	Phase IV Postdive
Not diving-related	x	x	x	x	x
Trauma	x	x	x	x	x
Fatigue	x		x	x	x
Heat stress	x		x		x
Dehydration	x				x
Immersion hypothermia		x	x	x	x
Marine life trauma		x	x	x	x
Drowning/near drowning		x	x	x	x
Gas contamination		x	x	x	
Hypoxia		x	x	x	
Oxygen toxicity		x	x		
Hypercarbia		x	x		x
Barotrauma/vertigo		x		x	x
Hypocarbia		x			x
Nitrogen narcosis		x	x		
HPNS			x		
DCS				x	x
POIS				x	x

Sources: US Department of the Navy. *US Navy Diving Manual*. Vol 1 and 2. Rev 3. Washington, DC: Naval Sea Systems Command; 1993; Edmonds C, Lowery C, Pennefeather J. *Diving and Subaquatic Medicine*. 3rd ed. Oxford: Butterworth-Heinemann Ltd; 1992; Noonburg G. *US Army Special Forces Diving Medicine Manual*. Key West, Fla: Special Forces Underwater Operations School; 1995.

water leaks into the system and contacts these chemicals, a caustic alkaline solution is produced. If this mix enters the pharynx, it produces painful choking. Although the on-site medical provider certainly can respond quickly to diving emergencies and can treat injuries, he or she is of greatest benefit in anticipating and preventing them.[5,6,27]

Monitoring the Dive

Based on the history of the presenting complaint and the dive profile, a differential diagnosis can be developed. The dive can be broken into phases, with certain injuries more prevalent in each phase (Table 26-8).

Before the Dive

The establishment of a dive site is often time consuming, and safety checks and equipment corrections will often require the diver to be in a "standby" mode for extended periods. The divers may be at risk for heat stress, dehydration, and fatigue. Additionally, since the effects of most drugs in the underwater environment are unknown, drugs are best avoided. The combination of pressure, increased concentration of gases in solution, and alterations in physiology with immersion can all affect the metabolism of pharmaceuticals.[5,6,27]

Descent

Medical personnel should anticipate barotrauma, caloric vertigo, and, if divers are using mixed-gas or surface-supplied equipment, hypoxia and CNS oxygen toxicity.

On the Bottom

Trauma is most likely in this phase, secondary to equipment and work requirements. Carbon dioxide toxicity, carbon monoxide poisoning, nitrogen narcosis, and, for specialized diving, high pressure nervous syndrome are all are more common at depth because of the increased partial pressure of gases. Drowning and difficulty with temperature extremes are also frequent here.

Ascent

POIS (ie, arterial gas embolism, pneumothorax, mediastinal emphysema, and subcutaneous emphysema) is most likely to occur in this phase, particularly if the diver should lose buoyancy control and experience an uncontrolled ascent or "blow-up." Additionally, alternobaric vertigo is most common in this phase.

On the Surface

AGE will generally occur within the first 10 minutes of surfacing, and most DCS symptoms appear within hours. Symptoms of inner ear barotrauma become increasingly easy to separate from other causes of vertigo as time passes. Casualties from heat and cold extremes are common at this point.

Summary

When treating a military diver, the DMO or DMT must immediately explore the possibility of a diving-related illness or injury, specifically DCS and AGE. The evaluation process requires constant awareness, insight into diving, and, ideally, a knowledge of the patient's baseline health status for comparison. Being alert to the oftentimes subtle presentations of these diving injuries can mean the difference between recovery and a permanent deficit.

DIVING ACCIDENT MANAGEMENT

Despite the potential for catastrophe, the vast majority of military dives are conducted safely. Medical problems during or following dives are infrequent and usually minor. Most of the advanced diving medicine training in the military focuses on treating the small percentage of more severe injuries and on prevention of diving-related illnesses. The primary function of medical personnel who support diving operations is prevention of diving accidents. If an injury occurs, however, those personnel must make a quick working diagnosis and render appropriate treatment in a timely fashion.[5,6]

Diving accidents can be grouped several ways. Many diving-related illnesses do not require recompression (eg, ear squeezes, POIS other than AGE and otitis externa). DCS, AGE, and more severe cases of carbon monoxide toxicity require recompression therapy. Extreme fatigue, although not considered a focal neurological symptom, correlates highly with cerebral DCS and is included as an indication for recompression treatment. Neurological symptoms arising after a dive may be caused by DCS or AGE. Symptoms of these disorders occur almost exclusively during the decompression phase of a dive, which includes the time after surfacing.

All cases of AGE are considered serious and all divers with an AGE require immediate recompression. Divers who hold their breath on ascent can suffer an AGE in as little as 4 fsw. Neurological symptoms secondary to AGE usually are obvious and dramatic and occur immediately after surfacing, so any diver developing neurological symptoms within 10 minutes of surfacing should be considered to have an AGE.[5] A diver with an AGE may be debilitated or unconscious in the water, requiring in-water rescue and respiratory support. He or she may also suffer from near drowning, a nonfatal condition resulting from immersion, fluid aspiration, and progressive hypoxemia.[27] A wide range of potential neurological, cardiac, and respiratory sequelae complicate postinjury management of these divers. An AGE may be confused with CNS oxygen toxicity, which may occur at depth with the LAR V oxygen rebreather. Such a diver may appear unconscious on the surface or develop altered consciousness or a seizure in the water. Nevertheless, a diver who surfaces unconscious is considered to have suffered an AGE until proven otherwise.[5]

In contrast to AGE, DCS may occur at varying times after a dive, with 98% of cases occurring within the first 24 hours following a hyperbaric exposure[5] (Table 26-9). However, divers also may experience DCS symptoms during decompression stops in the water or shortly after surfacing. Divers

TABLE 26-9

TIME COURSE OF SYMPTOM PRESENTATION IN DECOMPRESSION SICKNESS

Time to onset of symptoms	< 1 h	< 3 h	< 8 h	< 24 h
Percent of divers with symptoms	42%	60%	83%	98%

Source: US Department of the Navy. *US Navy Diving Manual*. Vol 1 and 2. Rev 3. Washington, DC: Naval Sea Systems Command; 1993.

who have uncontrolled ascents or who miss decompression stops are considered at risk for developing DCS or AGE. The risk is even more pronounced if they missed greater than 30 minutes total decompression time or the first decompression stop missed was deeper than 20 fsw. These divers need recompression treatment to reduce their risk of both DCS and AGE even though they may be asymptomatic. The initial symptoms of DCS may be mild and subtle, causing the diver to discount them as overuse injuries or mild trauma. Delays in initial treatment for DCS are very common in sport divers and not infrequent in military divers. Timely recognition of these conditions requires a high index of suspicion, especially in those cases without obvious neurological symptoms.[5,6,40]

Decisions regarding treatment options for DCI depend on the availability of a recompression chamber. If one is not immediately available, patients either must be transported to a chamber or undergo in-water recompression treatment. The latter is generally discouraged, and transport is recommended unless the chamber is more than 12 hours away.[5] In-water recompression treatment, especially with oxygen, is used with success in remote areas of the South Pacific and Australia.[27]

When transporting a patient with DCI, "fast and low" is preferred, taking into consideration availability of aircraft, stability of the patient, and life support requirements. The patient must not be flown above 1,000 ft or, preferably, the aircraft cockpit should be pressurized to 1 atm.[5,6] Ground transport should also travel the lowest possible route, avoiding mountain passes if possible. The referring physician must ensure the pilots understand the importance of pressurizing the aircraft because the patient's condition invariably will worsen if the ambient pressure is reduced. Transportable chambers, such as the Marine Corps' Transportable Recompression Chamber, were developed to bring recompression treatment closer to the theater of operations. This has obvious benefits for early treatment of patients with DCI, especially AGE.

Ideally, all patients requiring transport should have intravenous access, adequate fluids for resuscitation, 100% non-rebreather oxygen, and close monitoring by diving medical personnel. If a long transport of several hours is anticipated, the patient's bladder may need to be drained with a catheter. The goal is to avoid curing the patient's neurogenic bladder via recompression only to permanently lose bladder control from an atonic bladder, which had held a liter of urine the patient could not feel. Tracheal and bladder catheters should be inflated with saline, not air, to avoid compression injury or rupture with pressure changes. Finally, the referring physician should create a clear chain of responsibility for the care of the patient and communicate with the accepting physician.[5,6]

The urgency to initiate recompression therapy depends on several factors. If a chamber is readily available, divers who are suspected of having an AGE should have a complete examination delayed until they are at treatment depth and breathing treatment gas. Tissue injury occurs in a matter of minutes from an AGE, so time delays are associated with poorer recompression treatment outcomes.[5–7,40] The physician must not forget that divers suffering from an AGE have a primary lung injury and may develop other forms of POIS, especially if positive-pressure ventilation is required. If recompression treatment for serious DCI has been delayed longer than 1 hour, a quick examination (3 to 5 minutes) should be done before recompression to begin to map neurological deficits. If the delay is greater than 4 to 6 hours, a more complete examination can be done before recompression.[46] Military diving medical personnel are trained to do relatively complete neurological examinations within 10 minutes. In addition, adequate intravenous access, chest roentgenogram, bladder catheterization, and administration of medications may be performed before recompression if there have been long delays. Divers who present with pain following a dive must receive a complete evaluation at some point to rule out more serious injury or subtle neurological symptoms. The evaluator should assume that the diver has a neurological symptom until proven otherwise by a thorough examination.[5,46]

Rarely, a diver may suffer from cardiac arrest either secondary to DCI affecting the brainstem or from loss of the airway that progresses to cardiac arrest. Although a few civilian chambers are equipped with defibrillators, no military chambers allow defibrillation at depth. Cardiopulmonary resuscitation should be instituted on the surface as soon as possible. Advanced Cardiac Life Support (ACLS) should be initiated immediately because complete recovery rates are dismal if a pulse is not reestablished within 8 to 10 minutes of the arrest.[29] If the diver is resuscitated, it should be assumed he or she suffers from an AGE and should be recompressed appropriately. If ACLS will not be available within 10 to 20 minutes, the diver should be compressed to 60 fsw. If ACLS becomes available within 20 minutes of recompression, the pressure within the chamber

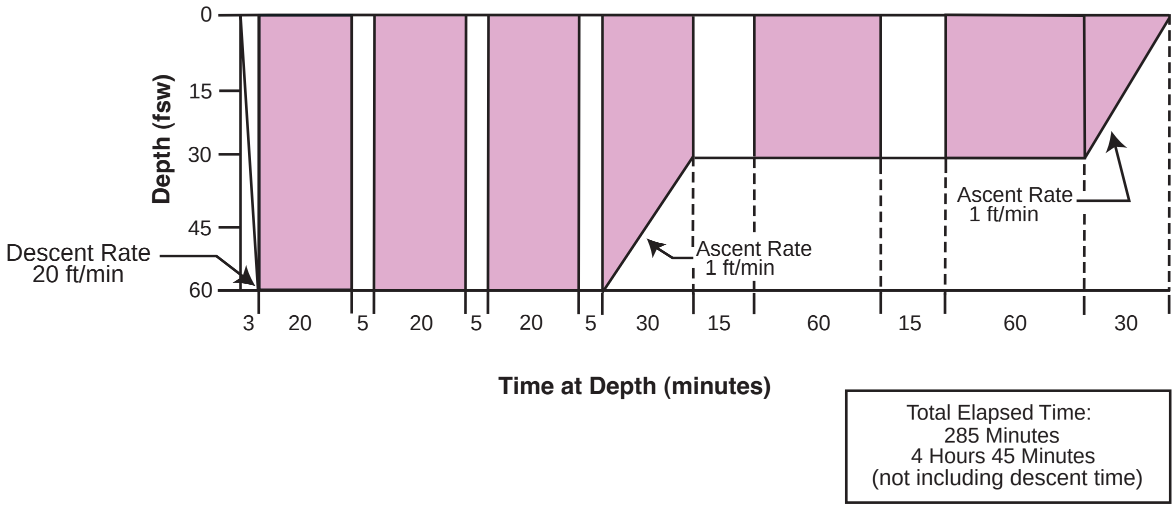

Fig. 26-10. Treatment Table 6.
Source: US Department of the Navy. *US Navy Diving Manual*. Rev 4. Washington, DC: Naval Sea Systems Command; 1999: 21–41.

should be brought to surface levels and ACLS started. If ACLS has been started, the diver must not be compressed or recompressed until a viable rhythm has been established. Diving medical personnel should be able to "call the code" if a pulse has not been established within 20 to 30 minutes.[47]

There are many DCI treatment algorithms used throughout the United States and the world. No treatment regimen has been proven effective for all cases of DCI. A few stricken divers, regardless of the extent or promptness of recompression treatment, will have permanent neurological sequelae. For the most part, however, military diving is standardized and well controlled, with minimal treatment delays for casualties. The US Navy Diving Manual is followed closely and most dives are single, no-decompression dives.[20] These factors greatly improve outcomes when treating DCI. The present Navy treatment algorithms are efficacious and respected worldwide.[6,7,10,28] Treatment Table 5 (TT-5) and TT-6 in particular, have been used to treat the large majority of DCI cases arising from standard, uncomplicated dives (Figure 26-10). These tables use an initial treatment depth of 60 fsw and a treatment gas of oxygen at 2.8 ata. Occasionally, deeper recompression (usually 165 fsw) may be required, especially for injuries occurring from nonstandard dives. Examples of these injuries are an AGE from an uncontrolled ascent from deeper than 60 fsw, serious DCS from deep, mixed-gas decompression dives, and serious DCS following large amounts (more than 30 minutes) of skipped or shortened decompression.[5] Special Operations dive profiles are typically shallow (less than 40 fsw), and DCI arising from these nonstandard dives usually responds well to standard treatment protocols (Table 26-10). Sport divers will often do multiple, repetitive, no-decompression

TABLE 26-10

A TREATMENT ALGORITHM FOR DECOMPRESSION ILLNESS

Diagnosis	Initial Treatment	Decision Point	Full Treatment
DCS Type 1	Compress to 60 fsw on oxygen	Complete relief within 10 minutes?	Yes, decompress on TT-5 No, decompress on TT-6
DCS Type 2	Compress to 60 fsw on oxygen	Worsening or need for deeper recompression within 20 minutes?	Yes, compress on TT-6A or TT-4 No, decompress on TT-6

dives on consecutive days.[40] Occasionally, they develop serious DCS requiring deeper recompression, but there is no consensus for treatment strategies in these cases. If recompression deeper than 60 fsw is deemed necessary, the best results are seen when high oxygen gas mixtures (nitrox or heliox) can provide treatment gas with oxygen partial pressures similar to those seen with a TT-6 (2.8 ata partial pressure of oxygen).[5,6,7,28] The algorithm in Table 26-10 offers a standard treatment protocol for uncomplicated cases of DCI from standard military dives and suggests a reasonable protocol for cases needing deeper recompression. The initial recompression treatment usually results in the most improvement in neurological function. Additional oxygen breathing periods, termed "extensions," may be added to most treatment tables. A rule of thumb is to strive for one symptom-free oxygen-breathing period before decompression to a shallower treatment depth. For patients with residual neurological symptoms following the initial treatment, neurological examinations should be done every 2 to 4 hours after surfacing, and subsequent retreatments rendered within 12 hours if symptoms worsen significantly. Otherwise, repeat treatments are given daily until clinical improvement plateaus for two consecutive treatments.[5] Usually one TT-6 or two TT-5s are administered within a 24-hour period for sequelae. Pulmonary oxygen toxicity may require the modification of the frequency of retreatments.[5–7,28]

EXHIBIT 26-2

LIST OF DISORDERS FOR WHICH HYPERBARIC OXYGEN THERAPY IS APPROVED

- Air or gas embolism
- Anemia from exceptional blood loss
- Carbon monoxide poisoning (may be complicated by cyanide poisoning)
- Clostridial myositis and myonecrosis
- Compromised skin grafts and flaps
- Crush injury, compartment syndrome, and other acute traumatic ischemias
- Decompression sickness
- Enhancement of healing in selected problem wounds
- Necrotizing soft tissue infections
- Refractory osteomyelitis
- Delayed radiation injury
- Thermal burns
- Intracranial abscess

Adapted with permission from: Hampson NB, ed. *Hyperbaric Oxygen Therapy: 1999 Committee Report*. Kensington, Md: Undersea and Hyperbaric Medicine Society; 1999.

Recompression Chambers

Recompression chambers are rigid-walled structures that are usually spherical or cylindrical to better tolerate the high pressures necessary to treat divers and others requiring recompression and hyperbaric oxygen therapy. According to the predominant theory, the high pressure in the chamber compresses bubbles and facilitates gas return into plasma or interstitial fluid, relieving obstruction and alleviating the tissue effects of AGE and DCS.[5–7,28] Concomitant use of oxygen (100% O_2 at 60 fsw) increases the amount of oxygen dissolved in plasma to levels where life can be sustained without red blood cells, thereby nourishing tissues that are poorly perfused due to an obstruction created by an AGE or DCS.[6,7,28] The same principle underlies hyperbaric oxygen therapy, which is used to treat carbon monoxide poisoning, gangrene, and other conditions of relative hypoperfusion (Exhibit 26-2). Chambers are pressurized with one or more patients and a medical tender or tenders inside to care for them. The DMO or other provider trained in hyperbaric medicine must never forget the decompression obligations of the tenders inside, especially if deeper recompression or a nonstandard treatment is rendered. In addition, life support requirements, to include chamber temperature control, chamber atmospheric control, and minimum staffing requirements, must be maintained for all hyperbaric treatments. During recompression treatments, DMOs must anticipate potential problems, such as oxygen toxicity, pneumothorax (especially for divers suffering from an AGE), or symptom recurrences on ascent. Consent forms for civilians should be completed before recompression but should not delay timely or appropriate treatment.[5] And liaison with a local medical treatment facility for the immediate care of the patient should be arranged before the end of the treatment. The patient and tenders should remain at the chamber for 2 hours following a TT-5 and 6 hours following a TT-6, and within 1 hour's transport of the chamber for 24 hours. Follow-up evaluation by a medical provider should be done within 12 hours for asymptomatic patients.[3,5]

EXHIBIT 26-3

DIVING EMERGENCY INFORMATION

Divers Alert Network (DAN)	3100 Tower Blvd, Suite 1300 Durham, NC 27707	(919) 684-8111
Navy Experimental Diving Unit (NEDU)	321 Bullfinch Road Panama City, FL 32407	(850) 230-3100 DSN: 436-
Naval Medical Research Center (NMRC)	503 Robert Grant Ave Silver Spring, MD 20910-7500	(301) 319-7699 DSN: 285-
Naval Diving and Salvage Training Center (NDSTC)	350 South Crag Road Panama City, FL 32407	(850) 234-4651 DMO Beeper: (850) 784-6516 DSN: 436-

Assistance is available 24 hours a day through the numbers listed in Exhibit 26-3.

Diving Accident Investigation

A diving accident that results in a fatality or serious injury or one in which a piece of equipment is believed to have malfunctioned or contributed to the accident must be investigated and reported. The chain of command, the Naval Safety Center, and the Naval Experimental Diving Unit must be notified as soon as possible with circumstances of the accident. All equipment worn by divers involved in the accident must be secured and shipped in its untampered state to the Naval Experimental Diving Unit for evaluation. Compressed gas cylinders must be shipped in accordance with current Department of Transportation and command guidance. Detailed equipment information sheets, which can be found in the *Navy Diving Manual*, must be completed and forwarded to the Naval Experimental Diving Unit also.[5]

SUMMARY

Military diving medicine is practiced by a small corps of professional DMOs, dedicated to safe and productive diving operations in the armed services. Many of these dives are conducted in remote locales under austere conditions, so DMOs must remain flexible. Additionally, they must rely on Master Divers and DMTs to enforce safe diving practices. Military DMOs often practice alone but must recognize when to contact more experienced practitioners at Navy and civilian institutions. Clinically, DMOs must maintain expertise in physiology and neurology, and they must retain a low threshold for initiating recompression therapy for diving injuries.

REFERENCES

1. US Department of Defense. *Single Manager Responsibility for Joint Service Military Diving Technology and Training*. Washington DC: DoD; 1996. DoD Directive 3224.4.

2. US Department of the Navy. *Dive Reporting*. Washington DC: DN; 1992. OPNAVINST 3150.28A.

3. US Department of the Navy. *Diving Mishap and Hyperbaric Treatment Reporting Procedures*. Washington DC: DN; 1996. OPNAVINST 5100.19C, Change 1.

4. Larson HE. *History of Self-Contained Diving and Underwater Swimming*. Washington, DC: National Academy of Sciences, National Research Council; 1959. Prepared for the Office of Naval Research under the auspices of the Committee on Undersea Warfare.

5. US Department of the Navy. *US Navy Diving Manual*. Vol 1 and 2. Rev 3. Washington DC: Naval Sea Systems Command; 1993. Also published as: US Department of the Army. *Military Diving*. Washington, DC: DA; 1995. Field Manuals 21-11-1 and 21-11-2.

6. Bove AA, Davis JC. *Diving Medicine*. 2nd ed. Philadelphia: W.B. Saunders; 1990.

7. Bennett PB, Elliott DH. *The Physiology of Medicine and Diving*. 4th ed. London: W.B. Saunders; 1993.

8. Bert P; Hitchcock MA, Hitchcock FA, trans. *Barometric Pressure: Research in Experimental Physiology*. Columbus, Oh: College Book Co; 1943.

9. Boycott AE, Damant GCC, Haldane JS. The prevention of compressed air illness. *J Hyg*. 1908;8:342–443.

10. Flynn ET, Catron PW, Bayne CG. *Diving Medical Officer Student Guide*. Washington, DC: Naval Technical Training Command; 1981.

11. Stillson GD. *Report on Deep Diving Tests*. US Bureau of Construction and Repair; 1915.

12. French GRW. Diving operations in connection with the salvage of the USS F-4. *US Navy Med Bull*. 1916;10:74–91.

13. Hawkins JA, Shilling CW, Hansen RA. A suggested change in calculating decompression tables for diving. *US Navy Med Bull*. 1935;33:327–338.

14. Yarborough OD. *Calculation of Decompression Tables*. Washington, DC: US Navy; 1937. US Navy Experimental Diving Unit Report.

15. Van der Aue OE, Kellar RJ, Brinton ES, Barron G, Gilliam HD, Jones RJ. *Calculation and Testing of Decompression Tables for Air Dives Employing the Procedure of Surface Decompression and the Use of Oxygen*. Washington, DC: US Navy Experimental Diving Unit; 1951. NEDU Research Report 1-51.

16. Desgranges M. *Standard Air Decompression Tables*. Washington, DC: US Navy Experimental Diving Unit; 1956. NEDU Research Report 5-56.

17. Workman RD. *Calculation of Air Saturation Decompression Tables*. Washington, DC: US Navy Experimental Diving Unit; 1957. NEDU Research Report 11-57.

18. Workman RD. *Calculation of Decompression Schedules for Nitrogen-Oxygen and Helium-Oxygen Dives*. Washington, DC: US Navy Experimental Diving Unit; 1965. NEDU Research Report 6-65.

19. Berghage TE, Durman D. *US Navy Air Decompression Schedule Risk Analysis*. Bethesda, Md: US Naval Medical Research Institute; 1980. NMRI Technical Report 1-80.

20. US Naval Safety Center. *Naval Safety Center Diving Database*. Norfolk, Va: US Department of the Navy; 1997.

21. Butler FK, Thalmann ED. *A Procedure for Doing Multiple Level Dives on Air Using Repetitive Groups*. Panama City, Fla: US Naval Experimental Diving Unit; 1983. NEDU Report 13-83.

22. US Department of the Navy. *Approval of the Naval Special Warfare Dive Planner*. Washington DC: DN; 1994. NAVSEA ltr 6420 Ser OOC38/3227, 16 May 1994.

23. Weathersby PK, Survanshi SS, Hays JR, MacCallum ME. *Statistically Based Decompression Tables III: Comparative Risk Using US Navy, British, and Canadian Standard Air Schedules*. Bethesda, Md: US Naval Medical Research Institute; 1986. NMRI Report 86-50.

24. US Department of the Navy. *Approval of Naval Special Warfare Dive Planner Version 6.0 with Appendix A*. Washington, DC: DN; 1996. NAVSEA ltr 10560 ser OOC/3264, 14 June 1996.

25. Valaik DJ, Parker EC, Survanshi SS. *Calculating Decompression in Naval Special Warfare SEAL Delivery Diving Operations Utilizing the Real Time Dive Planner*. Bethesda, Md: US Naval Medical Research Institute; 1996. NMRI Report 96-54.

26. US Naval Experimental Diving Unit. *High Altitude Decompression Procedures*. Panama City, Fla: NEDU; 1986. NEDU Ltr 10560/TA86-06 Ser 02/150, 28 Feb 1986.

27. Edmonds C, Lowery C, Pennefeather J. *Diving and Subaquatic Medicine*. 3rd ed. Oxford: Butterworth-Heinemann Ltd; 1992.

28. Kindwall EP. *Hyperbaric Medicine Practice*. Flagstaff, Ariz: Best Publishing; 1994.

29. American Heart Association. *Textbook of Advanced Cardiac Life Support*. Dallas: AHA; 1994.

30. Russell KL, Knafelc ME. *Low-Frequency Waterborne Sound: Manned Dive Series*. Panama City, Fla: US Naval Experimental Dive Unit; June 1995. NEDU Technical Report 10-95.

31. Smith PF, Sylvester R, Baran F, Steevens C. *Development of a General Hearing Conservation Standard for Diving Operations: Experiment 1 Comparison of Temperature Auditory Threshold Shifts Induced by Intense Tone in Air and Water*. Groton, Conn: US Naval Submarine Medical Research Laboratory; 1996. NSMRL Report 1203.

32. Noonburg G. *US Army Special Forces Diving Medicine Manual*. Key West, Fla: Special Forces Underwater Operations School; 1995.

33. Bove AA. Underwater hazards and the physiology of electric shock. In: National Academy of Sciences. *Underwater Electrical Safety Practices*. Washington, DC: NAS; 1976.

34. Halstead BW. *Poisonous and Venomous Marine Animals of the World*. 2nd ed. Princeton: The Darwin Press, Inc; 1988.

35. Francis TJR, Smith DH, eds. *Describing Decompression Illness*. 42nd Undersea and Hyperbaric Medicine Society Workshop. Bethesda, Md: 1991.

36. Hallenbeck JM, Bove AA, Elliott DH. Mechanisms underlying spinal cord damage in decompression sickness. *Neurology*. 1975;25:308–316.

37. Moon RE, Vann RD, Bennett PB. The physiology of decompression illness. *Sci Am*. 1995;273:70–77.

38. US Department of the Navy. *Manual of the Medical Department*. Washington, DC: Bureau of Medicine and Surgery; 1994. NAVMED P-117.

39. Howsare CR, Jackson RL, Rocca AF, Morrison LJ. US Navy decompression illness and fatalities, 1990–1995: patterns and trends. Presented at the 1997 Undersea and Hyperbaric Medical Society Annual Scientific Meeting; June 1997; Cancun, Mexico.3

40. Divers Alert Network. *Report on Diving Accident and Fatalities: The Annual Review of Recreational Scuba Diving Injuries and Deaths Based on 1994 Data*. Durham, NC: DAN; 1996.

41. Howsare CR. Process improvement: an assessment of the US Navy diving database. Presented in poster session at the 37th Annual Navy Environmental Health Conference; February 1997; Virginia Beach, Va.

42. Flynn ET. *Shallow Water Air No-Decompression Limits: Analysis of Naval Safety Center Data*. Notes from the presentation at the Annual Diving Research Conference; Groton, Conn, February 20, 1997.

43. Almond M. Personal Communication; Senior Flight Surgeon, US Naval Safety Center; 1997.

44. Wallace R. Personal Communication; Infantry Safety Officer, US Army Safety Center; 1997.

45. Butler FK. Medical fitness standards for military divers. Presented at the Medical Qualifications for US Military Divers Conference; January 1995; Panama City, Fla.

46. US Department of the Navy. *Medical Department Diving Medical Officer Course Manual*. Pensacola, Fla: Chief of Naval Education and Training; 1996. CIN A-6A-0010.

47. US Department of the Navy. *US Navy Diving Manual*. Revision 4 (Draft). Washington, DC: NAVSEA; 1996.