Chapter 28

INTRODUCTION TO SPECIAL ENVIRONMENTS

SARAH A. NUNNELEY, MD*

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*Senior Scientist, Wyle Laboratories, 2504 Gillingham Road, Brooks Air Force Base, Texas 78235; formerly, Research Medical Officer, Biodynamics and Protection Division, Air Force Research Laboratory, 2504 Gillingham Road, Brooks Air Force Base, Texas 78235

BACKGROUND

The mammalian body evolved to withstand the constant pull of gravity, motion due to walking or running, a variety of climates, and changes in altitude achieved on foot. Thus it is that humans possess considerable ability to adapt to a range of activities in varied climates and at high terrestrial elevations, natural environments which were discussed in earlier sections of this book. In contrast, the special environments involve artificial production, amplification or prolongation of environmental stress, and are based on the ability of the human mind to drive the body beyond the envelope for which it evolved. This can be viewed as a form of self-imposed stress, voluntarily undertaken for a variety of motives which may include altruism, ambition, curiosity and greed.

Historically, many types of exposure to special environments first appeared with the Industrial Revolution (Table 28-1). New challenges to physiology and medicine arose at each step as humans learned to sail on the sea or dive beneath it, speed over the ground, fly in the air, and launch themselves into space. In fact, many of the problems addressed in this Special Environments Section of *Medical Aspects of Harsh Environments, Volume 2,* result from the development of mechanized transportation. Rapid movement over long distances involves upsetting motion, changes in circadian timing, and abrupt exposure to thermal conditions and altitudes that are poorly tolerated because there is no time for adaptation. Paradoxically, problems also arise through artificially induced reduction in accustomed stress, as when sailors suffer *mal de debarkment* (sickness of disembarkation) or astronauts lose bone mass in orbit.

The natural limits of human adaptability sometimes curtail the use of technology, as when a pilot must ease off on an aerobatic maneuver to avoid blacking out. Such biological limits on system performance may be reduced by enhancing innate defense mechanisms or avoided by adding still more technology in the form of protective clothing and life-support systems. To return to the example, fighter pilots now increase their acceleration tolerance through a combination of systematic strength-training and pneumatic anti-G trousers.

ACADEMIC CONSIDERATIONS

Of the small numbers of physicians who concentrate their efforts on the special environments, many are trained and make their careers in the military services. Some possess additional qualifications as engineers or pilots, but the majority train in the fields of Aerospace Medicine, Hyperbaric Medicine, or Occupational Medicine—all of which fall under the purview of the American Board of Preventive Medicine (Table 28-2). These specialists focus on the prevention of environmental injury to healthy persons and the identification and protection of persons made more vulnerable by preexisting medical conditions. They must thoroughly understand normal responses to stress, adaptation processes, tolerance limits, and the mechanisms of decompensation and injury. These physicians often function as members of multidisciplinary teams, which may also include physiologists, engineers, human factors experts, and others with special knowledge related to technology and the interactions between humans and machines. The difficulty in communication among disciplines led to the development of compendia such as the *Bioastronautics Data Book*.[1]

Many physicians and physiologists have themselves served as pioneers in pushing the envelope for human exposure to hostile or potentially lethal environments. A French physician, Pilâtre de Rozier, piloted the first free ascent in a hot-air balloon in 1783, only to die 2 years later in the explosion of a hydrogen balloon. The French physician and physiologist Paul Bert demonstrated on himself a century later the usefulness of oxygen-enriched air at simulated altitude, then went on to provide supplementary oxygen for balloon ascents to very high altitudes; this extraordinary scientist also described oxygen toxicity and recognized that the new phenomenon, termed "compressed-air illness," was a consequence of bubble formation in body fluids during decompression.[2] Dr John Paul Stapp rode a rocket sled in repeated experiments to delineate the upper limits of human tolerance for sudden deceleration, and Dr Joseph W. Kittenger tested life-support equipment and parachutes at altitudes exceeding 100,000 ft.[3] More recently, a physician was launched into space with a central venous line in place to study the immediate effects of entry into zero gravity.[4]

Because of its multidisciplinary nature, the literature concerning work in special environments (sometimes termed "environmental ergonomics") is scattered through a large number of journals sponsored by a variety of learned societies in the

TABLE 28-1

NOTABLE EVENTS IN SPECIAL ENVIRONMENTS

	Special Environment				
Year	**Float**	**Dive**	**Fly**	**Other**	**Event**
1690		x			Diving bell with air resupply
1783			x		Balloon ascent
1800		x			Air pump for continuous supply to divers
1823				G	Passenger railroad train*
1830		x			Hard-hat diving suit to 100-ft depth
1841		x			Caisson for compressed air work
1854		x			Account of "compressed air illness"
1870s		x			Hyperbaric and hypobaric chambers developed and used to treat various ailments
		x			Submarine developed
	x				Steamship crossing of the Atlantic Ocean
	x				Armored ships
1874			x		Supplemental oxygen via pipe stem for balloonists
1893				G	Automobile*
1900		x			Submarine diver lockout system
1903			x		Flight of heavier-than-air craft
1906		x			Staged decompression schedules
1919			x		Oxygen mask for aviators
1927			x		Solo flight across the Atlantic Ocean
1929			x		Instrument flight
1930			x		Pressure suit for high-altitude flight
			x		Round-the-world flight
1934			x		High-G flight maneuvers (dive bombing)
			x		Human centrifuge
			x		Anti-G suit
1939		x			Helium used for deep diving
1942			x		Jet airplane
1943		x			Fully automatic scuba
	x				Aircraft carrier
1946	x				Hypothermia risk in sinkings recognized
			x		Pressurized aircraft
1954	x	x			Nuclear submarine
1960			x		Hyperbaric oxygen used to treat altitude decompression sickness
1961				O	Orbital flight
			x		Saturation diving
1968				O	Moon landing

*Not usually thought of as a special environment but notable for the motion sickness and rapid change in altitude its passengers experienced

G: ground; O: orbit

TABLE 28-2

PERTINENT ACADEMIC SOCIETIES IN SPECIAL ENVIRONMENTS

Organization	**Headquarters**	**Web Site**
Aerospace Medical Association	Alexandria, Virginia	www.asem.org
Undersea and Hyperbaric Medical Society	Kensington, Maryland	www.uhms.org
American College of Sports Medicine	Indianapolis, Indiana	www.acsm.org
American College of Occupational and Environmental Medicine	Arlington Heights, Illinois	www.acoem.org
American Board of Preventive Medicine	Washington, DC	www.abpm.org

US and overseas. Relevant American societies include the Aerospace Medical Association (founded in 1929 as the Aviation Medical Association), the Undersea and Hyperbaric Medical Society, and the American Academy of Occupational Medicine. Related research in basic science appears in the journals of the American Physiological Society and the American College of Sports Medicine, as well as publications by various engineering and ergonomics organizations (see Table 28-2).

ORIGINS AND LIMITATIONS OF RESEARCH

Special environments are often linked to military operations. Many of the technologies which create the special environments were originally developed to meet military requirements, only later finding their way into civilian industry, recreation, and exploration. Aerospace and undersea medicine received major infusions of effort in association with the two world wars (see Table 28-1). Indeed, much of our current knowledge regarding human stress physiology and protective technologies comes from research performed in military laboratories or supported through Department of Defense funding to universities and industry. Because this military orientation reinforced cultural bias, past research on special environments focused almost exclusively on the responses of healthy young men, using as subjects either military members or college students. This began to change in the late 1970s with gradually increasing interest in the stress tolerance of women and older individuals.

Women have always pioneered in special environments, although often in unofficial or unrecognized capacities and sometimes even disguised as men. Women flew in balloons beginning in 1784 and piloted early monoplanes[5]; they took up scuba and saturation diving and passed the qualification tests for the first astronauts (although only men were then allowed to apply to the program). With increasing numbers of women entering the ranks of serious athletes, explorers, military recruits, astronauts, and combat pilots, many of the old assumptions regarding women's supposed vulnerability to stress have been reexamined. This has been accomplished through replication of classic studies or design of new experiments for direct comparison of men and women who are reasonably well matched with respect to physical characteristics and conditioning. Other chapters in *Medical Aspects of Harsh Environments* provide references to such studies for physical work, heat, and cold (*Volume 1*) and high terrestrial altitude (*Volume 2*); landmark works in special environments include diving[6] and altitude decompression sickness.[7] Elements of the debate on inclusion of women in combat crews aboard ships and aircraft and their continued exclusion from Special Operations appear in the report of the Presidential Commission on Women in Combat.[8] Much of the recent research in this area was supported through congressionally mandated funding under the direction of the Defense Women's Health Research Panel.

COMMON THEMES AND SELECTED TOPICS

Although sea, air, and space are widely different environments, they are alike in their hostility to human life and thus share many aspects of physical and psychological stress. For instance, the submariner and the astronaut each dwell in a sealed capsule made habitable by sophisticated systems that closely control atmospheric pressure and gas composition as well as ambient temperature; pressurized aircraft differ from submarines and spacecraft only in that aircraft can use outside air to ventilate the cabin and scavenge oxygen. Divers, flyers, and astronauts all are subject to decompression sickness and may be required to wear impermeable protective clothing that not only impedes movement but also can cause body heat storage with attendant discomfort and hyperthermia.

Crews who dwell in special environments face high levels of physical risk, cramped quarters, and forced interpersonal closeness, all of which are combined with isolation from their families and society at large; these stressful conditions are found in ships, submarines, and saturation diving habitats, at Antarctic stations, aboard aircraft on globe-girdling flights, and in spacecraft. The development of these environments has gradually led to the need to select individuals who are resistant to stress or at least not unusually susceptible to stress-induced disability. Thus, submariners, pilots, and astronauts undergo initial screening examinations with inclusion and exclusion criteria designed to select individuals who are physically healthy and psychologically stable (see Santy P, *Choosing the Right Stuff,* in the Recommended Reading List at the end of this chapter). For such individuals, relatively minor variations from optimal health may have serious implications for their careers and livelihoods, and selection is usually followed by rigorous periodic examinations and aggressive programs of education in health and wellness to minimize the effects of self-induced stress such as tobacco, drugs and alcohol, obesity, and physical inactivity. Fortunately, research that focuses on seemingly exotic occupations such as space flight often provides major advances in general clinical medicine, including improved health risk appraisal, lifestyle modification, and the understanding of normal aging. Another outgrowth of work in special environments is improved understanding of human factors and accident investigation.

The Special Environments Section in this textbook is limited to selected areas that relate to military deployment and topics with which any military physician should have some acquaintance. It does not include areas that are covered in other volumes of the Textbook of Military Medicine series or are discussed extensively in textbooks on occupational medicine. Thus, we did not include noise, vibration, impact, radiation, or the problems of handling toxic fuels. However, we hope that the reader will be sufficiently intrigued to explore these and related topics in standard texts.

Afloat

The oldest of the special environments is the ship designed for long voyages. In the early days of sail, vessels traveled within sight of land and put in to shore at night, but commerce and curiosity—together with growing navigational skills—eventually took sailors across oceans and around the world, a progression described in detail by Boorstin.[9] Provisioning expeditionary vessels was the first human experience with the requirement to anticipate every need of a crew isolated for weeks or months in hazardous surroundings. Whether the craft were Chinese, European, or Polynesian, voyagers had to deal with confinement, water supply, food, and sanitation, as well as occupational risks and psychological stress.

The wooden ships of 18th-century Europe represented a combination of floating domicile and complex machine. The problems of provisioning and crewing the ships of the Royal Navy during the Napoleonic wars are well described in Rodger's *Wooden World,*[10] while an extraordinary feel for life on board as well as the problems encountered by the ship's surgeon (rarely a physician) can be obtained from the "Aubrey–Maturin" novels by Patrick O'Brian. Although we no longer "press" crews or provide grog (strong alcohol) as part of the ration at sea, a careful reading of Chapter 29, Shipboard Medicine, reveals that many of the old medical problems persist in some form aboard modern warships.

Under Water

Diving inspired the earliest development of an artificial life-support system for work in an inherently lethal environment (see Table 28-1). Humans had used breath-hold diving to harvest the sea floor since prehistoric times, and it is said that Alexander the Great had himself lowered into the Bosphorus in a glass barrel. The desire to reach beyond breath-hold limits prompted the development of diving bells: air-filled containers with open bottoms that were lowered to working depth to provide the diver with access to a limited volume of air, which was naturally compressed to ambient pressure. While work with bells was at first limited to the initial trapped air, divers soon learned to use barrels for resupply and later added air that was hand-pumped through a hose from the surface. This was followed in the 1800s by development of "hard-hat" diving suits tethered to an umbilical, which supplied a flow of compressed air to the helmet.

The advent of mechanized compressors permitted deeper, longer dives and the use of caissons filled with compressed air for construction of underwater bridge footings and tunnels. Medical problems arose when caisson workers and divers began to develop a crippling and sometimes fatal condition known as "caisson disease" or "bends." In 1874, Bert recognized that this illness (now termed decompression sickness, or DCS) was a consequence of decompression to 1 atm.[2] However, decades passed before prevention of DCS was made possible by the development in 1906 of the first schedules for staged decompression.

With increasing depth, decompression times came to exceed bottom time, and this inefficiency eventually became a limiting factor, which motivated the development during the 1960s of saturation diving, in which divers used pressurized living quarters as a base for a series of work bouts without the need for intervening decompression. Further complexities were added by the use of artificial gas mixtures (nitrox, heliox) to avoid nitrogen narcosis and the more dramatic high-pressure nervous syndrome. Recently, research on very deep saturation diving has dwindled with the development of practical unmanned systems for observation and work at great depth. Interested readers can find more detail on deep diving in the Recommended Reading list at the end of this chapter, particularly Bennett and Elliott's *Physiology and Medicine of Diving*, and Bove's *Bove and Davis' Diving Medicine*.

The material on diving in this section appears in two linked chapters, the first (Chapter 30, Physics, Physiology, and Medicine of Diving) presenting the special challenges of diving and hyperbaric environments, and the second (Chapter 31, Military Diving Operations and Medical Support) focusing on medical aspects of diving and submarine operations. Readers may wish to seek more detail in one of the several major textbooks on diving and hyperbaric medicine. These texts also provide information on the growing use of hyperbaric oxygen to treat medical and surgical conditions of particular interest to the military, including DCS, gas gangrene and necrotizing infection, crush injury, and nonhealing wounds.[11] A recent addition to the literature is a brief pictorial history of hyperbaric chambers.[12]

In Flight

As mentioned above, human flight began with balloon ascents in 1783. The first escape system was not far behind; in 1797 an aeronaut deliberately parachuted 2,000 ft from his balloon to a safe landing. Although balloons were generally regarded as showpieces for public spectacle, the armed forces adopted them as observation platforms in the American Civil War (1861–1865) and the Franco–Prussian War (1870–1871). In addition, balloons were used by scientist-aeronauts to explore the characteristics of the atmosphere at high altitudes, beginning with ascents above 20,000 ft in the 1860s and continuing to the edge of space in the 1970s.[3]

Powered flight was pioneered in the United States by the Wright brothers and was also quickly adopted for military purposes. Airplanes were employed for aerial observation early in World War I, but they soon began carrying machine guns and even hand-dropped bombs. Increased aircraft power and maneuverability soon brought a new set of medical problems (see Gibson and Harrison's "Into Thin Air: A History of Aviation Medicine in the RAF" in the Recommended Reading Section in this textbook). While birds are naturally adapted to aerial maneuvers and the rigors of high altitude, humans are not, and military commanders in World War I soon realized that more pilots were being lost to accidents than to enemy action. Aviation medicine was born as a specialty as physicians sought to reduce noncombat casualties by improving techniques for pilot selection and training as well as designing better personal equipment. Today, aerospace medicine encompasses all aspects of military and civil aviation as well as space flight (see DeHart's *Fundamentals of Aerospace Medicine* and Ernsting and colleagues' *Aviation Medicine* in the Recommended Reading Section at the end of this chapter).

First balloons and later powered aircraft achieved altitudes where hypoxia impaired mental function and then induced unconsciousness and death. Provision of oxygen in flight is a good example of the multidisciplinary problems of providing life support in a hostile environment. It began with Paul Bert's simple bladder of oxygen to be sucked through a pipe stem; unfortunately, laboratory tests with this system failed to allow for the increased oxygen requirement associated with physical activity and cold during actual flights, and fatalities ensued when balloonists received insufficient oxygen or exhausted their supply. Interest in high-altitude air operations in World War II led to major studies of respiratory physiology and the development of highly engineered oxygen systems: The pipe stem was replaced by the oronasal mask supplied by a demand regulator, followed by positive-pressure systems, partial pressure suits, and ultimately full pressure suits, as pioneered by Wiley Post.

Three chapters in this section present selected topics from aerospace medicine. Hypoxia and hypobaria (Chapter 32, Pressure Changes and Hypoxia in Aviation) are critical, intertwined challenges to flight at very high altitude. The piece on acceleration (Chapter 33, Acceleration Effects on Fighter Pilots) illustrates the combined use of autonomic mechanisms, crew training, and mechanical devices to enhance human tolerance to artificially induced stress. The chapter on space flight (Chapter 34, Military Spaceflight) summarizes the challenges to the US Air Force's emerging role as "the space and air force." Although US military use of space is currently limited to observation satellites, future developments may well parallel the progression of balloons and aircraft from passive to active roles.

The Trouble With Motion

Motion sickness poses a vexing problem associated with all forms of mechanized transportation (Chapter 35, Motion Sickness). The oculovestibular axis, which evolved to keep land animals oriented and their vision stabilized, becomes counterproductive in the face of artificially amplified or conflicting sensory inputs such as the "cross-coupling" produced by certain aerobatic maneuvers. A related syndrome, known as "simulator sickness," often limits the ability of personnel to train or work with realistic visual displays that lack corresponding motion inputs. While the evolutionary origin of motion sickness remains a matter for speculation, it is clear that the mechanisms are so embedded in the neurological system that there is little possibility for technological intervention to reduce or ameliorate these responses. Pharmacological agents offer some relief, but their use is limited by side effects including drowsiness or visual changes.

Studies of motion effects and related therapies are difficult for several reasons. Few subjects will volunteer for repeated-measures protocols that induce severe nausea or vomiting. Furthermore, data are noisy because the incidence and severity of symptoms vary widely between individuals and from day to day in the same person, and also show a strong relationship to expectation and emotional state. These psychophysiological linkages foster the public's acceptance of unproven therapies such as wrist bands and magnets.

Vulnerability to motion-induced symptoms can be minimized among pilots and other specialists by selecting resistant individuals and training them through repetitive, escalating exposure to the offending stimulus. Space flight presents special challenges in this regard, since astronauts often feel ill in the first hours or days after arrival in orbit; there is no way to simulate sustained zero gravity conditions on the ground, nor is the incidence of symptoms in orbit reduced among experienced test pilots (Chapter 34, Military Spaceflight).

Motion sickness is a far worse problem among nonspecialists. Consider the problems faced by operators of passenger ferries and cruise ships in rough weather, especially in these litigious times. Carnival rides and theme-park simulators cater to individuals who enjoy the thrill of vertiginous experiences but do not expect to have their day ruined. More relevant to this textbook, motion-induced discomfort and even incapacitation can have enormous impact on military deployments (eg, among troops brought to combat by ship or special operations forces transported aboard low-flying aircraft).

Clothing as Protective Burden

Personal protection and life-support systems play a variety of roles ranging from limited emergency back-up for cabin systems to primary defense against lethal environments, as in salvage diving, work in contaminated atmospheres, or extravehicular activity in space. All systems of personal protection share certain undesirable characteristics, including the hobbling effect of the clothing, limitations on environmental heat exchange, and restricted breathing, as well as adverse effects on visual fields, manual dexterity, and interpersonal communication. Thus, equipment intended only for emergencies must be evaluated for cost-to-benefit ratio. A classic example is the antiexposure (immersion) suit worn by military pilots flying over cold water: how does one balance the discomfort of wearing a hot, bulky suit for hundreds of hours of normal flight against the remote possibility that it may save a life in case of ditching? Analogous considerations apply to clothing worn by troops working in environments potentially contaminated by nuclear, biological, or chemical agents, where heat stress and other clothing-related problems may severely reduce operational capability (Chapter 36, Protective Uniforms for Nuclear, Biological, and Chemical Warfare: Metabolic, Thermal, Respiratory, and Psychological Issues). Personnel who are forced to wear protective clothing too often take unsanctioned measures to make themselves more comfortable, by loosening seals or removing a layer, even though such actions often render the item ineffective in a real emergency.

Special Operations

All four military services train units of highly selected personnel for Special Operations, ranging from aggressive military action to humanitarian missions. As described in the last two chapters of this textbook (Chapter 37, Medical Support of Special Operations, and Chapter 38, Organizational, Psychological, and Training Aspects of Special Operations Forces), Special Operations constitute a microcosm combining all the problems involved in deployment to harsh environments. In the course of training for and carrying out Special Operations, personnel may require the support of flight surgeons, diving medical officers, specialists in occupational medicine, and experts in sports medicine and rehabilitation.

A common thread for combat operations is the use of uncomfortable or risky modes of transportation so that troops arrive at the site of operations already stressed by some combination of anxiety, motion, dehydration, nutritional deficit, sleep deprivation, and circadian dysrhythmia. They may then be expected to carry out a mission that would represent a maximum effort for unstressed troops. Medical care of casualties can pose particularly difficult challenges owing to the minimal level of support available during a remote and sometimes secret operation.

CONCLUSION

For physicians and physiologists, the special environments pose unique challenges to their understanding of the effects of many kinds of stress. Military operations often present problems that deal with human limitations at the interface between biology and engineered systems.

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