DEPTH
DIVING • EQUIPMENT • PHYSICS • TECHNIQUE • HYPERBARICS
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Stresses in SCUBA and Breath-Hold Diving

Part I: Introduction and Physical Stresses

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Introduction

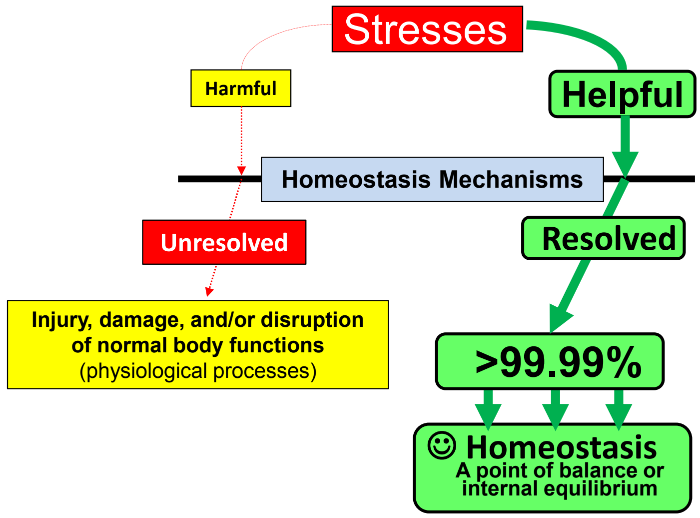
When SCUBA and breath-hold diving are done and done appropriately, divers are usually not aware of the stresses that constantly "bombard" them and are subliminally resolved. Only when the stresses are not resolved completely do diving-related medical problems occur (Figure 1).[1] Stresses associated with SCUBA diving can be divided into three categories; physical, physiological, and psychological (Figure 2). Different phases of SCUBA and breath-hold dives (because of the special challenges associated with each phase) have the propensity for generating specific medical problems.[2] This article discusses the physiology of the stress-response (stimulus-reaction) phenomenon, describes the medical problems that are associated with the physical stresses of diving, and integrates this information with the phases of the dive for which the stresses predominate. Subsequent articles will discuss the physiological and psychological stresses of diving. The goals of this introductory article are to make the SCUBA and breath-hold diver aware of the physical stresses associated with diving and what measures can be done to prevent them from leading to medical problems that will interfere with the dive or result in injury or death to the diver.

The Stress-Response Phenomenon

As mentioned above, when SCUBA and breath-hold diving is done and done appropriately, the divers are usually not aware of stresses that constantly occur and that are subliminally resolved. A few important concepts need to be appreciated with respect to stresses. For every stress that challenges an organism, a response from the organism results. Homeostasis is the goal of the organism's stress/stimulus—response/reaction mechanisms to cope with these challenges. Homeostasis (homeo = similar; stasis = standing still) is an organism's goal to keep all systems running on an "even keel." Perhaps the easiest example to appreciate is the body's regulation of blood sugar. A desirable

> Stimulus to Breathe
>
> The stimulus to breathe is another example of how imperceptible responses to stimuli maintain homeostasis in the body. The stimulus to breathe is initiated by elevation of blood carbon dioxide (CO_2) gas tensions. The elevation occurs because CO_2 is a waste product of metabolism. Receptors in the blood stream detect the elevation and send a stimulus to the respiratory center of the brain to initiate a breathing response (i.e. inhalation and exhalation) to dissipate the CO_2 accumulation in the blood stream through the lungs. To test this stimulus-response homeostatic mechanism, merely hold your breath. As the CO_2 levels in the blood stream increase, there is an increasingly stronger desire to breathe eventually reaching the point that a breath must be taken, the so-called breath-hold break point.
>
> Ondine's curse from mythology recognizes how important the homeostatic mechanism to breathe is and the consequences that result when it is impaired. Ondine was a water nymph who had a mortal lover. He swore to Ondine that "every waking breath would be a testimony of his love" for her. Upon witnessing his adultery, Ondine laid a curse on her unfaithful lover such that if he should fall asleep, he would forget to breathe. Inevitably he fell asleep from sleep deprivation, stopped breathing, and died. This insightful myth shows how important the CO_2 homeostatic mechanism is to breathe (without conscious awareness/brain stem involvement) and is labeled today as the congenital central hypoventilation syndrome. Its pathophysiology is due to brainstem nerve injury and dysfunction.

Figure 1: Stresses, Stress Resolution, and Homeostasis



Legend: The body is constantly subjected to stresses. Most are resolved spontaneously and usually without conscious effort to maintain homeostasis (homeo=constant, stasis=stable i.e. even, normal function).

When stresses are not adequately resolved, harm to the organism can result. The purpose of homeostasis mechanisms is to resolve stresses to maintain normal/orderly function.

homeostasis range (e.g. 60-100 milligrams per deciliter) exists. If food intake occurs, the sugar in the food raises the blood sugar (i.e. the stimulus) and the body responds by insulin secretion from the pancreas to keep the blood sugar in the optimal range. Like most homeostasis mechanisms that occur in the body, the blood sugar responses are imperceptible. Only when totally "out of whack" are the consequences for not maintaining homeostasis manifested. For blood sugars, this may be loss of consciousness from hypoglycemia if blood sugars are too low or diabetic ketoacidosis if too high.

Phases of a Dive and Diving Medical Disorders

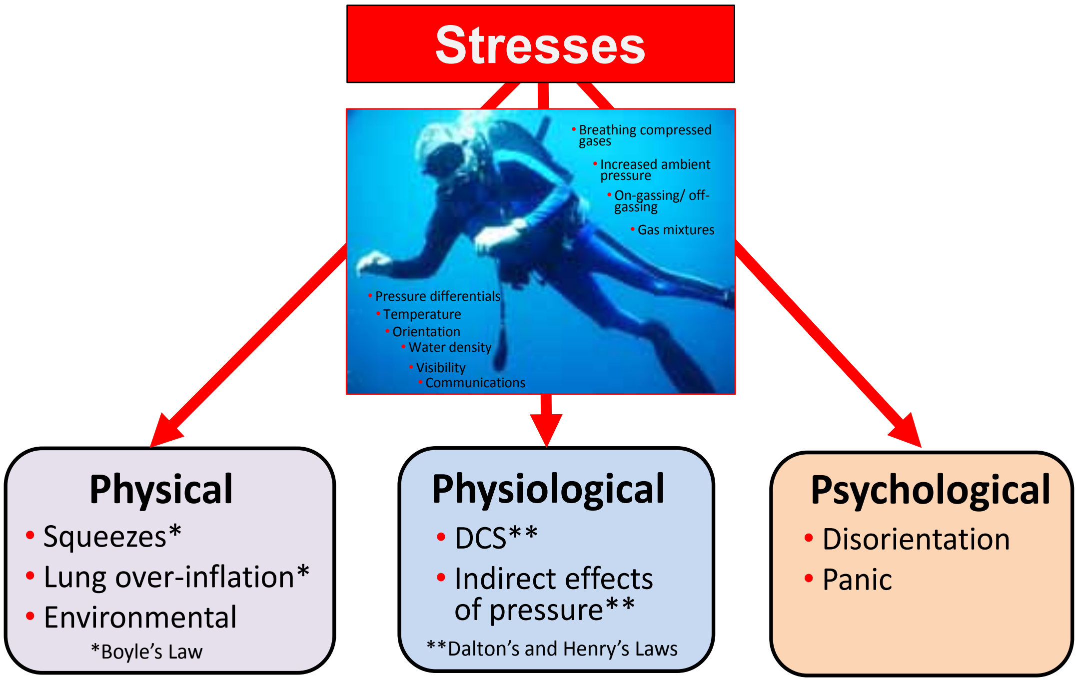
The stress/stimulus—reaction/response phenomena during diving, whether SCUBA or breath-hold, has similarities to land-based activities. However, the water environment imposes stresses that are prone to occur at specific phases of a dive. Diving activity can be divided into four phases which include: 1) Pre-dive/Surface, 2) Descent, 3) Bottom and 4) Ascent/post-dive segments (Figure 3). Each phase of the dive imposes stresses on the diver that in the majority of instances are resolved subconsciously or with minimal conscious effort. Only infrequently are the stresses not adequately resolved and thereby interfere with the diving activity (Figure 1). Fifteen disorders are the predominant ones that occur as a consequence of diving and each is usually associated with one of the four phases of the dive (Figure 3). The exceptions to this are the pre-dive/surface medical disorders that may occur at any of the dive phases, as well as drowning/near-drowning, cardiac arrest, and shock (possibly associated with marine animal injuries, propeller injuries, or trauma such as being hurled onto rocks from wave action). Physical stresses are experienced throughout the four dive phases and relate primarily to pressure related phenomena and environmental challenges.

Dive Scenario: A snorkel diver was found unconscious and in profound shock on the shore line with two large parallel gashes on his right leg. Initially, impressions were that he exsanguinated as a consequence of a shark bite. The victim expired en route to the hospital. A coroner's inquest concluded that the injury was from a boat propeller because of the parallel grouping of the gashes, absence of shark teeth in the wound, and appearance of the wound with no avulsed tissue.

Comment: This scenario illustrates a surface-phase medical problem of diving and how shock can occur with traumatic injuries. Many questions remain unanswered such as: Was the diver diving alone, did the motor boat "hit and run," how did the diver get to shore, and had a tourniquet been used, could his course have been altered?

Shock has many causes such as blood loss, infection, loss of sympathetic nervous system control of blood vessel diameter, heart problems, etc. In this scenario, blood loss was the obvious cause. With a circulation time of about 30 seconds, shock from bleeding from a large vessel such as in the patient's leg can occur in a minute or two and death from exsanguination shortly thereafter.

Figure 2: Types of Stresses in Diving and their Associated Medical Problems



Legend: When diving, three types of stresses must be resolved. This article describes the physical stresses with Boyle's law providing quantification for squeezes and lung overinflation (i.e. extra-alveolar air/ pulmonary over-pressure/air retention) syndromes.

Part I: Physical Stresses of Diving

Pressure-Related Phenomena

Pressure-related phenomena can be attributed to Boyle's law. Boyle's law explains the physics for ear, sinus, and other squeezes (e.g. tooth, mask, and diving suit) as well as arterial gas embolism. With any change in ambient pressure, there is a change of volume of the gas in the confined space. The stresses imposed by changes in ambient pressure are met by pressure equalization techniques such as "clearing" the ears to equilibrate pressure in the middle ear spaces during descents in the water and to breathe in a regular fashion during ascents with SCUBA gear to prevent extra-alveolar air syndromes (arterial gas embolism, pneumothorax, and mediastinal/ subcutaneous emphysema). For the squeezes, stresses (of pressure differentials between the confined gas-filled cavities and the ambient pressure) evoke responses of halting or slowing the descent rate and in this situation the stresses are perceptible. For arterial gas embolism, the stresses are typical imperceptible (as a consequence of breath-holding with uncontrolled ascent) and must be mitigated by training to not breath-hold during ascent. A cardinal principle with respect to pressure differentials is that the body "abhors" pressure differentials (i.e. a vacuum), and if not resolved through homeostatic and/or conscious-associated responses, they will lead to injury.

When considering squeezes, the body consists of three compartments (Figure 4, Table 1).[1] The first of these compartments is the liquid and solid structures of the body such as solid organs, hollow organs filled with fluid (e.g. heart, blood vessels, eyes, bladder), semicircular canals and cochlea of the inner ear, bones, blood, tissue fluids, skin, subcutaneous tissue, and fat. This compartment is not subject to squeezes, but because it transmits the changes of ambient pressure equally and undiminished (in accordance with Pascal's law), no pressure differentials develop (Figure 5). This compartment imposes no limitations on the depth or duration of dives with respect to squeezes.

Boyle's Law

This gas law quantifies volumes changes with changes in ambient pressure and formulated as $V_1 \times P_1 = k$ or $V_1 \times P_1 = V_2 \times P_2$ (where P = pressure, V = volume, k = a constant). In simplistic terms, Boyle's law explains that when pressure is increased (or decreased) on a confined volume of gas, the volume of the gas decreases (or in the situation of decreased pressure increases). For example, if the pressure on gas confined in a flexible enclosure such as a balloon doubles, the volume of the gas decreases by 50% (Figure 5).

Liquid Respiration

Theoretically, if all three body compartments could be converted to liquids and solids, no squeezes—or even gas embolism would occur no matter how deep the dive. This has been experimented with utilizing fluid respirations.[3] The lungs and tracheobronchial tree are filled with fluid such as normal saline or fluorocarbons and the fluid pressurized with oxygen. The oxygen in the fluid (analogous to physical dissolved oxygen in plasma as utilized in hyperbaric oxygen therapy) diffuses through the alveoli in the lungs to be delivered by the blood stream to body tissues to meet their metabolic demands. Two challenges limit the theoretical benefits of fluid respiration. These are elimination of carbon dioxide (CO_2) and the work of "breathing" a fluid. Whereas it is possible to deliver oxygen through this technique, measures to eliminate the one hundred-fold increases in CO_2 between inspired gas (or fluid) and the waste products of metabolism have not been solved. With respect to the work of breathing, it should be appreciated that water is over 700 times denser than air and results in an enormous work of breathing just to move fluid in and out of the lungs.

The science fiction-adventure movie *The Abyss* (1989) utilizes the technique of fluid respiration for one of its epic scenes. For the record, this movie was "truly" an underwater undertaking. Forty percent of the live action took place underwater. The actors themselves shot scenes at 33 feet of sea water (FSW) for periods of less than one hour so decompression (other than standard ascent rates) was not required. On the other hand, the camera crews stayed at depths of 50 FSW for five hour durations and did oxygen breathing during ascent.

The second pressure-volume related compartment is the air-filled, flexible wall cavities such as the lungs and gut. This compartment responds to the stress of increased pressure by decreasing in volume and vice versa with decreases in pressure as expressed by Boyle's law (Figure 4). Ordinarily, this compartment tolerates the compression stresses of diving without problems and merely decreases in volume. An exception to this is the point at which the lungs are compressed to their residual volumes. After this the alveoli assume the characteristics of the rigid-walled, air-filled compartment (as will be discussed in the next paragraph). Whereas compression stresses of this compartment are almost always well tolerated with ordinary SCUBA and breath-holding diving activities, alveoli tolerate overexpansion poorly. When these structures are filled to capacity with a maximal inhalation, further enlargement with decreases in ambient pressure (i.e. ascent) will cause them to rupture. This leads to one or more of the three presentations of extra-alveolar air syndromes, namely subcutaneous/mediastinal emphysema, pneumothorax, or arterial gas embolism (Figure 6). This is an example of a physical stress of diving that must be avoided by not breath-holding during ascent when diving with SCUBA gear because the homeostatic mechanisms of alveolar distention are very limited. That is, the elastic properties of the alveoli do not tolerate overexpansion beyond a few percentage points before they rupture.

Alveoli tolerate over-expansion poorly. Even though this tissue type has some elastic properties, overexpansion, rupture, and gas embolism can theoretically occur with breath-holding after full inspiration from a 3 foot depth. This equates to about a 10% overexpansion of the fully inflated alveoli.

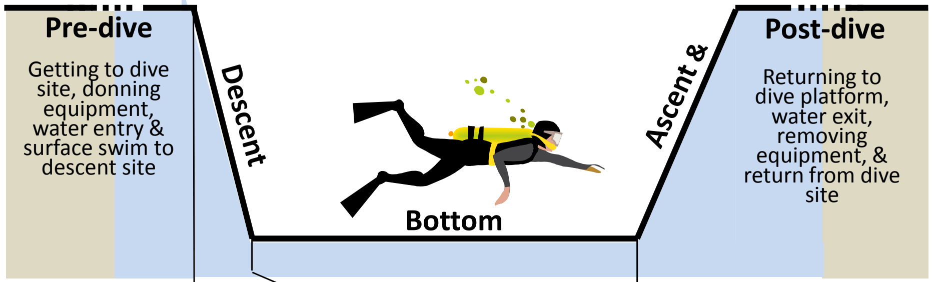
Arterial gas embolism has been observed with breath-holding from an eight foot depth after breathing compressed gas.

Dive Scenario: A couple of kids were playing in a backyard swimming pool. They decided to weight an upside down bucket filled with air so it would sink to the bottom of the pool then breathe air from the bucket in order to stay underwater. Soon the air became stale (from carbon dioxide accumulation) and with one last deep breath, one kid swam to the surface while holding his breath. Immediate loss of consciousness occurred and after rescue and breathing oxygen, consciousness was restored with no apparent brain damage. The presumptive diagnosis was arterial gas embolism from breath holding after breathing the compressed gas in the upside down bucket.

Comment: This scenario illustrates how minimal pressure differentials can lead to alveolar rupture and supports the theoretical estimates from the above text box. It is noteworthy that about 50% of arterial gas embolisms resolve with breathing 100% oxygen on the surface.

The third pressure-volume related compartment is that of rigid-walled, air-filled compartments such as the middle ear spaces, the sinuses, and the face mask. Less typical examples of this compartment included air pockets in carious teeth and wrinkles with air-filled cavities in wet suits. With changes in ambient pressure, pressure differentials arise between the solid, ridged-walled external structures and their gas-filled inner contents. Since a pressure differential is a stress that homeostatic mechanisms attempt to

Figure 3: Phases of the Dive, their Stresses and their Medical Problems

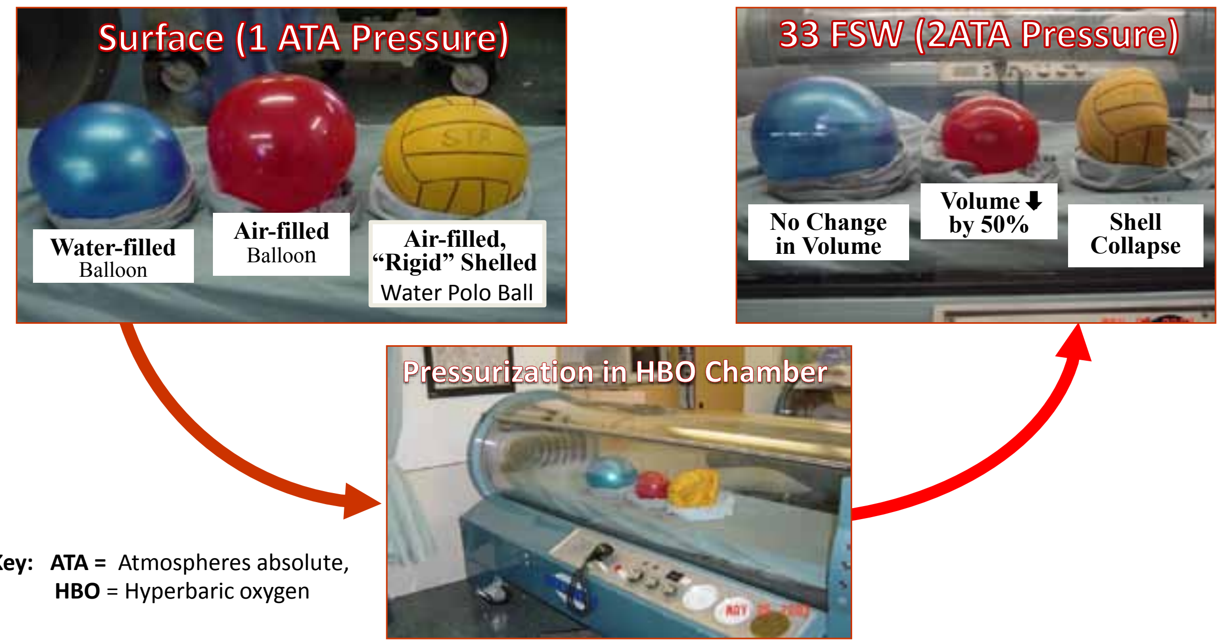


	Pre-dive	Descent	Bottom	Ascent & Post-dive
Major stress categories	Exertional Environmental	Pressure Direct effects of pressure	Physiological Indirect effects of pressure	Physiological (AGE) Physiological (DCS) Exertional
Problems that may occur	Panic Hypothermia Blackout Ear canal infections Injuries from marine animals	Squeezes Ear, sinus, face mask, etc. Thoracic squeeze	Nitrogen narcosis Oxygen toxicity CO_2 toxicity Hypoxia Carbon monoxide poisoning	Extra-alveolar gas problems Subcutaneous emphysema Mediastinal emphysema Pneumothorax Arterial gas embolism Decompression sickness Alternobaric vertigo
Stress prevention / elimination	Dive planning Fitness Equipment	Skill sets Experience	Training Equipment Dive planning	Dive Planning Fitness

Legend: This all-encompassing (an entire synopsis of diving medical problems) figure shows when, why, and what diving problems occur and how to prevent them. All the medical problems listed in the pre-dive column are not exclusive to this phase of the dive, and in contrast to the other disorders, can occur in other phases of the dive. Drowning, cardiac arrest, and shock (from traumatic injuries e.g. boat propellers) can also occur at any phase of the dive.

AGE=arterial gas embolism, **CO_2**= carbon dioxide, **DCS**=decompression sickness.

Figure 4: Effects of Pressure on Water and Air-Filled Balloons and on a "Rigid" Shelled Water Polo Ball



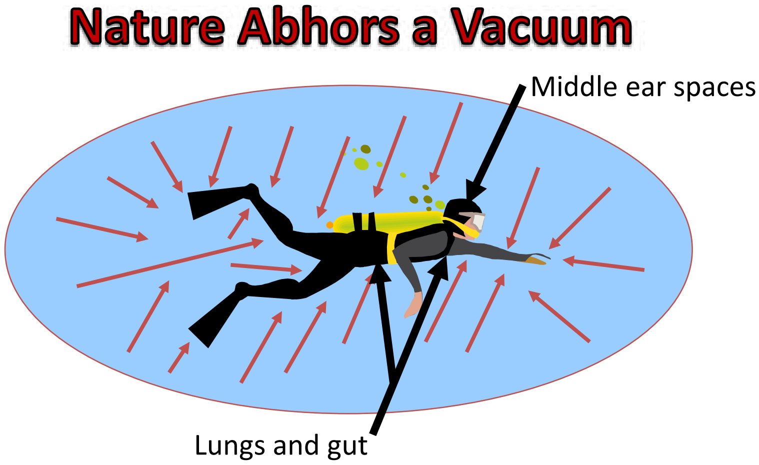
Key: **ATA =** Atmospheres absolute,
HBO = Hyperbaric oxygen

Legend: The above photos illustrate how the three body compartments respond to increased pressure. The water-filled compartment (blue balloon) corresponds to the **liquid-solid structures** of the body (> 90 of the body composition).

The air-filled, flexible walled structures (red balloon)decrease in size with increased pressure and **correspond to the lungs and gut.**

The rigid-walled, air-filled structures (water polo ball) **include the middle ear spaces**. Pressure differentials arise with increased pressure which lead to barotrauma. In these structures bleeding and ear drum perforation occur before collapse (as might happen in a submarine that exceeded crush depth and is demonstrated with the water polo ball).

Figure 5: Pascal's Law and Pressure Related Phenomena in Diving



Legend: Pascal's law states that fluids transmit pressures equally and undiminished in every direction. This has important ramifications for divers. In essence it means divers are "invincible" to the effects of pressure with respect to the body's liquid and solid structures.

The liquid and solid structures in the body subscribe to Pascal's law and transmit ambient pressures equally and undiminished so no pressure differentials develop in these structures with changing depths. Conversely, in air-filled structures, pressure differentials arise with changing depths. Pressure differentials lead to symptoms such as those associated with ear squeezes.

Body structures do not tolerate pressure differentials i.e. "abhor a vacuum" and divers need to initiate techniques such as clearing the ears to prevent pressure differentials in susceptible structures.

resolve, the linings of the cavities begin to swell, which in effect decreases the volume of the cavity. This is usually heralded by pain and is a "warning symptom" that the diver needs to equilibrate pressure in the middle ear spaces, usually an active process such as a Valsalva maneuver or related ear-clearing technique. The swollen lining of these cavities reduces the volume of the cavity and is an automatic, stress-invoked, teleological response to the pressure differential. With increasing pressure differentials, tissue fluids and ultimately blood leak (i.e. diapedesis) through the vessel walls in the lining of the rigid-wall cavities. The end-point in this continuum of squeeze pathology is rupture of the blood vessels lining the cavity and/or rupture of the tympanic membrane (in the ear squeeze). Once the cavity fills with fluid or the ear drum ruptures, pressure differentials are obliterated and the middle ear cavity responds to pressure as other liquid-solid structures of the body do. It is easy to appreciate at which stages of diving the pressure-related stresses will occur (Figure 3). The squeezes typically occur during the descent phase of diving although reverse ear squeezes can occur during ascent. Conversely, extra-alveolar air syndromes occur during the ascent phase of diving. Knowledge and training are effective prevention measures for these diving medical problems.

Environmental Stresses

Environmental stresses the diver encounters include exposure to cold water, infections of the external ear canal, injuries from marine animals, and the physical

Middle Ear Barotrauma and Hyperbaric Oxygen Therapy

Middle ear barotrauma is a recognized complication of hyperbaric oxygen (HBO) treatments. Because HBO therapy usually requires repetitive treatments, fluid accumulation in the middle ear spaces can make pressure equilibration increasingly difficult with each successive treatment. Much can be done to mitigate ear squeezes associated with HBO therapy including slowing the ascent rate and use of vasoconstrictors and antihistamines (if the patient has allergies). These same techniques are used by divers when they experience difficulty clearing their ears.

A device to equilibrate face-mask pressures and the external ear is purported to prevent ear squeezes. However, little information is known to the authors about its effectiveness and the mechanisms the device utilizes to equilibrate pressures in the middle ear spaces

The HBO patient has the option of insertion of ventilation tubes in the tympanic membranes. They prevent any pressure differentials developing between the ambient pressure and the middle ear spaces. Unfortunately, this is not an option for the diver because water can enter the middle ear space through the ear tubes and lead to infection, vertigo, and fluid retention in the middle ear spaces.

Table 1: Pascal's Law and Pressure Related Phenomena in Diving

Compartment (see Figure 4)	Examples	Effects of Increased Pressure
Liquid-solid 	blood bones, joints, teeth muscles, tendons solid organs skin, fat, connective tissue, nerves	Pressure transmitted equally & undiminished No pressure differentials No depth limitations
 Air-filled, flexible-walled	lungs, gut	Compress as pressures increase (Boyle's law) No pressure differentials
 Air-filled, rigid-walled	middle ear spaces sinus cavities face mask, creases in wet suits	Pressure differentials arise Tissue damage if not equilibrated

Note: See Figure 4 for description of the colored spheres.

characteristics of the aquatic medium itself. All can occur while on the surface of the water (i.e. surface phase of a dive), but also at any of the other phases of the dive. Rarely do the environmental stresses interfere with a dive, but in almost every dive, the diver initiates measures, usually without conscious awareness and/or initiated during the pre-dive planning to mitigate the environmental stresses that could lead to bodily harm.

The Physical Challenges of Cold Water

The specific heat of water is 1000 times greater than air of equal temperatures. This means to warm a volume of water one degree requires 1000 times the heat energy that it would require to warm an equal volume of air one degree. This, coupled with the thermal conductivity of water, which is 25 greater than air, imposes enormous thermal stresses on divers. The LD_{50} (lethal dose i.e. exposure where a 50% death rate occurs) for near-freezing water is about 5 minutes.

Challenges of Cold Water Cold water imposes enormous thermal stresses on the diver. Whereas survival in cold air is measured in days, in cold water of equal temperature it is measured in minutes. The stress of diving in cold water is mitigated by donning exposure suits. They insulate the diver from the thermal conductivity of water and generate a microenvironment that markedly lessens the specific heat challenges of cold water exposure. Many factors in addition to using exposure suits contribute to meeting the cold water stress challenge such as avoiding alcohol ingestion, minimizing swimming movements, slowing breathing rate, etc. (Table 2).

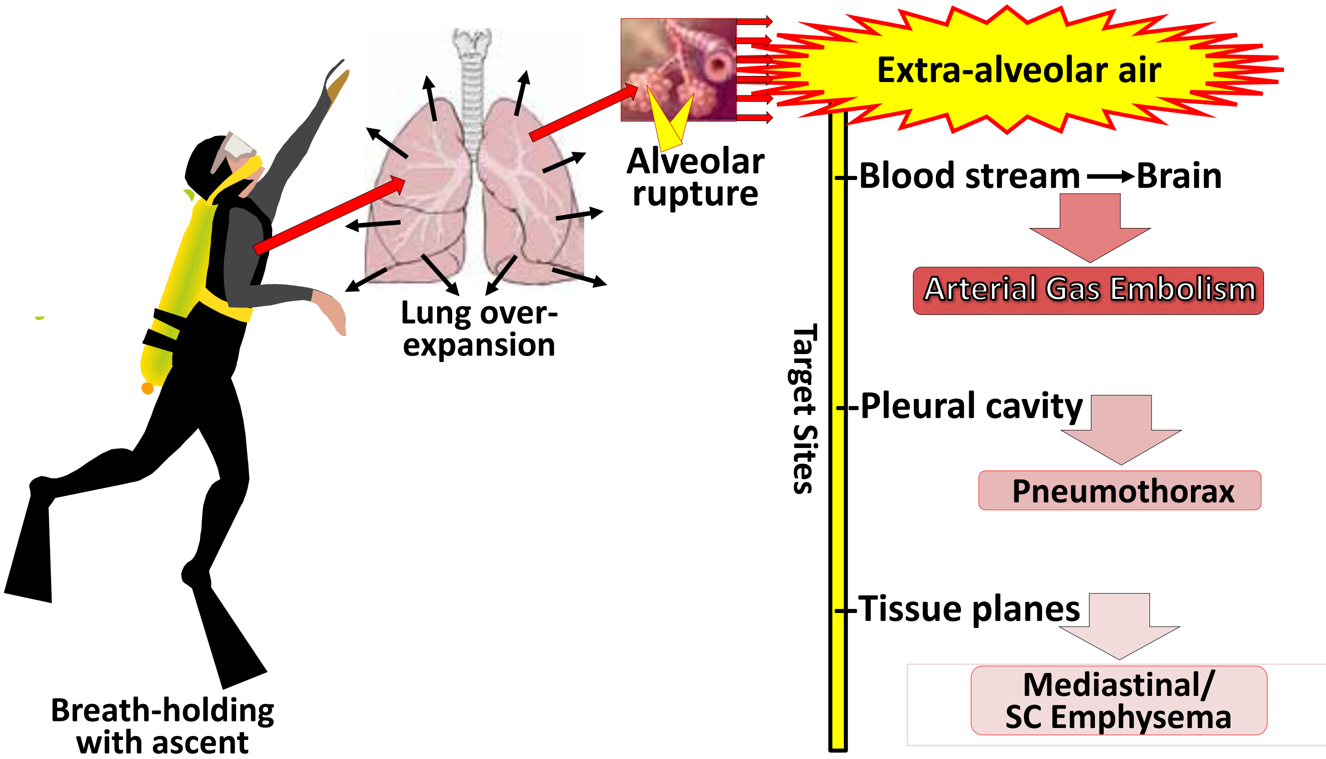
Mitigating the Stresses of Cold Water

It is interesting to note that prior to the era of using exposure suits, the commercial breath-hold diving activities in Japan and Korea (Ama divers) were performed by women. The natural selection of women was based on their increased tolerance to cold water as compared to men. The physiological explanation for this is that women have increased subcutaneous fat which acts as additional insulation from the cold water

It was observed that wet-suited Navy divers who sat nearly motionless in 40°F water for 6 hours in a simulated operational environment hardly dropped their core temperatures. However, their extremity temperatures approached that of the external water temperature as skin temperature measurements moving distally on the extremities were made. Physiology to explain this included heat conservation by minimizing blood flow (and the radiator effect of heat exchange of the extremities) to the almost motionless limbs through vasoconstriction (to reduce blood flow) and countercurrent heat exchange. In countercurrent heat exchange, the cold blood from the extremities (minimal flow secondary to vasoconstriction) allows heat in the blood flowing from the warm core to be transferred to the returning cold blood from the extremities. Conversely, with the heat exchange the blood flowing to the extremities is cold.

Conditioning as well as body habitus can also mitigate the challenges of cold water. A noteworthy example is the feat of Lynn Cox, who swam in freez-

Figure 6: Extra-Alveolar Air/Pulmonary Overpressurization Syndromes



Legend: Alveoli tolerate over-expansion poorly. Even though this tissue type has some elastic properties, overexpansion, rupture, and gas embolism can theoretically occur with breath-holding after full inspiration from a 3 foot depth. This equates to about a 10% alveolar overinflation. **SC** = Subcutaneous

Table 2: Mitigating the Effects of Cold water

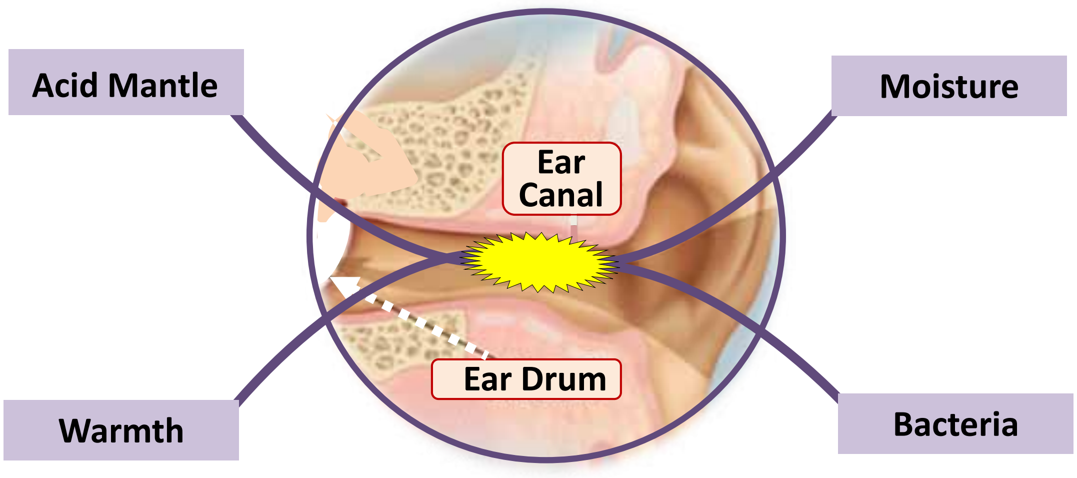
Techniques	Comments
Exposure suits --Lycra --Neoprene --Semi-dry --Dry --External heat sources (hot water, battery, chemical)	Exposure suits insulate the diver from the thermal challenges of cold water. Whereas, the Lycra suit provides 1 or 2 degrees of increased thermal comfort, dry suits and external heat sources allow divers to tolerate sub-freezing water. Chemical and battery heat sources only have a short (1 or 2 hour) duration of action. Hot water suits require tremendous logistical support and are only practical in commercial diving situations.
Monitoring breathing pattern	20% of body heat loss occurs imperceptibly through the lungs with breathing. Inhaled air must be heated to body temperature and fully saturated with moisture before it reaches the alveoli where gas exchange occurs. These two effects are magnified as one descents breathing compressed, dehumidified, ambient temperature gas. Slowing the breathing rate minimizes energy outlay as well as lessens respiratory heat and body fluid losses.
Maximizing propulsion efficiency	Vasoconstriction and counter current heat exchange are mechanisms to conserve heat. The extremities act as radiators to dissipate heat. Of course, this is undesirable in cold water. Alcohol acts as a vasodilator and increases heat loss through the radiator effect of the extremities. These heat conserving mechanisms are augmented by minimizing movements of the extremities while underwater. See text box on "Mitigating the Stresses of Cold Water."

ing Antarctic waters for 25 minutes without any thermal suit protection. Her determination, superb conditioning, and relatively high body mass index (i.e. 29 versus 21-24 for a female of equal height and weight), in addition to being female with a natural protective layer of subcutaneous fat, provide the physiological explanation for these amazing accomplishments.

Swimmer's Ear Ear canal infections (otitis externa, i.e. inflammation of the external portion of the ear) are a second consequence of an environmental stress to which divers (and swimmers) are subject. Normally the external ear canal maintains a healthy, homeostatic environment with four balanced components: Warmth, moisture, acid mantle of the ear canal lining, and bacteria (Figure 7).[4] When the environmental stresses of increased moisture from immersion and/or increased warmth from a tropical environment occur, bacteria proliferate and lead to inflammation and changes in the acid mantle. With progression, discharge (pus) develops in the ear canal. Early symptoms include itching sensations in the canal. This may progress to tenderness of the external ear structures and discharge in the ear canal. Ear canal infections are avoided by augmenting the homeostatic mechanisms that maintain ear canal health such as drying the canal with desiccating agents when moisture accumulates in the ear canal and using weak acid solutions to maintain the acid-base balance. With progression, antibiotic ear drops are used to control the bacteria flora.

Marine Animal Injuries Injuries from marine animals are another category of environmental stresses since diving as well as other aquatic activities subject the participant to encounters with these animals. The stresses imposed on the diver by these encounters can be both physical injury and psychological stress. This latter consideration will be additionally discussed in a subsequent article on psychological stress. While avoidance of encounters with marine animals is a way of eliminating these stresses, such is usually the antithesis of what divers seek. The physical injury marine animals cause can be classified into five injury types (Table 3).[5] The categories include biting injuries, stinging injuries, puncture injuries, poisonous bites, and lacerations. Each imposes specific stresses to the diver/swimmer/bather with resultant disturbances of the normal physiology of the body. For example, a stinging injury injects toxins into the skin. The body's stress response to this insult is the generation of an allergic reaction, usually local, but it can be systemic and life threatening. Much can be said about marine animal injuries, with dedicated chapters and entire books written about this fascinating subject.[6-8]

Figure 7: Maintaining Homeostasis of the External Ear Canal



Legend: Four factors interact to maintain homeostasis in the ear canal. When one or more become out of balance, ear canal problems develop. Increased warmth and moisture will foster the growth of bacteria. Desiccation will dry the canal and disrupt the acid mantle which provides an avenue for bacteria to invade the ear canal lining.

As in all homeostatic mechanisms in the body, too much or too little disrupts homeostasis. The ear responds when the stresses overwhelm the balance between the four factors above . This generates an inflammatory response with itching, pain, swelling and/or discharge.

Table 3: Injuries from Marine Animals

Injury Type	Examples	Pathology	Complications	Management
Bites, avulsions < 1% of Problems	Shark, eels, seals, etc.	**Disruption of tissues**	Bleeding, shock, tissue loss, death	Control bleeding, treat shock, repair tissue injuries
Stings ~ 20% of Problems	Jellyfish, hydra, corals, anemones	**Allergic reactions** Toxins injected with microscopic trigger devices (nematocysts)	Burning itching, welts, Shock, collapse	Inactivate with alcohol or acetic acid "Shave" off residual tentacles
Punctures ~ 20% of Problems	Sea urchins, sting rays, sculpins, cone shells, bristle worms	**Penetrating wounds** Injections of toxins and/or inflammatory proteinaceous debris	Pain, infection, granuloma formation, collapse & death	Soak in "hot" water until pain dissipates Tetanus prophylaxis Treat latent infections
Poison Bites < 1% of Problems	Sea snakes, blue ringed octopus	**Envenomations**	Muscle stiffness, myoglobinuria, respiratory arrest	Resuscitation, life support, antivenins
Miscellaneous ~60% of Problems Cuts, lacerations, rashes (shocks)	Barnacles, corals, parasites, (electric eels & rays)	**Persistent wounds & sores** (shocks)	Indolent wounds, festering sores (Arrests from shock)	Cleanse; debride persistent wounds, antibiotics (Resuscitation if arrest from shock)

Physical characteristics of the aquatic medium is the fourth environmental stress that the diver encounters. Water is approximately 775 times denser than air. This physical fact has both benefits and disadvantages for the diver. An important advantage of water's density is that it provides buoyancy. With proper control, buoyancy allows the diver to hover at any depth without any seeming effort (Figure 8). Exertion stresses arise when buoyancy is not controlled and the diver must expend energy with swimming movements to maintain depth or to ascend. A more serious concern is the total loss of buoyancy control. If too light, uncontrolled ascent may lead to lung overexpansion as discussed previously (Figure 6). If too heavy, uncontrolled descent into the abyss can lead to death. Response measures to mitigate imperfect buoyancy control include monitoring lung volumes and/or using swimming movements, though this is at the cost of increased energy expenditures.

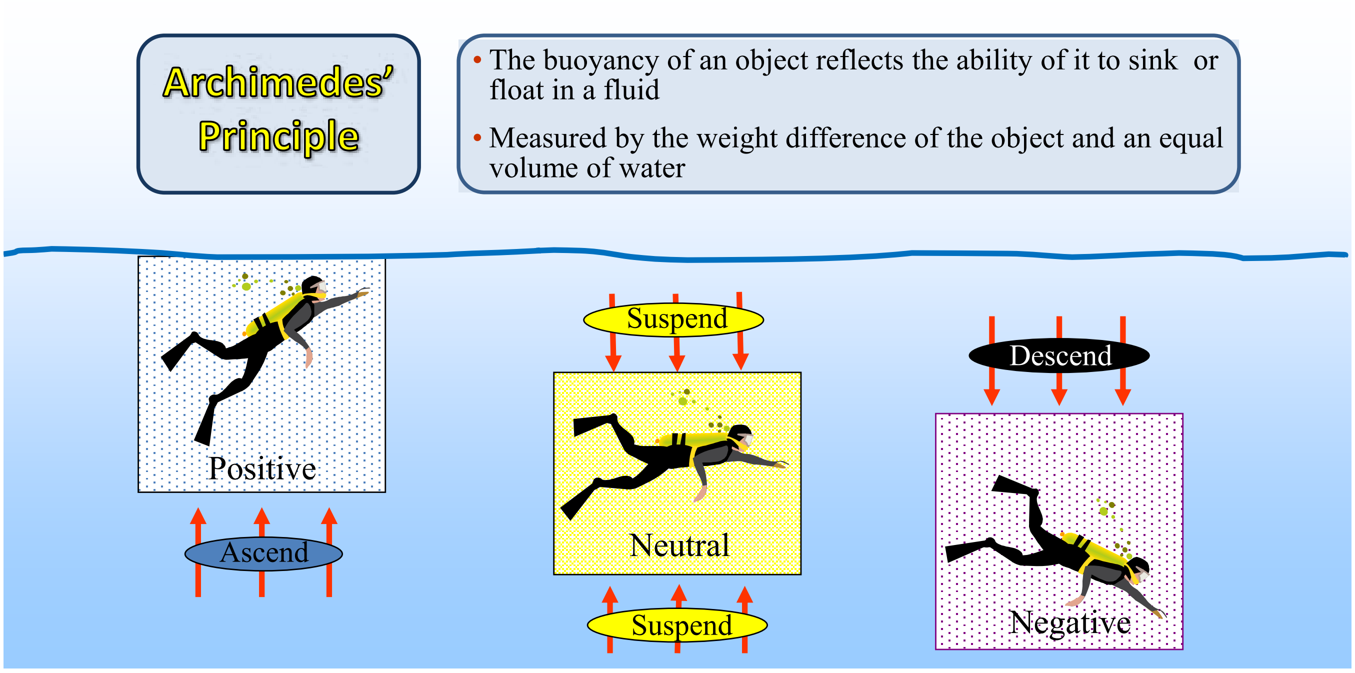
While the density of water provides buoyancy, it also interferes with movement. The reason is the viscosity or "thickness" effect of water, which causes resistance when moving though this medium (Figure 9). This stress is beneficial for the competent swimmer and lessened by the use of swimming fins, but still the ease and speed of moving through water does not approach that of moving through the terrestrial environment. Ramifications of the viscosity of water pose seven other physical challenges which

Dive Scenario: A mildly overweight SCUBA diver wearing a Lycra exposure suit did not think he needed any lead weight for buoyancy control. After a swimming descent with considerable effort, he could not maintain his depth without vigorous swimming efforts. After 20 minutes he had nearly expended the air in his SCUBA tank even though he was only at a 30 foot depth. Somewhat humiliated, he signaled to the dive guide that he was low on air and needed to surface. Meanwhile, his dive companions were able to remain submerged for the better part of the hour—and when they surfaced were concerned that something had gone wrong for the diver.

Comment: Obviously, the diver did not have neutral buoyancy control. The neoprene booties, Lycra suit, air tank, buoyancy compensator, fins, and adipose tissue all added up to giving the diver about 10 pounds of positive buoyancy. With the proper weights this diver was the last out of the water on the second dive.

Not only did the lack of buoyancy control rapidly expend the diver's air supply, but it also put him at risk for an uncontrolled ascent with possible consequences of arterial gas embolism and even decompression sickness (from failure to off gas the super-fast tissue compartments).

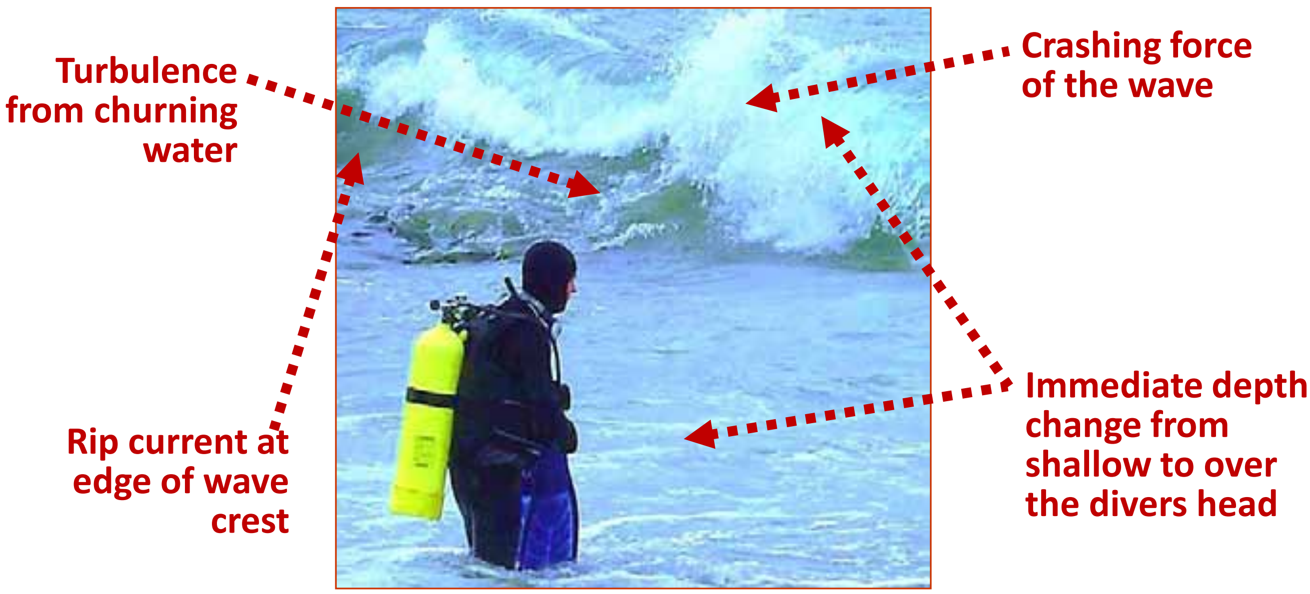
Figure 8: Buoyancy Management for Stress Reduction in Diving



Legend: Buoyancy control is often underappreciated and not fully considered as a stress reducer for divers. Archimedes' principle articulates buoyancy.

By neutralizing buoyancy, the diver does not have to expend energy to maintain position in the water through swimming movements. This reduces exertional stresses. Also, unrealized changes in depth can lead to ear barotrauma and extra-alveolar air syndromes.

Figure 9: Viscosity and Density Challenges of Water for the SCUBA Diver



Legend: A cresting wave can be a great challenge to the inexperienced diver. With water being over 700 times denser than air, even a small wave can cause enormous mechanical forces (see dive scenario).

Awareness of this information and pre-dive briefings can do much to prevent unpleasant experiences while transiting the surf zone.

Table 4: Challenges Related to the Viscosity of Water

Types	Description	Diver Challenges	Management
Current	Continuous flow of water moving in an evident direction	Exhaustion; a mild current of a knot is faster than a SCUBA diver can move through the water	Avoid with pre-dive briefings; swim diagonal to current, "ride" with the current to a safe exit point
Swell	A long often massive and crestless wave usually found beyond the surf zone	Generally not a problem for the diver while underwater Obscures line of sight vision for divers on the surface to see each other & support boats	Use of signaling devices, whistles, sausage tubes to improve visibility while on the surface
Wave	A moving ridge of water as the energy in a swell is transformed due to approaching the shallow bottom of the shore line	As the wave breaks, churning of water generates turbulence and obscures vision	Dive under the cresting wave while leaving the shore; ride with the wave when coming to shore; insure that all dive equipment is securely fastened
Tide	Periodic rising and falling of bodies of water in response to gravitational forces from the moon & sun	Tides can increase swimming efforts to get to and exit from a shore entry dive site	Pre-dive briefings should include tide information; shore dives should be scheduled for low tides
Rip Tide / Current	A strong, usually narrow surface current flowing outward from shore	Exhaustion/panic when trying to swim against the rip tide attempting to return to shore	Swim in a diagonal (or perpendicular) direction until out of the rip tide
Turbulence	Usually small areas of erratic, churning of water where currents mix or waves break	Disorientation, difficulty making swimming progress	Pre-dive briefing to avoid; Try to "ride out" of

include current, swells, waves, surge, tides, rip tides, and turbulence (Table 4). The responses to these stresses are both volitional and reflexive. Buoyancy control and swimming out of the danger zone are awareness actions made to meet these stresses, while increased heart and breathing rate to meet the exertion requirements are unconscious responses. Overwhelming exertion responses from the ramifications of the viscosity of water can lead to fatal outcomes from heart attack or drowning.

Dive Scenario: A petite female diver was making her first open water SCUBA dive entry. While wading out in waist deep water a wave crested over her. This lifted her off the bottom and disrupted the seal on her diving mask, filling it with water. She immediately began to struggle and yelled for help. After the wave passed the dive instructor walked the diver back to the beach. She decided not to continue her SCUBA diving training.

Comment: Although the seemingly innocuous combination of cresting wave and water turbulence frightened her enough to terminate her diving training, it reflects water's density effects and also its ramifications. A briefing before entering the water could have prepared her mentally for the unanticipated event. Had the dive instructor appreciated her timidity regarding the surf zone, he could have provided support by stabilizing and/or supporting her while transitioning through the turbulent area.

Conclusions

Stresses/stimuli and their responses/reactions are inherent to all living organisms. The goal of resolving stresses is homeostasis. Almost all stresses are resolved unconsciously (through physiological mechanisms in the organism), with appropriate conscious efforts or in rare situations with life or death (i.e. fight or flight) responses. With SCUBA and breath-hold diving, the situation is no different in terms of trying to achieve homeostasis. However, the aquatic medium imposes stresses that do not have counterparts on land (e.g. ventilatory with insufficient oxygen availability) or are greatly magnified (e.g. thermal, mobility, etc.). The physical stresses including pressure-related phenomenon and environmental challenges have been described in this first of three articles discussing diving stresses. Subsequent articles will deal with the physiological and psychological stresses of diving. The goal of every diver for every dive is a safe and enjoyable experience. While stress reduction is for the most part presupposed with SCUBA and breath-hold diving, awareness, pre-dive briefings, proper equipment, and conditioning should never be disregarded with these activities (Figure 10).

Figure 10: The Goals for Every Dive

Safe, Enjoyable Stress Reduction

Legend: Stress reduction is one of the essentials for sports diving. Three cardinal requirements are needed to make it is as safe and enjoyable as possible

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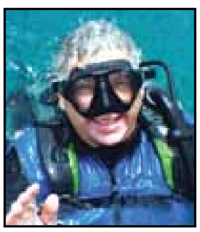

Michael B. Strauss, MD, FACS, AAOS, has had a long-standing and keen interest in diving and diving medicine. His formal training started with Navy Submarine and Diving Salvage Schools. This was followed by tours on a nuclear submarine, with salvage divers in the Philippines &Vietnam and as the undersea medical officer for Underwater Demolition & SEAL Teams in San Diego. Dr. Strauss's special interests in diving include panic & blackout, disordered decompression, the source of pain in decompression sickness, diving stresses (Part 1 in this issue), diving in older age (published in the previous edition of *WCHM*) and mammalian adaptations to diving. As Medical Director of the Long Beach [California] Memorial Medical Center Hyperbaric Medicine Program, he continues active in diving medicine having evaluated and managed nearly 500 diving medical problems, generating over 50 papers & posters on these subjects, conducting yearly worldwide diving-diving medicine programs and authoring *Diving Science*, a well-acclaimed text that describes essential physiology and medicine for divers.

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Test your Knowledge of Diving Medicine

1. Arterial gas embolism (AGE) symptoms will typically occur in a DCS case within 48 hours of surfacing.

   A. True
   B. False

2. What are the main stresses of diving?

   A. Physical
   B. Physiological
   C. Psychological
   D. None of the above
   E. All of the above

3. Which body function change is correct as one gets older?

   A. Increased cardiac output; decreased BP
   B. Improved judgment & reasoning ability
   C. Decreased metabolic rate/ weight loss
   D. Decreased ability & decreased time for injury recovery
   E. Decreased ant-post diameter of chest

4. Lungs, blood, brain and heart all equilibrate very quickly to new ambient pressures.

   A. True
   B. False

5. ______% of DCS symptoms will manifest within 48 hours of a dive.

   A. 60
   B. 100
   C. 83
   D. 98
   E. 42

Find the answers to this quiz and access to more FREE quizzes at

www.WoundEducationPartners.com/online-courses/free

Recommended Reading

For more information on diving and dive medicine we recommend the following books.

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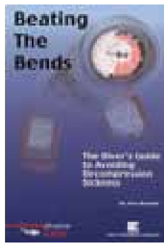
Assessment Of Diving Medical Fitness For Scuba Divers And Instructors
By Peter B. Bennett, Frans J. Cronje and Ernest S. Campbell

Basic Decompression Theory and Applications, 3rd Edition
By Bruce R. Wienke



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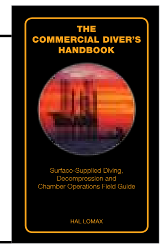

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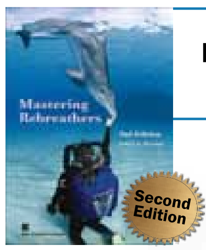

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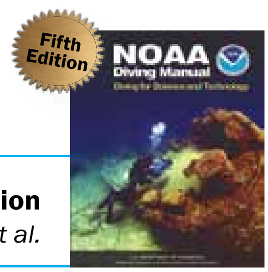

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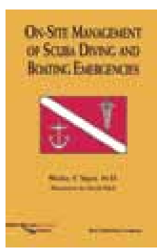

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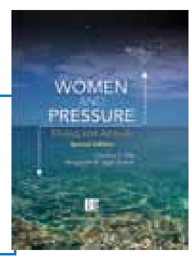

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