THE DEPTH AND GAS DILEMMA

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This paper was published in the "Conference Proceedings for the 1991 NAUI International Conference on Underwater Education" (Edited by H. Viders and F. Wells and published by the National Association of Underwater Instructors.) Today, most national recreational diver training agencies sponsor courses in extended range diving and the use of alternative gas mixtures. Physiologists and the diving now have a better understanding of human response to breathing air and various mixed gases at depth. Consequently, some information in this paper may no longer be valid. This paper is presented here as a historical informational document. It is not the author's or University's intent to promote extended range diving. This paper does identify recreational diving issues at the beginning of the 1990's. Neither the author nor the University of Michigan will accept responsibility for accidents or injuries resulting from use of the materials contained herein or the activity of diving. Please see Disclaimer on the last page of this document.

ABSTRACT

During the last decade, the recreational diving community demonstrated a renewed interest in deep scuba diving. In spite of instructional agency decree, increasing numbers of divers are answering the call of the deep. Mixtures of helium, nitrogen, and oxygen were used to extend scuba diving depth beyond 800 feet. This paper explores individual motivations, physiological responses, and diver responsibility associated with diving to depths beyond 130 feet. Human nature inspires individuals to explore the unknown and achieve the impossible. The diver has the right to confront the environmental, physiological, and psychological limits of depth. Unfortunately, today's educational programs do not address the true nature and limiting factors of breathing gases at high pressures. Although most recreational divers learn of nitrogen narcosis during deep diving specialty training, the potential problems associated with carbon dioxide and oxygen are seldom addressed. The roles of nitrogen-carbon dioxide synergism and elevated partial pressure of oxygen pose potential risks in deep air diving. Individuals who choose to challenge the depths of our aquatic environment and extend beyond conventional limits must recognize their responsibilities to families, friends, and themselves.

HISTORICAL REVIEW

In the late 1940s and early 1950s, a few recreational scuba divers breathed oxygen from closed-circuit scuba. However, by the mid-50s, Cousteau's compressed air Aqua Lung emerged as the dominate form of recreational scuba and compressed air was the breathing gas of choice. Breathing gases such as 100% oxygen and mixtures of nitrogen-oxygen (nitrox), helium-oxygen (heliox), helium-nitrogen-oxygen (trimix), hydrogen-oxygen (hydrox), and hydrogen-helium-oxygen (hydreliox) were reserved for military and commercial divers.

Depth has been an allurement since humans first ventured into the underwater world. Soon after development of the first modern Aqua Lung, Frederic Dumas in 1943, dived to 203 feet breathing compressed air. In 1947, Cousteau's team (formed in 1943) made experimental compressed air scuba dives to 297 feet [12].

In recent years, Andrea Doria dives have become popular. As I recall, it was July of 1956, when Peter Gimbel and Dumas made the first dive to the sunken luxury liner. Two weeks later, Ramsey Parks (LA County Lifeguard), Earl Murray (a Scripps geologist), Bob Dill (geologist at the Naval Electronics Laboratory in San Diego), and Peter filmed the sunken vessel for Life Magazine. These pioneer scuba divers used compressed air scuba at a depth of about 240 feet for these dives.

In 1967, Hal Watts (personal communication) made a record compressed air scuba dive to 390 fsw, and in 1968, one of his associates reached 437 feet. More recently (1989), Brent Gilliam completed a series of air dives in excess of 300 feet with an unofficial record dive to 452 feet (personal communication). In Lake Superior, 19 divers have dived to a particular shipwreck at a depth of approximately 250 feet. Apparently, two have died while diving on that wreck and two of the others while diving on other deep shipwrecks. The popular appeal and machismo associated with such deep dives tends to lure unsuspecting novice divers to depths beyond the capacity of their equipment, knowledge, skill, and physiology.

Today, recreational diving instructional agencies recognize 130 fsw as the maximum depth of compressed air scuba diving, and some recommend a limit of 100 fsw. In reality, recreational scuba divers, especially shipwreck and cave divers, often exceed these limits. Deep air diving has become quite fashionable in the recreational diving community. Published and unpublished accounts of recreational dives using compressed air scuba to depths of 200 to 300 fsw are not uncommon. Many recreational divers, including prominent certification agency instructor trainers, openly exceed the limits specified for recreational scuba diving. Unfortunately, they also get hurt. For example, during a five-day period in August of 1989, three Great Lakes shipwreck divers experienced decompression sickness, one experienced severe air embolism and decompression sickness, and one diver died. All were using compressed air scuba at depths of 190 to 250 feet.

In 1937, Max Gene Nohl dived to 420 feet in Lake Michigan using a self-contained helmet diving system and a mixture of helium and oxygen under the direction of Dr. Edgar End of Marquette University. The U.S. Navy conducted experimental dives to 500 feet in a chamber at the Experimental Diving Unit in Washington, D.C. The U.S. Navy conducted the first deep, operational heliox dives to a depth of 240 feet in 1938 during the rescue and salvage of the Squalus. Bollard of the Royal Navy completed a helmet dive to a depth of 540 feet breathing helium-oxygen in 1948. In 1954, Jean Clarke-Samazan made a 350 foot helium-oxygen scuba dive [12].

By the late 1950s, heliox had caught the attention of an expanding commercial diving industry [24]. In 1962, Dan Wilson dived to 420 feet, and in 1967 Ni,c Zinkowski made a record dive in the Gulf of Mexico to 600 feet. The first commercial saturation diving job was conducted in the summer of 1965 (Smith Mountain Dam), and heliox saturation diving soon emerged as the dominate mode of deep diving. As commercial divers pushed beyond depths of 1,000 feet, they encountered new physiological problems -- high-pressure nervous syndrome (HPNS) and articular joint pain. In the mid1980s Comex divers (French) successfully used hydrox during chamber dives to 520 meters to overcome HPNS and breathing resistance problems. In 1988 Comex divers saturated at 500 meters on hydreliox dove to 531 meters (1742 feet) for 4-hour works shifts in the open sea [9].

The use of nitrogen-oxygen breathing mixtures [18] (other than compressed air) was recognized as early as 1943 and was used by the U.S. Navy with semi-closed circuit scuba beginning in the later 1950s. Nitrox diving was introduced to the scientific diving community in the early 1970s and is currently used for operational diving by several research groups. Nitrox was introduced to the recreational diving community in the mid-1980s and is currently gaining popularity. However, to my knowledge, only one major recreational diving training agency has embraced the concept. Nitrox is advantageous in extending no-decompression dive time in the depth range of 40 to 130 feet, however, it is not intended as a deep diving gas mixture.

Mixtures of helium-nitrogen-oxygen (trimix) have been used to varying degrees in commercial diving since the 1960s. However, it wasn't until the 1980s that adventurous recreational divers began serious experimentation with trimix. Deeper diving with gases other than compressed air has always been limited by the volume of gas that a self-contained diver can carry, facilities for lengthy decompression, and the availability of safe dive tables. The gas volume problem has been addressed by over-pressurizing scuba cylinders, multiple-cylinder scuba, staging techniques, and oxygen supplied from the surface for decompression. Bill Hamilton pioneered an effort to design special trimix dive tables for the recreational diving community. In 1988 Sheck Exley used staging techniques and Hamilton's trimix tables in his record dive to 780 feet [11].

The cave and wreck diving communities have always maintained the "cutting edge" of advancement in recreational diving technique and technology. While the major recreational diving training agencies have been terrified and manipulated by the Great American Lawsuit Society, these communities have established their own standards. The national training agencies currently advocate no-decompression diving only, air diving only, open-circuit scuba only, and a depth limit of 130 feet (more ideally 100 feet). The recreational diving equipment manufacturers promote color coordinated diving equipment, high-tech regulators, and dive computers (some designed for air dives to 300 feet or deeper). The cave and wreck diving communities have embraced compressed air diving depths commonly exceeding 200 feet, trimix diving to approximately 800 feet, decompression diving, closed-circuit scuba, and a host of other advances in diving technology and techniques.

Today, we stand on the threshold of modern, deep, recreational diving. The commercial diving community was there in the early 1960s. Using diving bells, deck chambers, umbilical-supplied recirculating breathing equipment, active thermal protection, mixed-gases, and millions of dollars, they have extended their in-water diver working capability to nearly 2,000 feet. However, as they extended their depth, they recognized major logistical, economical, and physiological limitations. Today, almost 30 years later, atmospheric diving systems (ADS) and remotely-operated vehicles (ROV) with force-feedback manipulators enable commercial divers to perform safe and productive work at great depths. Where will the recreational diving community be in 2020 AD?

DEEP DIVING PHYSIOLOGY: A BRIEF REVIEW

To remain underwater, humans must don a breathing apparatus and carry a supply of the atmosphere to depth with them. The air is fed to the diver through a series of valves and tubes which offer some resistance to air flow. As the diver descends deeper into the ocean the air, which must be breathed at ambient pressure, becomes denser. The diver must now work harder to breathe. Increased quantities of carbon dioxide are produced and retained by the body.

As the diver descends deeper and deeper, the gases -- nitrogen and oxygen -- begin to affect the central nervous system. Soon the nitrogen becomes intoxicating and at greater depths the oxygen -- so essential to sustaining life -- becomes toxic.

The brief review of diving physiology given below addresses only those conditions specific to breathing gases (primarily compressed air) at deep depths and is not intended as a comprehensive discussion. Physiological conditions such as barotrauma, breathing gas contamination, and thermal stress are not addressed.

Inert Gas Narcosis

Among the major factors most likely to cause performance impairment in divers at increased ambient pressures is inert gas narcosis. Although the most common inert gas (nitrogen) associated with diving is physiologically inert under normal conditions, it has distinct anesthetic properties when the partial pressure is sufficiently high. The problem of compressed air intoxication has long been recognized by divers and researchers. Early researchers' inference was based on the hypothesis that narcotic potency is related to the affinity of an anesthetic for lipid or fat or the Meyer-Overton hypothesis [5].

In fact, the narcotic potency of inert gases may be related to many physical constants including molecular weight, absorption coefficients, thermodynamic activity, Van der Waal's constant, and the formation of clathrates. Lipid solubility appears to give the best correlation, although polarization and molar volume are also important to the mechanism of narcosis which involves interaction of the molecule with neuronal membrane. Consequently, the molecule size and the degree of electrical charge upon it are important considerations [6].

Many theories of compressed air intoxication were advanced by various early investigators. Damant attributed part of the intoxicating effects to the increased oxygen pressure [10]. Bean, a University of Michigan physiologist, expressed doubt that nitrogen was the responsible agent. He contended that the sole causative factor is a rise in body CO_2 tension brought about by raised gas density [2]. Manifestations of anxiety and claustrophobia, a combination of all of the aforementioned factors, or the pressure itself have also been suggested as causes [13]. However, encephalographic studies by Bennett and Glass leave little doubt that high nitrogen pressure constitutes an important causative factor of compressed air narcosis [5]. Associated causes may include the density and oxygen partial pressure of the respired mixture which in turn, may cause an increased carbon dioxide tension that synergistically potentates the narcosis [3].

Several predisposing factors may advance the onset of symptoms and ameliorating factors may help to increase the tolerance to nitrogen narcosis. Alcohol, marijuana, and social drugs taken prior to diving greatly enhance the nitrogen effect. Alcohol and nitrogen become almost additive. Rapid compression will also facilitate the onset of narcosis. Hard work and fatigue will increase susceptibility as will any circumstance causing retention of carbon dioxide.

Acclimatization may also play a role in nitrogen tolerance [13]. Studies have shown that the mean additional time to solve mathematical problems at elevated pressures is reduced by 5 to 10 percent in acclimatized divers compared to non-acclimatized divers. Acclimatization is accomplished by frequent and progressive exposures to higher pressures. Unfortunately, the acclimatization effect probably diminishes in about a week.

Oxygen Toxicity

The toxic effects of excess oxygen breathing are of considerable importance in diving and hyperbaric treatment of diving accidents. The administration of 100% oxygen to humans continuously for long periods (generally exceeding 24 hours) at normal atmospheric pressure causes pulmonary manifestations. Under pressures slightly above 1.0 atmosphere for a sufficiently long time or at sufficiently high pressures (2.5 ata), humans develop central nervous system oxygen toxicity which can eventually lead to grand mal seizures.

Oxygen toxicity is a function of pressure and duration. The safe period of oxygen inhalation is further reduced by immersion, exercise, and carbon dioxide inhalation. High pressure oxygen poisoning affecting the brain and causing convulsions can definitely occur at pO_2 of 2.0 ata and sometimes even lower. Central nervous system oxygen toxicity has been identified as the causative factor in an incident in which a diver convulsed at a depth of about 225 feet while breathing compressed air (D. Rutkowski, personal communication). This has led some individuals to suggest that the limit for compressed air dives of any type should be less than 218 feet (1.6 ata pO_2). Some physiologists consider oxygen toxicity to be a greater threat to compressed air divers at depths exceeding 200 feet than nitrogen narcosis.

Pure oxygen has been breathed during decompression since the 1950s to either shorten decompression or reduce decompression sickness risk. There are "stories" of divers developing symptoms of oxygen toxicity during decompression using scuba and apparently, at least one death has occurred. Oxygen decompression appears to be increasing in popularity among cave and wreck divers. There is certainly some potential risk of oxygen toxicity, especially at deeper stops, in oxygen sensitive individuals, and in individuals who have experienced exceptionally high doses of oxygen during extended exposures at depth.

Oxygen tolerance varies with individual divers and may also vary from day to day. Exercise while breathing oxygen increases susceptibility to oxygen toxicity. The Navy administers an oxygen tolerance test which requires breathing pure oxygen for 30 min. at 60 ft in a dry chamber. The US Navy recommends a 25-ft (1.6 ata) depth limit for a duration not exceeding 75 minutes [22]. Scientific divers breathing mixtures of nitrogen and oxygen currently use a 1.6 ata/30 minute limit [18].

Carbon Dioxide Retention

Conditions which enhance the retention of CO_2 in the body include unusual exertion, inadequate ventilation, high oxygen tensions, increased density of breathing medium, and inadequate gas supply to ventilate the breathing system and remove carbon dioxide; this is extremely important under conditions of heavy exertion. Increased alveolar oxygen pressure affects the carbon dioxide response. Increased breathing resistance, due to apparatus design or gas density favors CO_2 retention and, therefore, decreases sensitivity to CO_2. Increased breathing resistance causes pCO_2 and exertion levels to rise in parallel, whereas ventilation response remains constant or even decreases.

If divers do not ventilate their lungs sufficiently to eliminate as much CO_2 as is produced, self-poisoning can occur. A number of accidents in which the diver has lost consciousness for no apparent reason have been explained on this basis. Deliberate reduction in breathing rate to conserve air in the use of open-circuit scuba is an extremely dangerous practice. Most authorities consider it better to breathe normally and consume more air than to practice periods of breath-holding between inspirations and risk the lethal consequences of CO_2 buildup.

Alteration of breathing pattern and reduction in breathing rate is some what normal for experienced divers at low exertion levels. It has become quite fashionable to breath lightly and conserve air. Many instructors and guides encourage air conservation techniques. In addition, deep divers use air conservation breathing techniques to increase dive time at depth with a limited air supply.

Some divers use a technique called skip-breathing. The diver draws a full breath and simply holds that breath for 20 to 30 seconds or more, exhales, draws another breath, and repeats the process. This pattern of breathing can lead to significant carbon dioxide retention. If the process is carried to extremes, the diver can lose consciousness without prior respiratory warning from carbon dioxide poisoning. The term "shallow water blackout" has also been used to identify this condition. Needless to say, skip-breathing is discouraged.

Unfortunately, there is a fine line between acceptable air conservation techniques and skip-breathing. I certainly endorse techniques for efficient use of air supply; however, I discourage competitiveness and peer pressure techniques used to promote air supply conservation. Some individuals are more physiologically efficient and others will tolerate a slightly higher level of carbon dioxide without adversity.

Breathing Resistance

Resistance to turbulent flow of air or other gas mixtures within the bronchopulmonary system is proportional to the square root of the gas density. At great depth, work capacity is more directly determined by the effectiveness of pulmonary ventilation. The factor tending to limit complete ventilation at depth is that the density of the breathing gas mixture causes increased resistance to gas movement. One advantage of substituting helium and hydrogen for nitrogen is reduction in gas density. For example, the density of a helium-oxygen breathing mixture at 1,000 feet is about 4.3 times that of air at the surface or about the same as breathing air at a depth of 110 feet.

Early studies demonstrated that divers equipped with scuba and breathing nitrogen-oxygen during exercise were impaired by a reduced ventilatory response. Divers whose pulmonary ventilation in response to exercise is inadequate for carbon dioxide elimination are more susceptible to carbon dioxide poisoning and oxygen toxicity. Furthermore, divers in poor physical condition produce significantly more carbon dioxide that divers in good physical condition.

Nitrogen-Carbon Dioxide Synergism

Nitrogen-carbon dioxide synergism is seldom addressed in the discussion of nitrogen narcosis; however, in recreational diving it may be an important factor. Synergism involves the combined action of two separate agents having a greater total effect than the sum of their individual effects if used separately. Recreational scuba divers encounter several factors that may influence carbon dioxide retention. First, some divers are less than physically fit. Poorly conditioned individuals produce and retain more carbon dioxide than highly conditioned individuals. Recreational scuba divers carry a limited amount of air and thus practice controlled breathing techniques. Improper breathing can result in carbon dioxide retention. The density of air increases significantly with depth. Normal breathing resistance afforded by the scuba, as well as potentially less than adequate pulmonary ventilation caused by higher density air, can lead to increased carbon dioxide retention. Finally, increased oxygen partial pressure also apparently enhances carbon dioxide retention.

Depth Blackout

Cave diving researchers have documented cases of depth blackout [13]. The victims simply appears to fall asleep with their eyes open and does not move except for breathing. For unknown reasons the sleeping victim apparently retains the scuba mouthpiece and continues to breath, lying inert on the bottom until their air supply is exhausted. Cases of 15 survivors (rescued by other divers) were analyzed. In all cases, the incident of blackout occurred on the individual's deepest dive to that time, and the shallowest occurrence involved heavy exertion prior to blackout. Victims do not recall any symptoms prior to blackout. Authorities suspect that this condition results from a cumulative and combined effect of nitrogen, oxygen, and carbon dioxide.

Decompression Sickness

The term decompression sickness refers to the signs, symptoms, and basic underlying pathological processes caused by rapid reduction in ambient pressure (i.e., ascending from a dive). The basic underlying pathological process in decompression sickness is the local formation of bubbles in body tissue, both intravascular and extravascular. The resulting symptoms vary widely in nature and intensity depending on the location and magnitude of bubble formation. When the diver is breathing air, the primary constituent of these bubbles is nitrogen with a small fraction of carbon dioxide.

To understand the basic causes of the bubble formation phenomenon, it is necessary to examine what happens to air when breathed under increased ambient pressure. In accordance with the laws of physics the govern gas absorption, the amount of a given gas that will dissolve in a given liquid is determined by the percentage of that gas in the total mixture, the ambient pressure, and the solubility coefficient of the given gas. When the pressure of the gas mixture is increased, a pressure gradient exists between the tensions of the dissolved and undissolved phases of the gas. This gradient drives each gas into solution in proportion to its partial pressure until an equilibrium is established between the dissolved and undissolved phases of the gas. If the ambient pressure is then decreased, the tension of the gas in the dissolved phase exceeds that of the gas phase, and the pressure gradient is reversed. The factor of time for equilibrium to be established in either direction is a principal factor in the discussion of decompression sickness.

Nitrogen is the only principal component of air that is inert; it therefore is unaltered in the respiratory process and, for all practical purposes, quantitatively obeys purely physical laws. Consequently, at gaseous equilibrium, the partial pressure values of nitrogen in the alveolar air, venous and arterial blood, and body tissues are identical. Oxygen and carbon dioxide are actively functional in the metabolic processes and under ordinary diving circumstances, the metabolic cushion renders the tissue tensions of these two gases of little significance in the mechanism of bubble formation.

Nitrogen will not dissolve in all body tissue at the same rate or in the same amount. This is because nitrogen is transported from the alveoli to the tissue in solution by the blood. Consequently, tissues rich in blood supply will equilibrate at a faster rate than those having more limited circulation. Nitrogen is approximately five times more soluble in fat than in water; tissues high in lipid content (e.g., spinal cord, bone marrow, and fat deposits) must take up a proportionately greater amount of nitrogen before saturation (equilibrium) is reached. When the pressure gradient is reversed, the slowest tissues to release all extra nitrogen will again be those with limited circulation or high lipid content.

From the diver's point of view, the degree of tissue saturation and, consequently, the amount of time required for tissue desaturation (subsequent decompression time) is dependent upon the depth or pressure of the dive and the amount of time at depth. Unfortunately, individual physiological variables also influence tissue saturation and desaturation.

Bubbles tend to form in any tissues that are saturated with nitrogen whenever the ambient pressure is reduced to a point where a steep pressure gradient is driving the gas out of solution. Haldane first postulated that when the tissue partial pressure of nitrogen is more than twice that of the ambient partial pressure of nitrogen, symptom-producing bubble formation will occur [14]. Once this 2:1 threshold pressure gradient is exceeded, the number and size of symptom-producing bubbles formed will be directly proportional to the magnitude of the disparity between these two partial pressures. Under these conditions the rate of diffusion of gas from the tissues into the expired air, via the blood and alveolar membrane is too slow to cope with the volume of nitrogen evolved. Hence, the nitrogen comes out of a solution locally in the tissue in the form of bubbles.

Spencer demonstrated that bubbles can be detected in the venous circulation using the Doppler bubble detector without giving rise to symptomatic manifestations of decompression sickness [20]. Bateman had previously suggested that some degree of bubble formation probably occurs whenever the tissue partial pressure of nitrogen even moderately exceeds that of the surrounding atmosphere [1].

The above discussion would lead one to believe that internal gas bubbles is the principal factor in decompression sickness. These tiny bubbles are just one factor, possibly the initiating one, in the development of decompression sickness. Numerous changes in blood including clumping of red cells, rouleau formation, shunting of blood in small vessels, and decreased platelet count have been noted following decompression. Hemoconcentrations or fluid shifts and blood chemistry changes also occur. Numerous biologically active substances associated with stress have been observed in the blood of decompression sickness victims.

Obesity, physiological aging, excessive physical exertion during the dive, pre-dive physical condition, alcohol consumption, dehydration, and poor general physical condition are factors that may predispose an individual diver to decompression sickness . As previously pointed out, fatty tissues constitute a large nitrogen reservoir due to the 5:1 oil-water solubility ratio. During a deep or lengthy dive a considerable amount of nitrogen is dissolved in the body tissues. Obviously, if the diver is obese, during ascent the blood -- essentially a watery tissue -- will not be capable of transporting in solution the increased volume of gas evolved from the excess fatty tissues. Consequently, the blood will supersaturate and lead to intravascular bubble formation on the capillary level. This will result in subsequent supersaturation and extravascular bubble formation in blocked tissue. Aging introduces an increasing proportion of tissue with sluggish circulation and, therefore, the increased possibility of local bubble formation.

Excessive physical exertion increases the respiration rate and the rate of circulation of the total blood volume. Consequently, during excess exertion under pressure, larger amounts of nitrogen are transported to the tissue per unit of time than normally. Consider the circumstances where a diver is working hard underwater, e.g., moving heavy objects, swimming against a strong current, etc. This diver's tissues may absorb excessive nitrogen equivalent to 10-20 min. of extra diving time under normal conditions, and even if the diver is on a no-decompression dive schedule, he/she may suffer decompression sickness when surfacing without decompression stops. Poor physical condition is a direct extension of the above situation.

It has also been demonstrated that forceful movement of muscles and joints under increased ambient pressure results in an increase in bubble formation at those sites during decompression. Excessive carbon dioxide buildup in tissue has also been empirically and experimentally observed to lower the threshold for bubble formation during ascent. Scuba divers commonly use various methods (e.g., skip-breathing or controlled breathing) to lower air utilization and increase dive time. These practices can result in excessive carbon dioxide retention in tissue and could possibly be a factor predisposing a diver to decompression sickness.

Negative pressure breathing (as when using scuba), the effect of immersion, and trigeminal stimulation all trigger diuresis. This loss of fluid from the body via diuresis, combined with fluid loss associated with breathing dry air, causes a degree of dehydration which may well reduce the efficiency of the circulatory system. Reduced circulatory efficiency may in turn modify the normal nitrogen absorption/elimination functions and contribute to the formation of extravascular bubbles (i.e., decompression sickness). Consequently, it is possible that drinking large quantities of liquid (such as fruit juice and water) prior to and between dives could be significant in avoiding decompression sickness.

Most divers do not realize how important it is to avoid drinking alcoholic beverages before and between dives. The immediate apparent effects such as mental disorientation, impaired physical coordination, vertigo, poor judgment, and general physical weakness are serious enough in themselves to disqualify the diver. However, it is also an established medical fact that alcohol produces a diuretic effect thereby causing a dehydration of the body. This results in blood thickening and reduced circulatory efficiency which could contribute to the onset of decompression sickness. It is recommended that the diver refrain from alcohol before and, in the opinion of some physiologist, for a reasonable period of time after diving.

Although specific time periods between alcohol consumption and diving are not clearly defined in the literature, some authorities suggest that the diver should refrain for 12 to 24 hours prior to the dive. Consumption of small quantities such as wine or beer with dinner the evening prior to diving is a matter of individual discretion. However, those consuming large quantities of alcohol and exhibiting signs of intoxication are at a much greater risk of decompression sickness and should refrain from diving for at least 24 hours. Persons exhibiting signs of after effects of intoxication (hangovers) should not be permitted to dive.

Needless to say, these modifying factors cannot be overlooked in operational diving. If all of these factors were accounted for in standard dive tables, the tables would be impractical for normal diving and divers. Consequently, the discretion of the diving supervisor and the individual diver must be relied upon to take these factors into account when planning the dive schedule.

Dysbaric Osteonecrosis

Dysbaric osteonecrosis (aseptic bone necrosis or avascular necrosis) refers to destructive sclerotic and cystic changes in bone which are not infectious in origin. It may occur in association with a variety of conditions such as chronic alcoholism, pancreatitis, sickle cell anemia, and ailments stemming from pressurization and depressurization. Historically, dysbaric osteonecrosis has been known as caisson disease of the bone because it was diagnosed early in this century among compressed air tunnel workers. The condition was first described in a diver in 1941 [3].

Dysbaric osteonecrosis is characterized by lesions in long bones such as the femur or humerus. As long as the lesions are confined to the shaft, they appear to be of limited consequence [16]. However, if the lesions develop in sites adjacent to the joint surfaces of the hip or shoulder (juxta-articular lesions), the consequences can be very serious. Areas of dead bone and marrow (infarct) in these sites can result in buckling of the cartilage around the area infarcted or loss of the subchondral plate over the area of infarct. In the latter case, fragments of bone grind into the cartilage during movements of the point. Continued fragmentation or crumbling of the bone can grind away large portions of the joint. Eventually, the weight bearing joint fractures and collapses. Disruption of the bearing surface or collapse of the dead bone can lead to secondary conditions of incapacitating arthritis. Other types of bone lesions are also associated with dysbaric osteonecrosis [3].

The exact etiology of dysbaric osteonecrosis (bone necrosis) remains to be unequivocally demonstrated. There is general agreement that dead bone and marrow are the result of gas absorption and release from tissue. However, there is no agreement about how gas absorption or release results in dead bone and marrow. Beckett summarized the major hypothesis [3]. Various investigators have suggested that gas bubbles from anywhere in the body can lead to obstruction of the small blood vessels of bone tissue. Others state that these gas bubbles can damage the lining of small blood vessels and cause chemical alterations that produce clots in the vessels of the bone. An alternate hypothesis is that fat cells which break up upon release of gas anywhere in the body can lead to fat emboli in the small blood vessels in the bone. Some researchers suggest that expanding gas within the cells expands the fat cells to the point where circulation is inhibited.

It has also been suggested that complications may arise from excessive compression rates rather than decompression. The compression phase causes an increase in the osmotic pressure of the blood. In response to a pressure gradient between blood and bone tissue, plasma water is shifted from the blood vessels into the spaces of the bone, thus restricting the bone blood flow. Some investigators feel that there is a correlation between dysbaric osteonecrosis and the number of compression and decompression phases while others have related it to elevated oxygen pressure [15]. None of the above hypotheses appears to be entirely satisfactory.

Dysbaric osteonecrosis has apparently resulted from as little as a single decompression exposure. In tunnel workers, the lowest pressure associated with the disease is 17 psig or equivalent of 39 fsw [16]. Survey radiographic examination is the primary method of detecting dysbaric osteonecrosis [3].

Published data from approximately 3,800 professional divers throughout the world show that about 800 had radiological evidence of significant skeletal lesions. Navy divers using standard tables appear to exhibit the lowest incidence of lesions (2.3%). Commercial divers have reported incidence in the range of 3 to 33%. Divers in Japan using traditional techniques have incidence of osteonecrosis reportedly as high as 40 to 75% [3]. There appears to be no survey data available on the recreational diving population.

Until the etiology of dysbaric osteonecrosis is clearly defined, it is difficult to establish preventive measures. At present, the population of divers at risk appears to include all those diving to a depth in excess of 33 fsw. The apparent predisposing factors include obesity, age, prior decompression sickness, and the number, depth, and duration of dives. In other words, a higher element of risk appears to exist for those participating in large numbers of dives, to greater depths, for longer durations. The incidence is probably greatest among saturation divers. Until this condition is better understood, divers must also assume that there is a relationship between osteonecrosis and inadequate decompression and/or decompression sickness.

Dysbaric osteonecrosis has, to my knowledge, not been described in recreational divers and the topic is seldom mentioned in a recreational diving training program. However, as recreational divers become more aggressive -- diving deeper and longer and bending more frequently -- they are predisposing themselves to this condition. Furthermore, as the number of aging deep divers increases, the likelihood of bone necrosis appearing in this population increases. Scientific saturation divers are also at higher risk of bone necrosis. I feel that every diver should be aware of the potential risks that they are taking -- even the minor risks.

Treatment of dysbaric osteonecrosis is an important consideration in commercial diving and saturation diving. As recreational divers extend their depth and dive durations to near saturation levels and experiment with new dive tables, dysbaric osteonecrosis may also appear in that population. For additional information, the reader is encouraged to consult the medical and references list at the end of this discussion [3, 4, 6, 9, 10, 16].

Other Physiological Considerations

As recreational divers venture to deeper and deeper depths, they will invariably encounter problems associated with thermal stress. The high thermal conductivity of helium (approximately 6 times that of air) draws heat away from the diver at a great rate. At 600 feet, a diver may lose more heat through respiratory heat loss than the body can generate even with exercise and active thermal protection. With a cold breathing gas (approximately equal to ambient water temperature), the diver can suffer from respiratory distress in the form of incapacitating shivering, chest pain, nasal and tracheo-bronchial secretions, and difficult and labored breathing.

As divers exceed 1,000 feet breathing heilox or trimix, they may experience articular pain during descent or after arrival at depth. This is frequently associated with rapid compression (descent). High-pressure nervous syndrome (HPNS) can seriously impair a heliox diver beyond 1,500 foot depths. Muscular temors, dizziness, decreased alertness, a desire to sleep, and electroencephalograph (EEG) changes have been noted. The onset of HPNS has been reduced or eliminated by slowing compression rates and breathing hydrogen-helium-oxygen. Reports of recreational divers having experienced significant temporary physical and mental impairment when switching from air to trimix have also been noted.

THE RIGHT TO *DIvE*!

Where do we go from here? Do recreational divers have the right to dive as deep as they wish? If so, why is there so much dialogue on this topic? Why do some authorities in diving stand so firmly opposed to deep diving? Why do major recreational diving training agencies recommend that all recreational scuba diving be limited to depths of 130 feet? Are deep recreational divers breaking the law? Do we endorse or condemn deep diving? Do we take measures to protect divers from themselves through legislation?

In America, we believe in individual rights. A criminal is assumed to be innocent until proven guilty. For the most part, we are a society of self-determination. In essence, an American citizen has the right to do almost anything that he/she wishes as long as it does not transcend the laws and legislative acts addressing the common good of society.

To my knowledge, there are no laws that govern the depth of recreational diving. There is a commonly accepted standard of the community that is recognized by major recreational diving training agencies. A review of literature distributed by recreational diver training agencies leaves little or no doubt regarding their position. On the other hand, recreational divers do knowingly and wantonly exceed a depth of 130 feet every day of the year in waters ranging from the warm, clear Caribbean to the dark, cold Great Lakes.

Legally, in America, it is my opinion that recreational divers have a right to dive as deep as they wish. Participants in other recreational activities such as rock climbing, skiing, and mountaineering appear to have the right to extend the limits of their sport to and beyond those considered prudent by most of society. Their accomplishments are deemed spectacular to say the least. In 1980 Reinhold Messner ascended to the summit of Mt. Everest without using supplemental oxygen and alone. Did he break a law? No! Did he violate a standard of the climbing community? Some might say "yes," others would say "no!" In mountaineering, the standard of the community is often viewed as, "to challenge the limits of human endurance and capability!"

In the diving community, we tend to ridicule a recreational diver who dives to 250 feet using compressed air scuba. This exceeds both the physiological and technical limits that most authorities regard proper for compressed air scuba diving. Therefore, the recreational diver is insane, brain-dead, or stupid.

Mountain climbers die each year in an attempt to defy nature and extend their personal limits. Their deaths are mourned by family and fellow mountaineers. To some, they are heroes. Monuments are erected on mountain sides to their memories. I doubt that a monument has ever been placed on a seashore to commemorate a recreational diver who lost his life during a deep dive.

For the past three decades, wreck diver-film makers have devoted their attention to exploits that are beyond the scope of the recreational diver's training and community standards. They have filmed diving excursions to great depths -- over 250 feet -- and commonly beyond 160 feet. These films have both taunted and lured divers. The concept of virgin (or near-virgin) wreck or cave exploration is extremely appealing to divers. The concept of going where no human has gone before becomes a compulsion -- a driving force. The film accomplishments have been deemed as spectacular, feats of expertise, daring, and talented. They have been viewed as outstanding accomplishments by some and reckless abandonment by others. The film makers have been both worshiped and ridiculed.

Recreational divers have the right of self-determination and are not subject to the standards and regulations that regulate commercial divers. It is a well-established fact that recreational deep divers knowingly and wantonly exceed both the currently published standards of recreational, military, and commercial diving.

Regardless of the opinions of educators, physiologists, physicians, and other authorities, the recreational diver must be allowed to retain his/her right of self-determination and freedom to pursue his/her recreational activity to its fullest extent as long as they do not endanger the health and well-being of other individuals. Only when the act of deep diving can be defined as an illegal activity such as attempting suicide or knowingly and wantonly endangering the lives and well-being of others can the rights of the individual be superseded.

However, by the same token, the rights and well-being of any and all agencies, businesses, and individuals who provided services or goods to this diver as well as individuals and agencies that may be called on to provide services in the event that said diver is lost or injured must also be provided with the fullest protection of the law. It must be clearly established that any recreational diver participating in deep diving shall accept sole, full, and complete responsibility for his/her actions and well-being. There must be clear and complete acknowledgment and assumption of risk. No recreational diver who knowingly and wantonly participates in deep diving or his/her heirs, executors, administrators, or assigns shall prosecute or present any claim for personal injury, property damage, or wrongful death against any dive charter operator, diving instructor, diving companion, dive travel business, diving equipment manufacturer, diving equipment retailer, physician, or any of their said agents, servants, or employees for any cause of action.

It is difficult, if not impossible, to address recreational diver responsibility through legislative avenues; nor should they be. The recreational diver by virtue of citizenship has certain rights of self-determination. Along with these rights, one must assume responsibility to society and family. The recreational diver who elects to exceed the standard of the diving community with regard to diving techniques, procedures, and depth must, at a minimum, accept the following responsibilities:

- The individual diver must be completely aware of the risks associated with extended depth diving and breathing various gas mixtures and, more importantly, accept these risks.

- The diver shall be responsible for fully and completely informing spouse, family, and loved ones of the risks, both short term and long term, associated with their chosen diving activity and to make said parties fully and completely aware of the fact that they have elected to exceed the standard of the recreational diving community.

- The spouse, family, and loved ones shall be prepared to accept the potential consequences of injury associated with diving including both short term and lifelong disability, loss of sexual partnership, and death.

- The diver shall acquire and maintain adequate medical insurance to cover any and all costs of treatment and hospitalization that might result for injury sustained during or as a result of diving.

- The diver shall maintain full and complete disability insurance that will cover the cost of long term disability and loss of earning to the family.

- The diver shall maintain appropriate life insurance or other financial means to assure full and complete support of spouse and children until the children are 21 years of age and/or have completed college education. Sufficient funds shall be available for the surviving spouse to live in an appropriate fashion and acquire whatever education necessary to enter employment and take a self-sufficient place in society.

DIVING COMMUNITY RESPONSIBILITY

An even more difficult issue to address is the question of responsibility of the recreational diving community to the deep diver. The recreational diving industry has, at least to date, refused to officially recognize or endorse the exploits of the deep recreational diver. The community is divided. The recreational diver training agencies stand firm on no-decompression diving with a depth limit of 130 feet.

On the other hand, other segments of the recreational diving community (i.e., cave divers and shipwreck divers) openly defy this rather limited standard and routinely dive to considerably deeper depths on dives requiring extensive decompression. Furthermore, with some exception, these deep divers are primarily self-taught deep divers. The deep diving specialty courses supported by the major training agencies are, to many deep diving enthusiasts, a joke. Only the National Association of Cave Divers and the Professional Scuba Association (PSA of Orlando, Florida) appear to provide training in deep and/or decompression diving at this time. The Professional Scuba Association will train individuals for compressed air scuba diving to depths of 300 feet.

Unfortunately, the beginning diver receives many mixed signals with regard to dive depth and decompression. The major training agencies stand firm -- 130 feet and no-decompression. Books, manuals, promotional materials, and course standards are all directed at maintaining this standard. The largest recreational diver training agency in the world has developed and promotes dive tables that are strictly for no-decompression diving. Exceeding the limits of these tables is considered to be an emergency situation.

Yet, recreational diving businesses actively promote deep diving activities such as excursions to the Andrea Doria. Shipwreck diving filmmakers produce films of recreational divers exploring at depths exceeding 200 feet. Magazine articles praise deep diving exploits.

An even more difficult item for the beginning diver to comprehend is the fact that many recreational diving instructors aggressively maintain the party line of the training agencies in their course lectures -- 130 feet and no-decompression. Yet, the same instructor boasts of dives to great depths and proudly displays the special equipment of the deep diver. Is there a double standard? Everyone knows the rules or standards of the recreational diving community. Also, even the most novice diver has difficulty imagining that there are significant physiological differences between them and their instructor. However, these rules or standards simply do not appear to apply to many recreational diving instructors. Although the physiological difference may be slight, the psychological differences appear to be significant.

The recreational diving community has an obligation to beginning divers to sort out the deep diving issue. In the meantime, I encourage deep divers and recreational diving instructors to refrain from boasting of their exploits. Most recreational divers are followers. They often follow -- often blindly and without questioning -- the lead of their instructor and idols. Some of the followers will be lured into deep diving even though they lack the training, experience, equipment, and knowledge of risks.

I further recommend that the recreational diver training agencies stop burying their heads in the sand and face the real issues of the day. Many recreational divers exceed the recommended limits for compressed air diving daily. Let's not promote one thing and do another! It is time to re-examine depth limits, diver training, and community responsibility.

During the decade of the 90s, I predict that increasing numbers of recreational divers will dive deeper than ever before in history. Dive computers have opened a new door to the depths. Yet more and more recreational divers will challenge the depths with only very limited knowledge of the risks. Home study dive courses, three lesson dive courses, take home video lectures, weekend certification courses and the like will increase the numbers of divers significantly over the next decade. The concept of continuing education is sound. However, subjectively I feel that only a very small percentage of the divers who are exposing themselves to deep dives on their Caribbean vacation have the advantages of continuing education courses or even understand the risk of their exposure.

The above may seem somewhat extreme to some individuals. I am not an advocate of deep recreational diving and risk-taking. However, freedom of self-determination is fundamental to the American way of life. On the other hand, each and every individual has a responsibility to society and their loved ones. It is time that individuals who demand these freedoms also accept full and complete responsibility for their actions. God willing, both the individual and society will emerge unscathed.

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DISCLAIMER

Neither the author nor the University of Michigan will accept responsibility for accidents or injuries resulting from use of the materials contained herein or the activity of diving. All diving activities have inherent risks. An individual may experience injury or disease that can result in disability or death. Variations in individual physiology and medical fitness can lead to serious injury even with adherence to accepted standards of performance and the correct use of dive tables. All persons who wish to engage in any form of diving must receive instruction from a qualified instructor and complete nationally recognized requirements. Trained and certified divers are informed of the risks associated with deep and alternative gas mixture diving and ultimately bear responsibility for their own actions. Any individual has the right to refuse to dive. Persons should not engage in any form of diving if they are unwilling to complete a course of instruction, pass certifying examinations and evaluations, maintain their skill/knowledge through active participation in diving activities, and accept responsibility for their own actions when participating in diving activities.