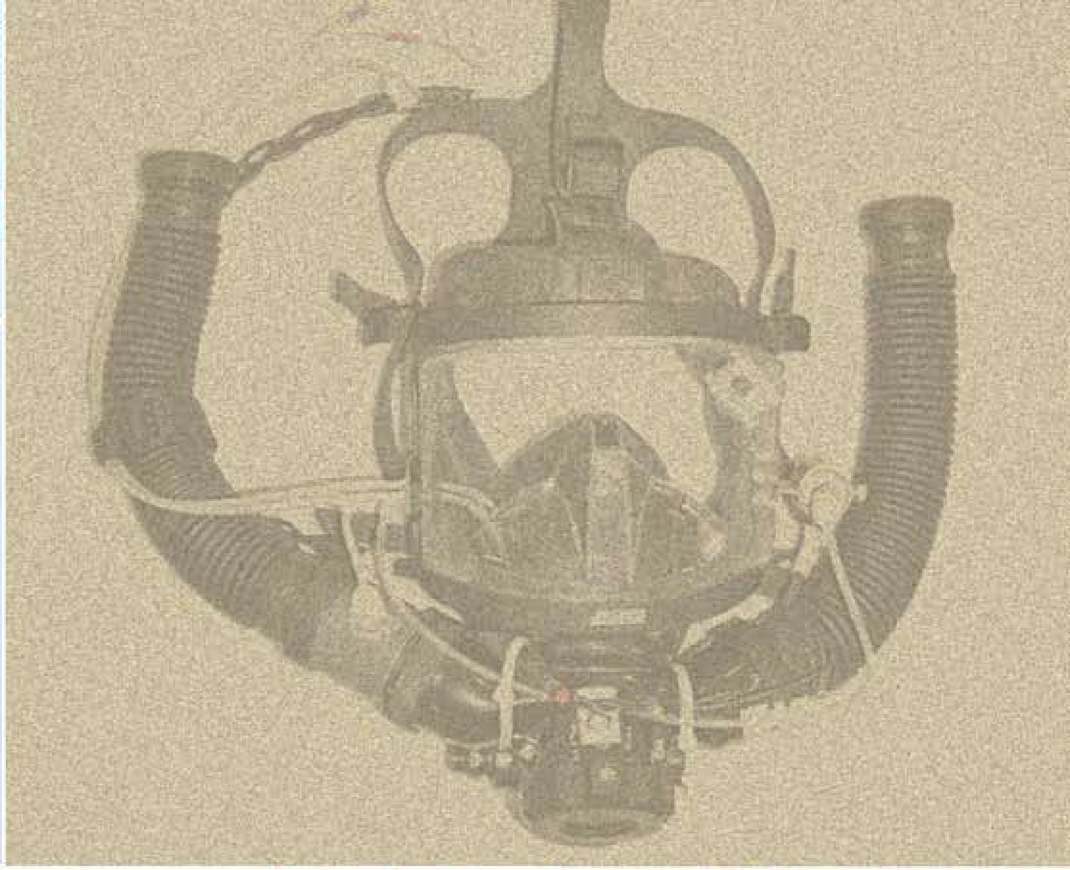

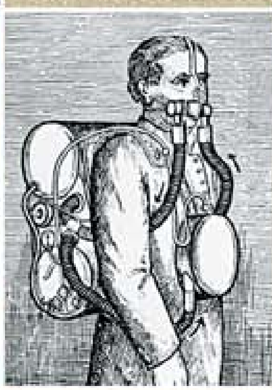

Technical Diving

Conference Proceedings

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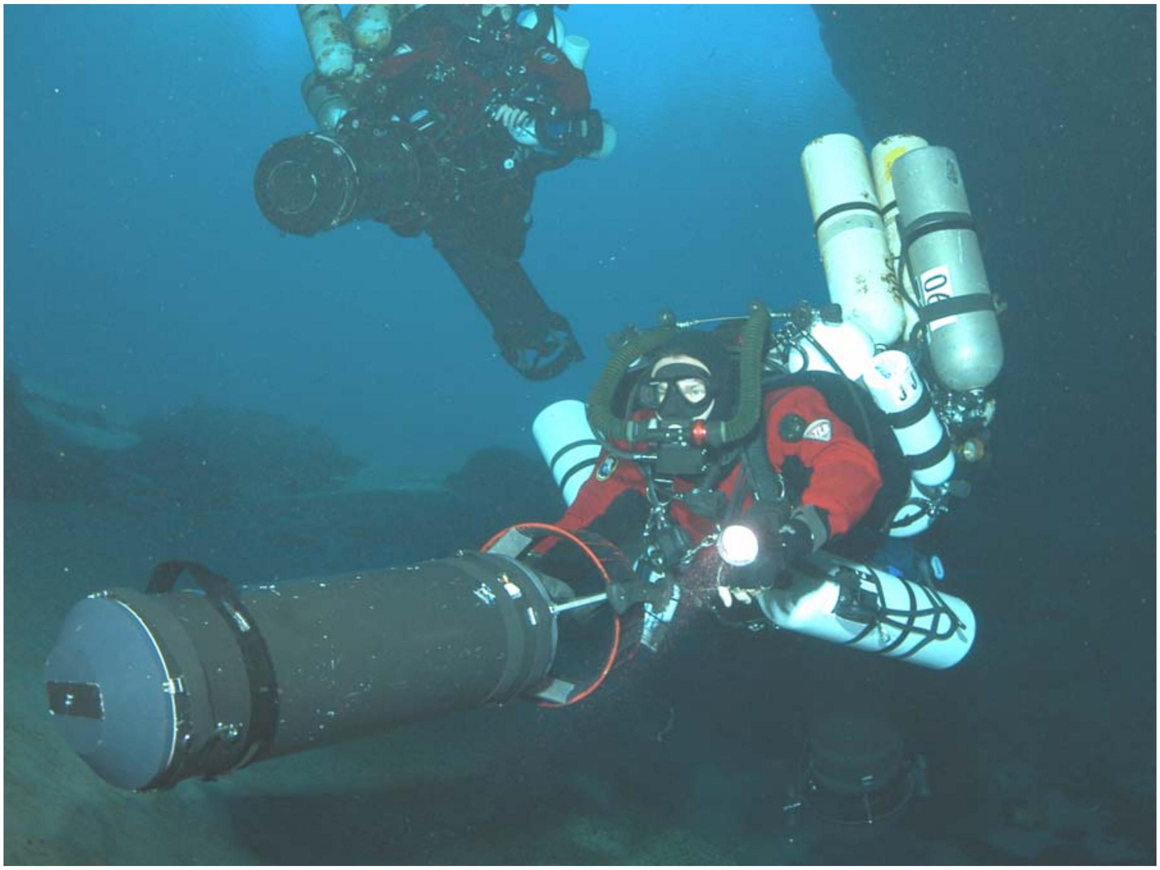

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Technical Diving

Conference Proceedings

January 18-19, 2008

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TECHNICAL DIVING CONFERENCE SUMMARY

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The Divers Alert Network (DAN) held a two-day technical diving conference on January 18-19, 2008 in Durham, NC. Included were four half-day workshops that addressed relevant issues pertaining to physiology, decompression, rebreathers, and training. These proceedings are the written record of the conference. Presentations and discussions are also available as video recordings.[1] Topics covered in the workshops are described below.

Physiology Workshop. The objectives of technical diving are to dive deeper and stay longer, which exposes a diver to physiological stresses absent at sea level. Carbon dioxide is a particular concern. The lungs must be adequately ventilated with fresh gas to eliminate carbon dioxide or there are risks of headache, shortness of breath, unconsciousness, and increased likelihood of narcosis and oxygen toxicity. Many factors that influence the occurrence of oxygen toxicity, nitrogen narcosis and the high pressure nervous syndrome (HPNS) are well-understood, but their thresholds are ill-defined. Hypothermia is exacerbated by long dives, and insight into its physics and physiology is useful for understanding new active and passive thermal protection.

Decompression Workshop. Longer and deeper dives require slow ascent to avoid decompression sickness (DCS). Much is known but much is uncertain. Bubbles have acute physical effects and delayed biochemical effects. Mechanisms leading to objective signs and subjective symptoms differ in according to affected tissues. Several environmental factors can cause large increases or decreases in DCS risk. Available evidence concerning deep decompression stops does not support their effectiveness. DCS is probabilistic, not deterministic. Risks can be reduced but not realistically abolished. DCS severity differs widely with probabilities that depend on dive conditions and inert gas species. Recompression on oxygen remains the gold standard for therapy, but methods that provide rapid intervention, such as in-water recompression, deserve consideration.

[1] The PowerPoint® and mp4 video files may be viewed on line at the DAN website (www.dan.org) or downloaded to your computer by right-clicking on the file name. A high-resolution DVD is available at no cost. Please contact DAN Member Services at (800) 446-2671, Option 3, and ask for Product # 171-0010.

Rebreather Workshop. Rebreathers are an essential part of technical diving as they allow ready extension of depth and endurance due to their low gas consumption. Unmanned and manned testing is essential to ensure minimum performance capability, however. Standard U.S. Navy (USN) and European Union (EU) tests and their rationale were described. Common standards are under negotiation. Carbon dioxide toxicity is a major and unappreciated concern. Except for the few cases reviewed by the USN and EU, diving accident investigation is poorly-funded, non-standard, and lacks a competent investigative body. A panel discussion of nine rebreather manufacturers addressed key aspects related to design, manufacture, and operation.

Training Workshop. Complex equipment and procedures allow long underwater penetrations but with numerous challenges whose mastery requires systematic training, experience and currency. Accidents happen nonetheless. Causes of fatalities were reviewed for recreational diving, cave diving and rebreather diving. During a sequence of adverse events, a diver may be incapable of self-help but might be rescued if adequate resources were available. Planning is essential for reducing risk, and an expedition risk assessment plan was presented as an example. A training agency panel discussed formal courses, compliance with training procedures, diver self-reliance, and role models. Communication within the diving community was recommended as a means of improving safety and efficacy.

PHYSIOLOGY WORKSHOP: CHAIRMAN'S SUMMARY

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Technical diving techniques are usually employed to facilitate either (or frequently both) of two goals: to visit greater depths or to extend underwater duration. Fulfillment of these goals exposes the diver to several problematic physiological stressors, which we have chosen to address in this workshop.

Simon Mitchell describes the dependence of CO_2 elimination on ventilation of the lungs with fresh gas. He points out that the use of any given gas mix at increasing depths requires the diver to respire a denser gas. This increases resistance to the flow of gas through airways and equipment, and combined with other relevant respiratory effects of diving, such as the effects of immersion on the lung, creates conditions under which the diver may not ventilate adequately and therefore retain CO_2. This is a significant issue because CO_2 retention may cause unpleasant symptoms such as headache and shortness of breath, and thereby precipitate distress. It can also increase the risk of the oxygen toxicity and enhance narcosis. Avoidance of CO_2 retention is dependent on appropriate gas selection, equipment configuration, limitation of work at depth and recognition of early warning signs.

Richard Vann and Bill Hamilton describe the inevitable increase in risk of cerebral oxygen toxicity that occurs with prolonged exposure to inspired hyperbaric pressures of oxygen. There is no clearly defined 'safe' threshold for PO_2, though hyperoxic seizures are extremely rare at an inspired PO_2 of ≤ 1.3 atm. Attempts to refine recommendations for pressure/time limits for oxygen exposure are discussed as are the various symptoms of oxygen toxicity. The remarkable inter- and intrapersonal variability in their latency is emphasized. This characteristic significantly complicates the prescription of safe oxygen exposures for individuals. Risk factors, such as hypercapnia, and their mitigation are discussed.

Peter Bennett and Simon Mitchell reveal that by visiting depths greater than 180 msw (~600 fsw) some technical divers are exposing themselves to the risk of the high pressure nervous syndrome (HPNS). This appears to be caused by a physical effect of pressure on membranes and/or their associated structures which produces tremors, changes in cognition, nausea, and other adverse effects. Strategies to reduce HPNS include a marked slowing of descent rates (which is not practical in technical diving), and the incorporation of some nitrogen in the breathing mix. However, the latter imposes the more familiar risk of nitrogen narcosis, whose mechanism is also discussed. Enhancement of narcosis by CO_2 is proven, while the significance of any contribution from high inspired PO_2 is more controversial.

Lew Nuckols describes the inevitable thermal stresses imposed on divers undertaking increasingly longer technical dives. Given that many technical dives take place in temperate marine environments or coldwater caves, there is particular interest in avoiding heat loss and hypothermia. The consequences of hypothermia are discussed, and the relative performance of currently employed insulating strategies (wetsuits, drysuits and undergarments) under resting and working conditions is reviewed. Novel super-insulating materials that may vastly improve the efficacy of drysuit undergarments are likely to become available in the near future.

RESPIRATORY ISSUES IN TECHNICAL DIVING

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Introduction

Immersion, the use of underwater breathing apparatus and the breathing of gases at densities higher than air at 1 atmosphere have important effects on respiratory function for all divers. These effects are potentially magnified for technical divers who venture deeper and may breathe denser gas. This paper will review respiratory issues of high relevance to technical divers, and attempt to answer the following questions:

1. How does normal respiration and gas exchange work?
2. How is ventilation controlled?
3. What are the effects of immersion, diving equipment, and increasing gas density on respiratory function?
4. How does hypercapnia (excessively high CO_2 levels) occur?

Like many niche areas in medicine, respiratory physiology is a complicated and jargon-rich subject. This paper will attempt to provide a simplified account that emphasizes the practical issues. It must therefore be understood that it is aimed for the most part at technical divers rather than those with physiological or medical training.

How Does Normal Respiration and Gas Exchange Work?

The respiratory system provides a mechanism to bring blood and air into close contact primarily so that oxygen may be taken up into the blood and carbon dioxide removed into the lungs. What follows is a simple account of the normal anatomy and function of the respiratory system based partly on Lippmann and Mitchell (1).

Structure of the respiratory system

The respiratory tract can be divided into two portions, the “conducting” and the “gas exchange” portions. The "conducting portion" connects the external environment with the gas exchange area of the lung. It consists of the nasal passages, pharynx, larynx, trachea, bronchi and bronchioles (Figure 1). In a normal adult the volume of the conducting portion is approximately 150 ml. This will be increased when any sort of breathing device (such as a snorkel or scuba regulator) is added. The "gas exchange portion" is the alveolar sacs where actual gas exchange occurs. Other important components include the ribs, intercostal muscles and diaphragm, which provide the mechanical drive to ventilate the lungs as will be discussed.

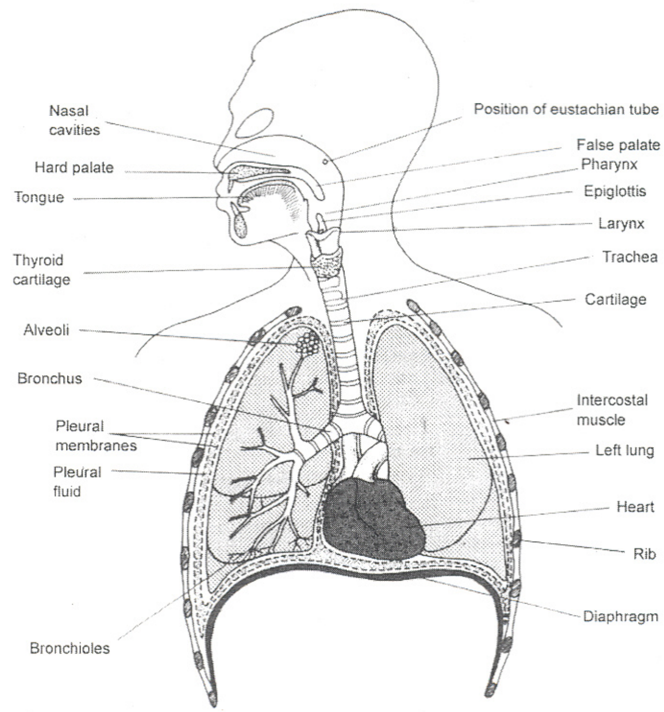


Figure 1. The respiratory system.

The two lungs are roughly cone-shaped and are situated in the thoracic cavity which is bounded by the spine (posteriorly), ribs (laterally), sternum (anteriorly), and the diaphragm (a dome-shaped muscle attached to the vertebrae and lower ribs) which separates the thorax from the abdomen. All the ribs are attached to the vertebral column (spine) at the back; however, only the first seven ribs on each side are attached directly to the sternum ("breast bone") at the front. The next three are attached to the ribs just above, while the front ends of the last two ribs are free. Between the ribs lie the intercostal muscles, which assist breathing.

The lungs themselves are surrounded by two very thin membranes, the "pleura." One membrane is attached to the lung itself and the other to the chest wall and diaphragm. The space enclosed between these membranes is sometimes called the pleural cavity, although it is not really a "cavity" under normal circumstances. It normally contains an extremely thin layer of fluid that acts as a lubricant to allow free movement of the lungs during breathing. It is notable that the lungs are not physically attached to the chest wall or diaphragm in any way. It is only the adhesion between the two pleural membranes, facilitated by the thin layer of fluid that keeps the lungs from collapsing down to a much smaller size. This is best conceptualized by thinking of two sheets of glass stuck against each other with a microfilm layer of fluid in between. The two sheets of glass (one representing the chest wall or diaphragm and the other representing the lung) can slide over each other, but they cannot be pulled apart. Of course, should air get between the two sheets of glass, they would come apart quite easily, and this is the situation that can arise in a pneumothorax: air gets introduced into the pleural cavity and the lung, being an elastic structure that is stretched in its normal inflated state, can collapse.

Air is drawn into the mouth and nose and then passes into the pharynx, which is a short common pathway for air and food. The pharynx divides into the esophagus posteriorly and the trachea (via the larynx or "voice box") anteriorly. The esophagus takes food and fluids into the stomach. Food is normally prevented from entering the larynx by the epiglottis, a flap of tissue which folds over the laryngeal opening during swallowing. Air travels through the larynx into the trachea. The trachea passes down into the thorax and divides into the right and left bronchi, which enter the lungs. Inside the lungs, the bronchi progressively divide into smaller passages. The trachea and bronchi are lined by cells with tiny moving hairs (cilia) on their surface. These cilia, along with mucus secreted by glands, act to trap foreign particles and move them back up into the pharynx where they are subsequently swallowed. Ciliated cells may be damaged in chronic smokers who need to resort to the "smoker's cough" to bring up the mucus and trapped particles. The smallest branches of the respiratory tree are called the bronchioles and it is from these that the alveoli or air sacs arise.

The alveoli have extremely thin walls that are only one cell thick and are surrounded by many capillaries. The inner surfaces of the alveoli are coated with a surfactant, which decreases the surface tension of the thin fluid layer lining the inside of the alveoli. This reduces their tendency to collapse. If this surfactant is washed out, as may occur during drowning, the alveoli may collapse. The walls of the alveoli and the capillaries are so thin that the distance separating the gas in the alveoli from the blood in the capillary is only 1 µm. Molecules of gas can freely diffuse across this so-called alveolar-capillary membrane. There are approximately 300 million alveoli (in both lungs) and if all were opened out and laid flat they would cover an area of about 1090 ft^2 (100 m^2), which is approximately the area of a tennis court.

<u>Mechanism of breathing</u>

Inspiration and expiration are brought about by the up-and-down movement of the diaphragm and the elevation and depression of the ribs by the intercostal muscles. Upward movement of the chest wall and downward movement of the diaphragm causes the pressure in the thorax to fall, creating a pressure gradient between lungs and mouth, and so air flows through the nose and/or mouth into the lungs. Expiration occurs when the diaphragm and intercostal muscles relax. The lung is very elastic, and from its stretched state after inspiration the "recoil" of this elastic tissue causes an increase in chest cavity pressure, and so air flows outwards.

Thus, normal ventilation is achieved by active movement of the diaphragm and the intercostal muscles (for inhalation), followed by passive recoil of the lung, chest wall and diaphragm (for exhalation). In fact at rest, breathing is brought about almost solely by the action of the diaphragm. During exercise, the intercostal muscles also become involved, actively expanding the thorax during inhalation and contracting to help force the air out of the lungs during exhalation.

In respect of quantifying the movement of gas in and out of the lungs, there are some definitions that may arise later which are worth noting now:

Tidal volume = is the volume of gas moved with each breath.

Functional residual capacity (FRC) = the volume of gas left in the lungs at the end of a normal "tidal" exhalation.

Residual volume = the volume of gas left in the lungs at the end of a maximal exhalation.

Vital capacity = the volume of gas that can be exhaled down to residual volume after a maximal inspiration. Put simply, this represents the biggest breath that can be moved in and out.

Maximal voluntary ventilation (MVV) = the volume of gas that can be moved in and out of the lung over one minute when the subject is panting as possible.

<u>Work of breathing</u>

It is important for divers to understand that breathing requires physical work. It is fairly obvious that if the lung is elastic, then work must be done during inspiration to overcome that elasticity and stretch the lung. Similarly, there is work involved in moving the "weight" of the chest wall and other soft tissues during inspirations. Less obvious is the work that must be performed to overcome resistance to gas flow through the conducting passages in the lung. Like any other work, the work of breathing results in the consumption of oxygen and production of CO_2.

We don't notice the work of breathing under normal circumstances because we are well adapted to the normal demands. However, it is important in diving because it can be increased by immersion, the use of underwater breathing equipment and by increases in gas density. Though perhaps stating the obvious, the diver's ability to respond to increases in work of breathing is not unlimited. The corollary is that respiratory muscle exhaustion or failure to respond to increased work demand for any reason will result in inadequate ventilation ("hypoventilation") and an increase in arterial CO_2 (see later).

Gas exchange

Gas exchange occurs in the alveoli. It is often assumed that the alveoli are flushed with "fresh air" with every breath. In fact, there is no complete "flushing" in the alveoli, and the composition of alveolar gas is determined by a complex and dynamic balance between the arrival of new gas down the airway, and gas exchange with the blood.

To put some numbers on this, we must introduce the somewhat confusing unit of "millimeters of mercury" (mmHg) that is used to express physiological gas pressures, where 1 atmosphere = 760 mmHg. Divers are familiar with simple calculations using Dalton's law to derive partial pressures. Thus, since oxygen constitutes 21% of air, its partial pressure at 1 atm in mmHg is 0.21 x 760 = 160 mmHg. In the alveoli, oxygen is both arriving and being removed into the blood and the result of this dynamic process is that oxygen constitutes only about 13 - 14% of alveolar gas. Calculating the partial pressure of O_2 in the alveolus is a little more involved, so it is best to just accept that in a healthy person breathing air at 1 ata, the alveolar PO_2 is about 100 mmHg. Although there is virtually no CO_2 in the inspired air, CO_2 moves from the venous blood into the alveolus such that the PCO_2 in the alveoli of a normal healthy person breathing air at 1 ata is about 40 mmHg.

One important point to understand is that the contact between the gas in the alveolus and the blood in the lung capillaries is so intimate that the pressures of gas in the alveolus and the fluid of the blood equilibrate in an instant, and therefore, under most circumstances, the partial pressure of gases in the blood leaving the alveolus (which ultimately becomes the arterial blood) are the same as the partial pressure of gases in the alveolus. This is summarized in diagrammatic form in Figure 2. In reality, the partial pressure of oxygen in arterial blood is slightly lower than you would predict from this diagram for a number of reasons that are unimportant to this discussion.

Carriage of oxygen and carbon dioxide in the blood.

Oxygen

The blood carries oxygen in two forms: dissolved in plasma (the liquid component of blood) and combined with hemoglobin (a protein which is found in the red blood cells). Hemoglobin (Hb) is necessary because oxygen is not very soluble in plasma. Indeed, only 0.03 ml of oxygen can be dissolved in each liter of plasma for every mmHg pressure. For our normal subject breathing air at 1 ata (as in Figure 2), the amount dissolved would be 100 mmHg x 0.03 ml/L = 3 ml/L.

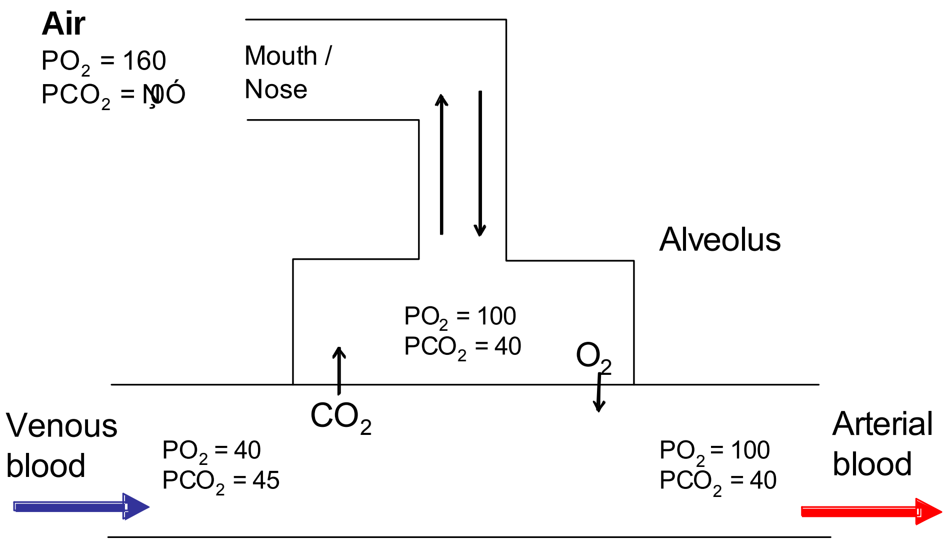


Figure 2. Partial pressures of O_2 and CO_2 at the mouth, in the alveolus, and in blood entering and leaving the alveolar capillaries.

In contrast, the body extracts about 50 ml of oxygen from every liter of blood on each pass, so there would be a dramatic shortfall in oxygen delivery to tissues in the absence of Hb. Hemoglobin has multiple binding sites for oxygen and can carry about 1.34 ml per gram of Hb when all those sites are occupied (or "saturated" as is the usual term). Not surprisingly, we have evolved in such a way that the oxygen binding sites on Hb are fully saturated when exposed to the normal PO_2 in our alveoli during air breathing (i.e., 100 mmHg as shown in Figure 2). Assuming a "normal" Hb level in the blood of 150 g/L (this is variable and less in women) than the oxygen carrying capacity on Hb is given by 150 g/L x 1.34 ml/g = 200 ml/L of oxygen (see Figure 3). This is markedly greater than the 3 ml/L carried as dissolved oxygen, and exceeds the usual extraction of oxygen (50 ml/L) by 4 times.

When arterial blood enters the capillaries of various tissues, the pressure of dissolved oxygen (at a PO_2 of approximately 100 mmHg) is much greater than that in the surrounding tissue, so oxygen diffuses out of the blood. As the dissolved oxygen diffuses outward the PO_2 in the blood falls, and this "stimulates" the Hb to release more oxygen, which itself diffuses out into the tissues. In this way, the tissues are delivered the oxygen they rely on. The tendency for Hb to lose oxygen as the PO_2 falls is described by the so-called oxygen-hemoglobin dissociation curve (see Figure 3). With the usual oxygen extraction by body tissues, the PO_2 in the venous blood falls to 40 mmHg and you will note from the curve that the Hb is still about 75% saturated.

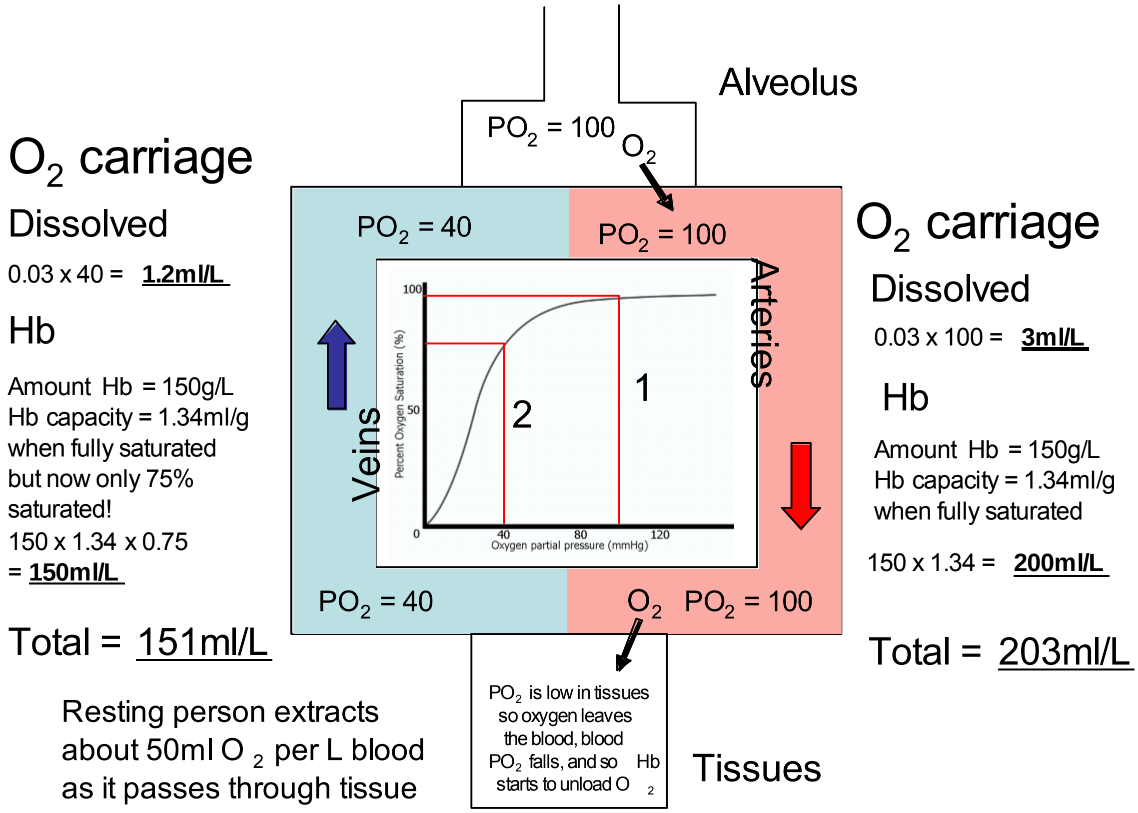


Figure 3. Comparison of oxygen carriage in arterial and venous blood during air breathing at 1 ata. Start at the alveolus and work your way around this diagram in the direction of blood flow (clockwise). Much of what is depicted was explained in the preceding text. The graph in the middle is the oxygen-hemoglobin dissociation curve. You will see (line 1) it predicts nearly 100% saturation of oxygen binding sites when the PO_2 is 100 mmHg (as in arterial blood), but only 75% saturation when the PO_2 is only 40 mmHg (as in venous blood) (line 2).

Finally, it is interesting and useful to consider the effect of breathing an elevated PO_2 on oxygen carriage. For example, what would be the effect of CCR rebreather diving at a set point of 1.3 atm, or decompressing at 3 m on 100% oxygen? In either case the inspired PO_2 is 1.3 atm. This would result in an alveolar PO_2 of about 900 mmHg, but how would it change oxygen carriage? The first thing to note is that Hb is almost fully saturated with oxygen even at a PO_2 of 100 mmHg (see Figure 3). Hb can't be more saturated than 100% so the amount of oxygen carried on Hb would still be about 200 ml/L (Figure 3). However, the amount of dissolved oxygen will change. Using the same calculation as in Figure 3 we can see that there will be 0.03 ml/L x 900 mmHg = 27 ml/L. This is about half of the 50 ml/L normally extracted by the body tissues with each pass of blood. Under these circumstances, the Hb will not have to unload quite as much oxygen for the tissues and its saturation in the venous blood may be a little more than usual. Of note, if you breathe 100% oxygen at 2.5-3 atm (which divers never do in the water!), you can virtually dissolve enough oxygen in plasma to obviate the need for Hb altogether. This is why hyperbaric oxygen is sometimes used to treat exceptional anemia in Jehovah's Witness patients who will not accept a blood transfusion.

Carbon dioxide

Carbon dioxide is produced as a waste product of metabolism and must be eliminated. As will be discussed, disturbances of CO_2 elimination can have important effects on diving safety.

Arterial blood entering the tissue capillary beds has a lower PCO_2 than the surrounding tissues, so CO_2 diffuses into the blood. In the blood it is carried in three ways. First, it may dissolve in plasma as does oxygen, except that CO_2 is more soluble and more is carried in this way. Second, it may undergo a chemical transformation to form bicarbonate; a transformation that is reversed when the blood enters the lung capillaries. Third, it may bind to proteins in the plasma and to hemoglobin. Indeed, the blood's carrying capacity for CO_2 increases when oxygenated Hb unloads oxygen in the tissue capillaries because this frees up sites to which CO_2 can bind. You may recall from the discussion above that Hb might unload less oxygen in the tissues if we breathe a significantly elevated PO_2. This is raised as a concern from time to time on internet forums in relation to CO_2 toxicity. The concern is that high PO_2s impair CO_2 carriage and result in impaired elimination. In fact, this should not be a practical concern, especially at the maximum PO_2s breathed by divers. While CO_2 carriage might be altered in a minor way, it would not usually result in an important impairment of CO_2 elimination. The truly important causes of CO_2 toxicity will be discussed in the next section.

<u>Dependence of CO_2 elimination on ventilation</u>

Before leaving the subject of gas exchange, it is worthwhile highlighting the critical dependence of CO_2 elimination on ventilation of the lungs. One could be excused for suggesting that oxygen uptake must also be dependent on ventilation. As you will see in the next paragraph, that is only true to a point, depending on how much oxygen is breathed. Indeed, there are some important differences between O_2 uptake and CO_2 elimination that are especially relevant in technical divers who frequently breathe high fractions of oxygen.

Ignore diving for the moment and consider a normal 70 kg adult at rest breathing 100% oxygen. The question is: what happens to his arterial oxygen and arterial CO_2 levels if he exhales normally, and stop breathing for 5 minutes? A few more numbers are required to answer this adequately. First, the approximate volume of the functional residual capacity (see the earlier definitions) is 30 ml/kg, so if we assume that the lungs only contain oxygen, then there will be 30 ml/kg x 70 kg = 2100 ml of oxygen in the lungs. Second, the approximate oxygen consumption for an adult at rest is about 300 ml/min. Thus, in theory, there is enough oxygen in the lungs to keep this person going for 2100 ml ÷ 300 ml/min = 7 minutes. Most importantly, oxygen carriage in the arterial blood will not be disturbed at all for most of this time. We know from our earlier discussion that all that is required for near complete saturation of the arterial Hb with oxygen is a PO_2 of 100 mmHg in the alveoli. This subject breathing 100% oxygen at 1 ata will initially have an alveolar PO_2 close to 700 mmHg. This will fall as oxygen is removed, but it will not fall below 100 mmHg until late in the 7-minute period. We can conclude that in this scenario it would be possible not to breathe for at least 5 minutes with no deficit in oxygen delivery to tissues.

In contrast, from the moment this subject stops breathing, CO_2 will begin to accumulate. It will be still delivered to the alveoli in the venous blood, but with no ventilation it will not be removed from the alveoli. As discussed earlier, the PCO_2 in the arterial blood merely reflects what is in the alveoli, and so arterial CO_2 will rise. It is analogous to a circular conveyor where one person puts objects on and another takes them off. If the latter stops working and the former continues, then the conveyor will become congested with objects.

The point of this example is to illustrate that when inspired and alveolar PO_2s are high and there are large volumes of oxygen in the lung relative to metabolic needs (as is commonly the case in technical diving), divers could ventilate a lot less than they do and still remain well oxygenated. However, from the moment ventilation falls below that required to maintain alveolar (and therefore arterial) PCO_2 at the desired level, then the alveolar and arterial PCO_2 will begin to rise. It does not require divers to actually stop breathing as in the illustrative example above; a period of relative "hypoventilation" will still cause CO_2 accumulation (just a bit more slowly). This is a problem because, as most technical divers know, arterial CO_2 levels do not have to rise much for the adverse effects to begin.

Finally, as will be discussed later, there are several reasons why a diver might hypoventilate thus allowing toxic levels of CO_2 to accumulate. This point is poorly appreciated by many divers, especially rebreather divers, who immediately link CO_2 toxicity with scrubber failure. Scrubber failure and rebreathing of CO_2 can certainly cause CO_2 toxicity, but as this discussion illustrates, it is not the only (or even the most common) cause. Merely not breathing enough is often to blame!

How is Respiration Controlled?

Control of respiration is a complex and incompletely understood area of physiology. However, some aspects that are relevant to diving and relatively well understood are discussed here.

Control of respiration arises from the brainstem. There is a center, which acts as a respiratory "rhythm generator," instigating periodic inspirations and maintaining a basic respiratory rhythm. This center receives modifying input from a variety of other centers in the brain and brainstem. Perhaps the most important of these comes from specialized nerve cells or "receptors" that lie nearby, also in the brainstem. These receptors are very sensitive to the hydrogen ion concentration (which we measure using the pH scale) of their surrounding tissues. Carbon dioxide is free to diffuse from the arterial blood into these tissues and the nearby cerebro-spinal fluid. Here, it rapidly reacts with water to form bicarbonate and hydrogen ion, and the consequent increase in the concentration of hydrogen ions is sensed by the receptors. This is a potent breathing stimulus. Simply put, when CO_2 rises, respiration will be stimulated, and when CO_2 falls, respiratory drive will be reduced.

After the previous discussion of the crucial influence of lung ventilation on CO_2 levels,it may not be surprising to learn that this response to changes in arterial CO_2 appears to be more important than the arterial blood PO_2 in the fine tuning of respiration. Nevertheless, the PO_2 is monitored primarily by receptors in the carotid arteries, which have links to the respiratory control center in the brainstem. A slightly lowered PO_2 appears to sensitize the response to increasing CO_2, rather than to stimulate breathing directly. However, if the PO_2 falls sufficiently, then there will be direct stimulation of breathing.

There are several variable characteristics of this control system that are relevant to diving. First, there appear to be differences between individuals in respect to their response to CO_2 (2). These differences may be innate or acquired, and in respect to the latter, there is some evidence that diving may reduce sensitivity to CO_2. Second, it seems that if maintenance of CO_2 requires more work than is involved in normal air breathing, the respiratory control center in some individuals seems "content" to allow the CO_2 to rise somewhat, rather than perform the work (i.e. breathing) required to lower it again (3). Finally, just as low PO_2 increases the brainstem's sensitivity to CO_2, high PO_2 and high PN_2 may decrease sensitivity (4). All of these factors potentially contribute to an increase in arterial CO_2 during diving, and we will return to this issue later in the paper.

What are the Effects of Immersion, Diving Equipment and Increasing Gas Density on Respiratory Function?

<u>Immersion</u>

Immersion, even in shallow water, causes a number of important physiological changes which impact on respiratory system function.

Redistribution of blood volume

Irrespective of a diver's orientation in the water, there is a centralization of blood volume because of peripheral vasoconstriction and the loss of the gravitational effect that usually results in pooling of blood in the dependent veins, especially in the legs. This blood volume shift results in a relative (though tolerable) "congestion" of the distensible pulmonary circulation with blood. This makes the lungs a little "stiffer," which may marginally increase the work required to maintain the same ventilation. As an aside, this blood volume shift is also responsible for the highly annoying (especially if you are a drysuit diver) increase in urine production that occurs in diving. The body's blood volume control mechanism incorrectly interprets the "central hypervolemia" as an indication of fluid overload and signals the kidneys to make more urine.

Static lung load (SLL)

When immersed, the body is exposed to a vertical pressure gradient in the water column. Simply put, and as every diver knows, pressure increases with depth. This sets up an important interaction between diver and breathing apparatus.

Consider a rebreather diver with a front-mounted counterlung lying horizontally in the water. Notwithstanding the presence of one way check valves in the loop, the diver's airways are in continuity with the counterlung which lies slightly deeper and therefore at higher pressure than the lungs. This means that the lung airways are subject to a positive pressure equal to the vertical height of the water column between counterlung and lung. We refer to this as a "positive static lung load" (see Figure 4). The diver will notice that inhalation seems assisted, whereas exhalation requires extra effort. The reverse would be true for a horizontal diver wearing a back-mounted counterlung. The resulting "negative static lung load" would make inhalation seem harder and exhalation seem easier. These effects are not limited to rebreather divers. The same phenomenon arises when there is a vertical differential between an open-circuit demand valve (which supplies gas at ambient pressure) and the lungs (see Figure 4). Because the demand valve is higher than the lungs, the gas is supplied at a slightly lower pressure than that to which the lungs are exposed, thus constituting a negative static lung load.

It would seem natural to assume that the opposite effects of a SLL on the effort of inspiration and expiration would somehow "balance each other out," and that overall it would be of negligible importance. Unfortunately, this does not seem to be the case. In fact, the physiological significance of a SLL is actually quite complex, and we discuss it here at only a superficial level.

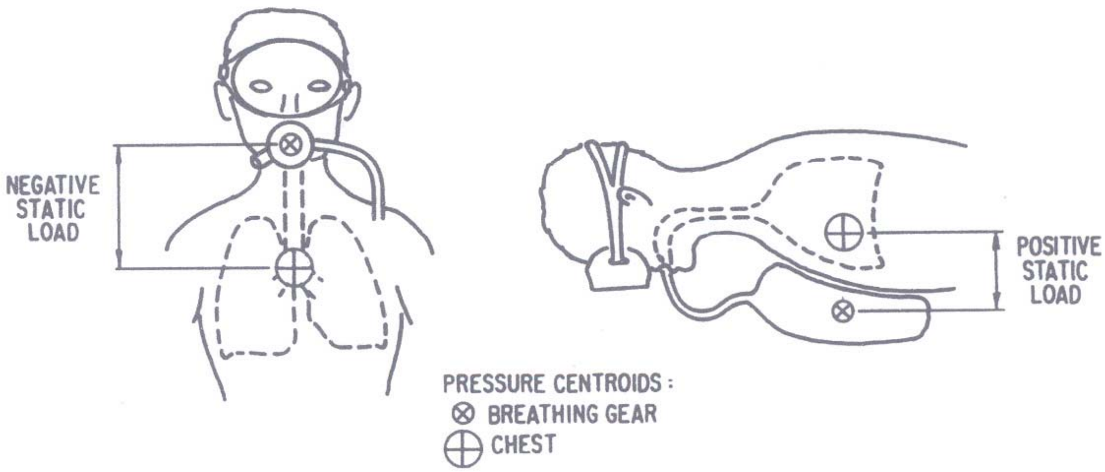


Figure 4. Diagrammatic representation of static lung load (5).

The negative SLL is arguably the most relevant to the majority of diving situations since it applies to an upright (or slightly head up) open circuit diver and most rebreather diving scenarios. Even operation of rebreathers with "over the shoulder" counterlungs is likely to result in a negative SLL because gas will tend to migrate to the highest point, which will often be above the lungs.

A negative SLL further enhances the redistribution of blood into the very distensible vessels of the chest cavity (described above in relation to immersion). This redistribution is simply in response to pressure gradients. It is the same as going below the water-line of a ship, drilling a hole in the side, and somehow sealing a balloon over the hole. The balloon would fill with water until its elasticity overcame the pressure tending to force the water inward. In the case of the lung in the upright diver, the "water" is the blood of the circulatory system, which is exposed to the surrounding water pressure, and the "balloon" is the distensible lung blood vessels.

From the heart's perspective, the significance of this at the degree of SLL encountered in practical diving situations is uncertain, but extremes can certainly be harmful. An experiment in which breathing was attempted through a 2m snorkel (representing a massive negative SLL) resulted in acute heart failure due to dilation of the chambers by excess volumes of blood (5)!

From the lung's perspective, even modest and commonly encountered degrees of SLL are probably "important." The increased congestion of the lung circulation with blood causes further "stiffening" of the lung tissue, and the volume of gas left in the lungs at the end of a normal expiration falls. This means that at the start of an inspiration the lungs are at a lower volume and the airways are narrower, thus increasing the resistance to gas flow (see later). Not surprisingly, there are data that demonstrate both an increase in the work of breathing and an increase in the subjective sense of breathlessness when a negative SLL is imposed (6). Positive SLLs are less commonly encountered, but can also be disadvantageous at extremes. Nevertheless, there is some data to suggest that divers are most comfortable and work is best facilitated at a slightly positive SLL (7).

There has been much discussion on how to compensate for SLL during diving, but there are significant practical obstacles and virtually all diving is undertaken with uncompensated equipment. In this regard, it is important to maintain some perspective on the problem represented by SLLs. This phenomenon is part of everyday diving and most dives do not result in overt respiratory discomfort let alone accidents resulting from respiratory failure. It follows that under normal circumstances the physiological challenge of a modest SLL can be met and managed without problems. However, the issue is worthy of note as one of several potential contributors to respiratory difficulties (other examples being hard work, high equipment breathing resistance, and denser gas) that, should they become relevant simultaneously, might result in difficulty maintaining adequate ventilation.

Case: A diver using a rebreather with over-the-shoulder counterlungs had not attached the counterlungs to his harness correctly. During a long physically taxing descent in a strong current he was observed to be floating very high (above his head! – a profound negative SLL). The diver, who later reported that breathing seemed “incredibly hard” during the descent, became unconscious soon after arrival at 50 m and had to be rescued. He survived. Verdict: CO_2 toxicity due to hypoventilation.

<u>Diving Equipment</u>

The use of diving equipment will almost invariably impose an extra resistance to breathing that would not be present if the diver was simply breathing from their own airway. This is another potential contributor to increased work of breathing and respiratory failure (inadequate ventilation), and it is universally agreed that minimization of equipment-related breathing resistance is desirable. At the same time, it is acknowledged that some resistance is inevitable. For example, the CO_2 scrubber canister in a rebreather will always cause some resistance to gas flow.

Since the order of components in a rebreather can be varied, there has been investigation of where their associated resistance might be best tolerated. Warkander et al. (8) separated equipment-related breathing resistance into its inspiratory and expiratory components, and showed that divers react to an imposed resistance by prolonging the phase (inspiration or expiration) that is loaded. More importantly, they showed that expiratory resistance seems better tolerated in terms of both the divers' subjective impressions of discomfort and objective respiratory parameters. This suggests, for example, that rebreather CO_2 scrubbers should be placed on the expiratory side of the counterlung and not the inspiratory side. Warkander et al. also published maximum thresholds for inspiratory and expiratory resistance, but these technical issues are beyond the scope of this paper.

Increasing Gas Density

The density of any given breathing gas increases linearly with depth. Technical divers substitute helium for nitrogen in gas mixes for deeper diving, which substantially reduces density. Nevertheless, at the depth targets being set by some extreme exponents, gas density still increases significantly despite the use of helium. For example, on David Shaw's widely reported fatal dive, the use of trimix 4:82 at 264 mfw equated approximately to air at 70 m (8 ata) in terms of gas density (9).

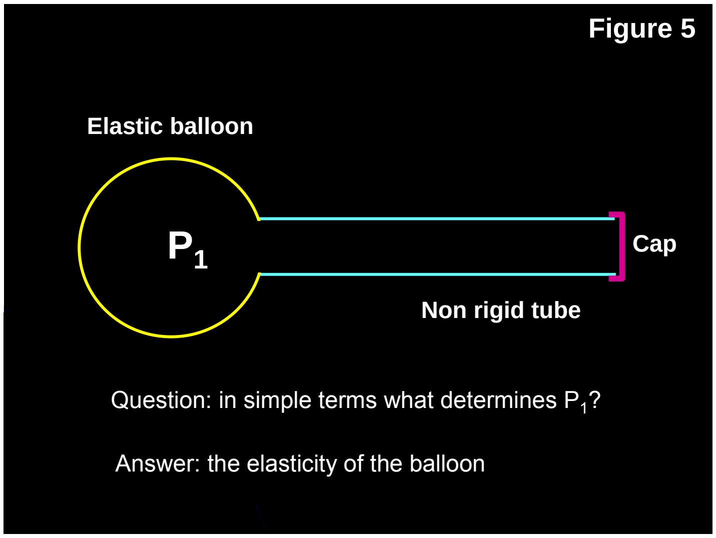
Dense gas impacts significantly on respiratory function primarily by increasing resistance to flow through airways and thereby limiting ventilatory performance. Indeed, if you ask a subject to ventilate as hard as they can whilst breathing air at the modest dept of 30 m (4 ata), the maximum volume they can shift over a minute is only half of that at the surface.

Work and exercise requires gas exchange, and gas exchange (particularly CO_2 elimination) requires ventilation. The clear implication of progressively limited ventilation with increasing depth is that as depth increases the diver's work capacity decreases. Indeed, it is plausible that the maximum depth, which technical divers can visit, may ultimately be determined by their ability to cope with the work of breathing, let alone any other work such as swimming. Even at more modest depths, there is some evidence that self-perpetuating respiratory failure (inadequate ventilation) scenarios might be encountered during diving where the work of breathing is high, and other heavy exercise is also attempted.

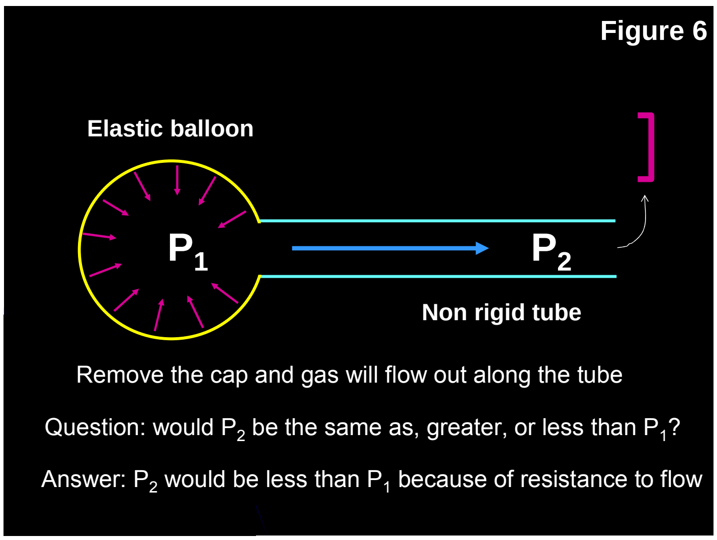
Increased gas density will increase the work associated with both inhalation and exhalation. However, arguably the most dramatic and limiting effects may relate to a phenomenon seen during expiration called "effort independent exhalation."

Effort Independent Exhalation and Respiratory Failure.

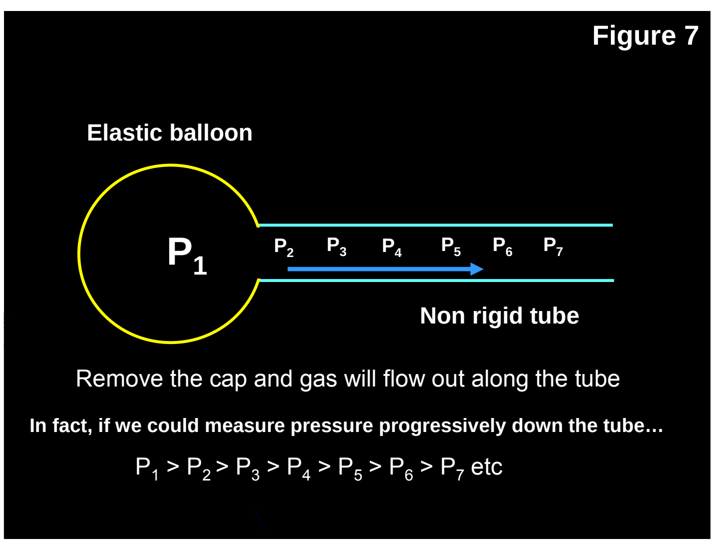
This complicated physiological phenomenon is explained in a step-wise simple manner below. Follow the series of diagrams through in sequence, along with the explanatory notes.



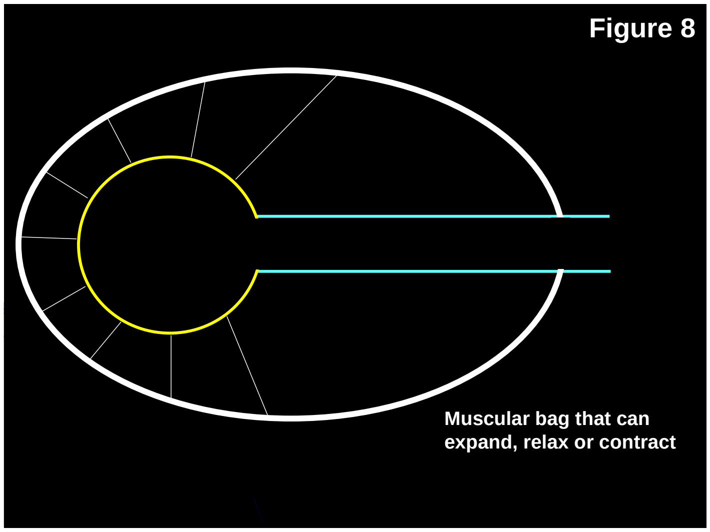
Consider a non-rigid tube with an inflated balloon on one end and a cap over the other (Figure 5). The balloon will be generating a pressure that is determined by its elasticity.



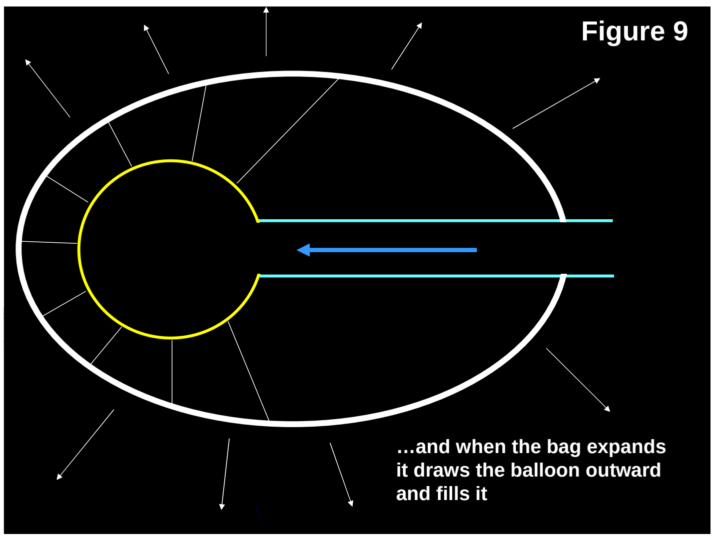
Now, the cap is removed from the tube and the elastic balloon contracts forcing air out along the tube (Figure 6). Because of resistance to flow, the pressure of gas driving flow through the tube will fall the further along the tube you go.



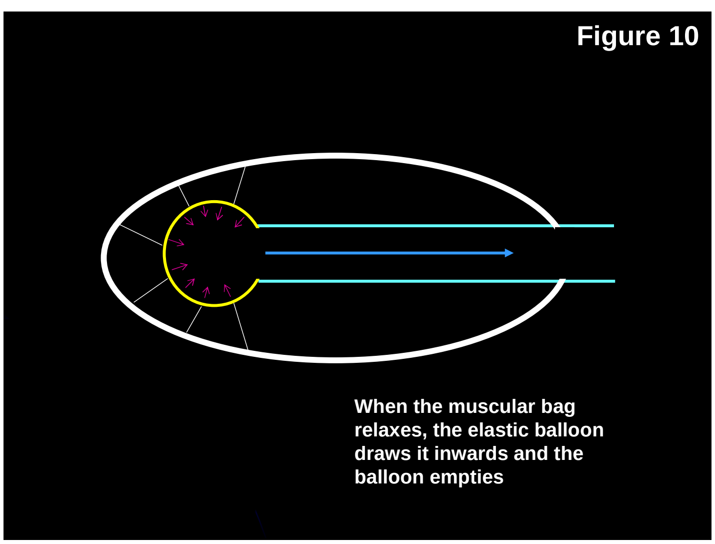
Indeed, if we could measure the pressure at many points along the tube we would find a progressive fall in pressure. A key point is that if the gas inside the balloon were denser, then the pressure drop along the tube would occur more quickly because resistance would be greater.



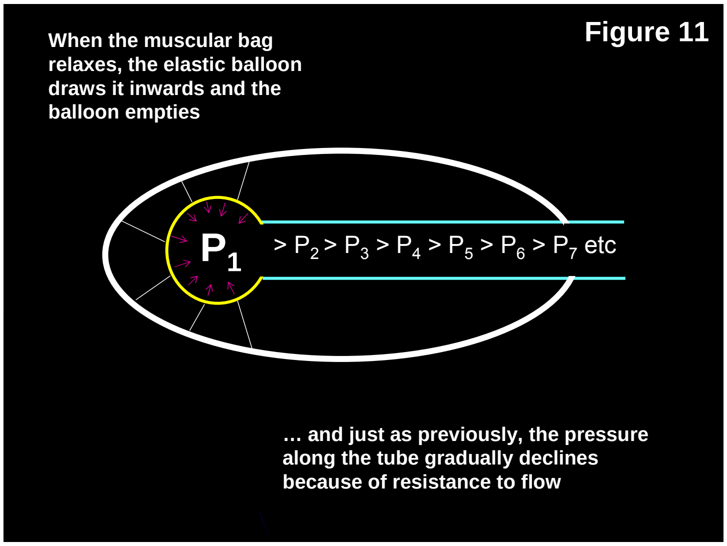
Now we place this balloon and tube structure inside a muscular bag that can expand, relax, or contract. The balloon is tethered to the bag so it is responsive to these movements. This is a “single alveolus” model of the lung, where the bag represents the chest wall and diaphragm, the balloon is the alveolus, and the tube is the airway. Obviously, the real lung has millions of alveoli.



When the muscular bag expands the balloon is stretched outwards and gas is drawn inwards.

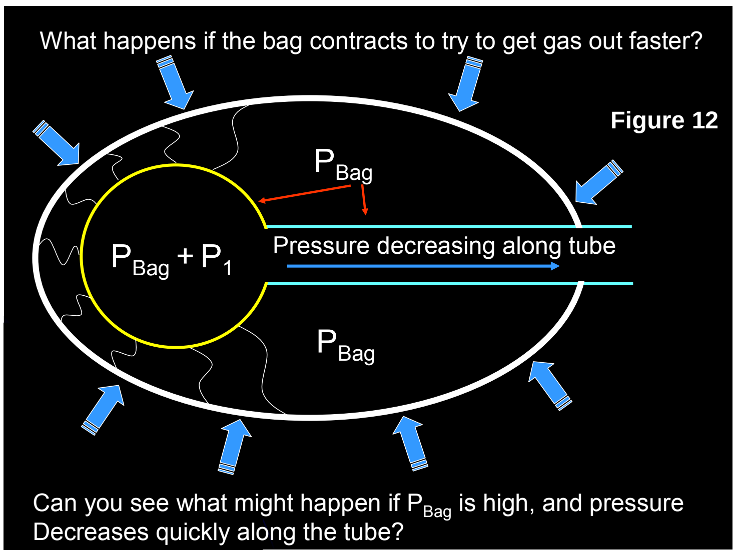


When the muscular bag relaxes, the elastic balloon draws it inward and the gas in the balloon moves outward along the tube. Note that the bag only has to relax and the elasticity of the balloon does the work, just as is the case during a normal exhalation in a real lung.

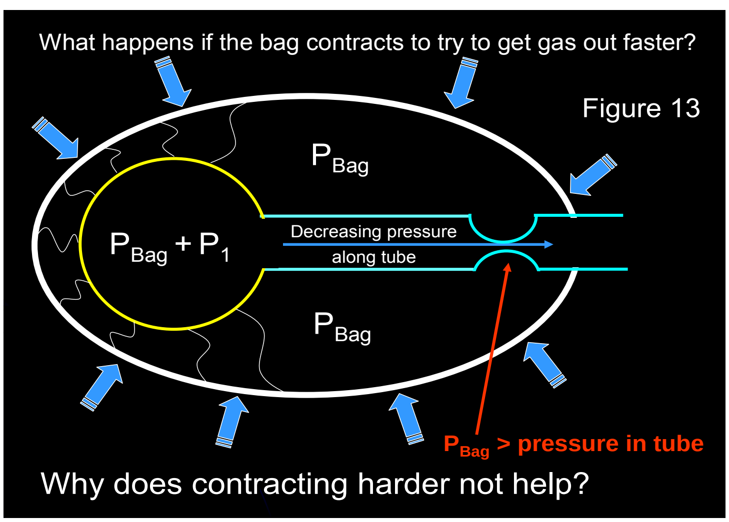


And just as previously, as gas flows out along the tube the pressure gradually declines because of resistance to flow.

Question: What happens if the bag contracts hard to try to force gas out of the balloon more quickly as in a forced exhalation during exercise?



There is positive pressure in the bag (P_{Bag}). Thus, the pressure forcing gas out of the balloon is now P_1 (the elasticity of the balloon), plus P_{Bag}. However, the positive pressure in the bag is also applied to the distensible tube (airway) leading out of the balloon. What will happen if the pressure in the bag is high and pressure decreases quickly along the tube?



If the pressure in the tube drops quickly as gas passes out, then there may come a point where P_{Bag} exceeds the pressure in the tube, and the tube will tend to collapse. This would be more likely to happen if the gas in the balloon was dense and the pressure drop along the tube was consequently greater.

The phenomenon illustrated in Figure 13 is "effort-independent exhalation," named so because once it occurs, no amount of extra expiratory effort will increase the flow of gas out of the balloon. This is because any extra pressure created inside the bag is applied to both the balloon and to the distensible tube leading out of it, thus there is no net gain. Effort independent exhalation occurs in "real-life." In fact, it is seen during a forced exhalation in normal subjects breathing air at 1 ata. But in this setting it occurs at such high flow rates that it doesn't really matter. The exercising person can still shift huge volumes of gas in and out of the lungs despite the presence of effort independent exhalation.

The problem in diving is that effort-independent exhalation will occur at much lower flow rates when a denser gas is breathed because the pressure drop along a tube is much greater. Thus, Wood and Bryan demonstrated that effort independent exhalation was almost encountered during normal tidal breathing when breathing air at 10 ata (10). Put in more practical terms, if divers breathing air at 10 ata tried to do much more than normal quiet breathing, they would have difficulty increasing their ventilation no matter how hard they tried. While air at 10 ata seems farfetched, it is not difficult to imagine gas mixes of equivalent density being used at extreme depth given the rate at which technical diving is progressing. Indeed, as previously mentioned, David Shaw's trimix on his 264 mfw dive had an equivalent density to air at 8 ata (9).

Perhaps most frightening of all, the phenomenon of effort-independent exhalation sets up the scenario described as a major contributor to David Shaw's death (9). Thus, a diver undertakes exercise during a very deep dive, breathing gas at high density. Various factors (see below) cause an initial rise in arterial CO_2 and the diver starts to feel breathless because of the consequently increased drive to breathe. Instead of stopping and resting, the diver tries to work through the problem. If this sounds implausible, think about the last time you made a descent to a deep wreck into a current! The attempts to increase ventilation intensify, and this is where the problems really start. Increased arterial CO_2 is driving the diver to breathe harder, but exhalation (and therefore ventilation) becomes effort independent and the extra effort fails to produce the increase in ventilation required to lower the arterial CO_2. In fact, the extra effort is just wasted work and only serves to produce more CO_2. The diver enters a vicious spiral in which increasing CO_2 drives greater respiratory effort, which just produces more CO_2. This will ultimately result in respiratory muscle exhaustion, rapidly rising CO_2, and CO_2 narcosis leading to unconsciousness. This scenario was predicted by Wood and Bryan in 1969 (10), and may well have been demonstrated in a practical sense by both the Shaw accident and other accidents caused by hypercapnia.

How Does Hypercapnia Occur?
Hypercapnia is a potentially dangerous state of excessive arterial PCO_2. Most of the mechanisms that might contribute to its occurrence have been mentioned in the previous sections of this paper, but it is such an important subject that it justifies an integrated summary.

In its early stages hypercapnia may produce a headache and mild shortness of breath. At more severe levels, it can produce debilitating shortness of breath, disorientation, impaired cognition, and ultimately unconsciousness. Hypercapnia also enhances the effect of nitrogen narcosis and increases the risk of oxygen toxicity.

As implied earlier, in the absence of CO_2 rebreathing (see later), hypercapnia is always due to inadequate alveolar ventilation relative to CO_2 production. Indeed, the determination of alveolar (and therefore arterial) CO_2 can be expressed by the simple equation:

$$PACO_2 = VCO_2 \div VA$$

where $PACO_2$ = the alveolar PCO_2
VCO_2 = CO_2 production
VA = alveolar ventilation

Thus, anything that increases CO_2 production, or reduces alveolar ventilation will favor an increase in alveolar and arterial CO_2. Potential contributors are listed below.

Causes of inadequate ventilation

1. Reduced sensitivity to the drive to breathe caused by CO_2.
Several mechanisms which by the brainstem respiratory controller (see earlier) may become less sensitive to rising CO_2 have been mentioned in this paper.

Individual variability. Some individuals appear to be less sensitive to CO_2. That is, arterial CO_2 can rise further before a significant drive to breathe harder is developed. The term "CO_2 retainer" is sometimes used in relation to such individuals. There is some evidence that this desensitization to CO_2 can be acquired as a result of diving (2). A consequent small increase in arterial CO_2 which does not produce any symptoms is, of itself, not necessarily harmful. However, the main concern is that such individuals may be at higher risk of oxygen toxicity and more susceptible to the effects of nitrogen narcosis. As a result, formal testing of the ventilatory response to CO_2 has sometimes been advocated for individuals who have suffered a hyperoxic seizure. In practice, this is difficult to do accurately, and the results of the test are hard to interpret.

Increases in work of breathing. As previously mentioned there is a tendency for the respiratory controller to reduce its sensitivity to CO_2 when work of breathing increases (3). Put another way, the respiratory controller will tolerate higher levels of CO_2 if an increase in work would be required to eliminating it. Although there may also be some individual variation in this tendency, this is relevant to all divers because, as previously discussed, the work of breathing virtually always increases during diving.

Higher pressures of oxygen and nitrogen. There is some suggestion that the sensitivity of the respiratory controller to CO_2 falls in the presence of hyperoxia or when high pressures of nitrogen are breathed (4).

2. Conscious overriding of the drive to breathe.

To a point, divers can consciously override the urge to increase ventilation. This is sometimes invoked as a strategy to conserve gas and has in the past been referred to as "skip breathing." The earlier discussion of gas exchange and dependency of CO_2 elimination on ventilation should make it clear why skip breathing with an elevated inspired PO_2 would be fine from an oxygenation point of view, but will result in CO_2 retention. This is a dangerous practice and should be discouraged.

3. Adoption of a disadvantageous breathing pattern

There is about 15 ml of dead space in the respiratory tree and this is inevitably increased by the addition of underwater breathing apparatus, though good equipment is designed to minimize this. For arguments sake, let's assume that a diver has about 200 ml of dead space accounting for both the anatomical and equipment dead spaces. Dead space gas is "last out and first in." Thus, it is gas from the alveoli that occupies the dead space at the end of an exhalation, and it is the first gas to be drawn back into the alveoli during an inhalation. Dead space gas is oxygen-depleted, and CO_2-rich when compared to fresh gas, and its re-inhalation with each new breath represents wasted ventilation.

Under normal circumstances, this should not matter much. The normal tidal volume is about 10 ml/kg, so for a 70 kg adult it is approximately 700 ml. Assuming 200 ml of dead space for a diver this means that 500 ml of each breath is fresh gas. However, problems can arise if a diver adopts a rapid breathing pattern with low tidal volumes. If the tidal volume were to drop to 400 ml, then dead space gas represents half of each breath. It is for this reason that divers are encouraged to adopt a pattern of slower deep breaths in preference to a pattern of fast shallow breaths.

4. Respiratory failure

This term implies that ventilation is inadequate despite a strong drive to breathe. The main contributors to this scenario in diving are the breathing of a dense gas and the physiological consequences of this (such as effort independent exhalation), the extra breathing resistance imposed by underwater breathing apparatus, and potentially, respiratory muscle exhaustion as a terminal event. These concepts have been discussed in detail earlier and so will not be amplified here.

<u>Causes of increased CO_2 production.</u>

Fundamentally, the only cause of increased CO_2 production is increased work. Thus, exercise results in production of more CO_2 whereas rest should reduce it. The only point that requires emphasis in regard to diving is that breathing itself requires work and results in production of CO_2. When a diver breathes dense gas, and/or if the underwater breathing apparatus imposes significant degrees of resistance, then the work of breathing can be a significant contributor to CO_2 production and in some scenarios may be virtually all that the diver is capable of doing.

<u>The issue of CO_2 rebreathing</u>

Rebreather divers should note that this extensive discussion of mechanisms of hypercapnia has taken place to this point in the absence of any mention of CO_2 scrubber failure. Yet the potential causes of hypercapnia that have been discussed here are often ignored in the analysis of hypercapnia events during rebreather diving, where most commentators immediately target scrubber failure as the culprit.

This is not to say that scrubber failure is unimportant, for it certainly is another potential cause of hypercapnia. In the presence of inspired CO_2, as occurs during scrubber failure, the relationship described by the equation

$$PACO_2 = VCO_2 \div VA$$

is no longer strictly true. Depending on the amount of CO_2 in the inspired gas, the $PACO_2$ may continue to rise no matter what the level of alveolar ventilation. The technical aspects of CO_2 scrubber failure is discussed in the conference Rebreather Workshop.

<u>Preventing and treating hypercapnia</u>

A relatively simple list of strategies for the avoidance of hypercapnia during diving can be constructed from perusing the list of its causes. Thus, one might aim to:

- Ensure that the underwater breathing apparatus used is optimally maintained and configured to reduce breathing resistance. In rebreather diving one might choose a larger mesh scrubber material to reduce flow resistance for very deep diving.
- Choose a bottom mix gas with low density, and make this a priority over other considerations for very deep dives where significant exercise is anticipated.
- Avoid significant exercise if possible on any deep dive. The use of DPVs in this context is a significant safety advantage.
- Adopt a breathing pattern that is slow and deep rather than fast and shallow.
- Never intentionally resist the urge to breathe, or "skip breathe."
- Stay physically fit, which might help avoid respiratory muscle exhaustion.
- Discard scrubber material well before its predicted "end of life" and always pack and install the scrubber meticulously (discussed elsewhere in this meeting).

In terms of treating hypercapnia, the time-honored "PADI advice" for an out-of-breath diver to "stop, breathe deeply, and rest" remains valid, but should be appended with "… as soon as you feel symptoms of hypercapnia" because it is often not followed until it is too late by highly motivated technical divers. The period of rest should be used to review options to favorably modify the situation. A quick review of the breathing equipment may be rewarding. For example, hypercapnia may be caused by the added breathing resistance of partially closed cylinder or rebreather mouthpiece shutoff valves. Consideration can be given to lowering the density of the breathing gas by changing to a different mix (often not possible) or by decreasing the depth.

Rebreather divers are taught to "bail out" to an open circuit gas supply in the event of hypercapnia because of the possibility that the problem is caused by failure of the CO_2 scrubber. This is valid advice, which should be followed, but several cautionary points arise. First, if the problem is caused by respiratory rather than scrubber failure, then bailing out is unlikely to help unless the work of breathing is actually lowered by changing to an open circuit regulator. Indeed, if the regulator is poorly tuned it could make the problem worse. Second, many rebreather divers have reported extreme difficulty in removing their rebreather mouthpiece to facilitate a change to open circuit whilst affected by CO_2-induced breathlessness. This illustrates the advantage of a "bail-out valve" which allows access to open circuit gas without removing the rebreather mouthpiece. Finally, the gas consumption will be extremely high when a breathless rebreather diver changes to open circuit, especially if the change occurs in deep water. Small open circuit supplies will not last very long.

References

1. Lippmann J, Mitchell SJ. Deeper Into Diving. Melbourne 2005, Submariner Publications:19-25.

2. Lanphier EH. Nitrogen-oxygen mixture physiology, phases 1 and 2 (Technical Report). Washington DC: US Navy Experimental Diving Unit; 1955.

3. Poon CS. Effects of inspiratory resistive load on respiratory control in hypercapnia and exercise. J Appl Physiol 1989;66:2391-9.

4. Linnarsson D, Hesser CM. Dissociated ventilatory and central respiratory responses to CO_2 at raised N_2 pressure. J Appl Physiol 1978;45:756-61.

5. Warkander DE, Nagasawa GK, Lundgren CEG. Criteria for manned testing of underwater breathing apparatus. In: Lundgren CEG, Warkander DE (eds). Physiological and Human Engineering Aspects of Underwater Breathing Apparatus. Proceedings of the Fortieth Undersea and Hyperbaric Medical Society Workshop. Bethesda MD, 1989. UHMS:77-86.

6. Taylor NAS, Morrison JB. Lung centroid pressure and its influence on respiratory and physical work during immersion. In: Lundgren CEG, Warkander DE (eds). Physiological and Human Engineering Aspects of Underwater Breathing Apparatus. Proceedings of the Fortieth Undersea and Hyperbaric Medical Society Workshop. Bethesda MD, 1989. UHMS:33-42.

7. Lanphier EH. Immersion effects and apparatus design: The view from Wisconsin. In: Lundgren CEG, Warkander DE (eds). Physiological and Human Engineering Aspects of Underwater Breathing Apparatus. Proceedings of the Fortieth Undersea and Hyperbaric Medical Society Workshop. Bethesda MD, 1989. UHMS:45-56.

8. Warkander DE, Nagasawa GK, Lundgren CEG. Effects of inspiratory and expiratory resistance in divers' breathing apparatus. Undersea Hyperb Med 2001;28:63-73.

9. Mitchell SJ, Cronje FJ, Meintjes WAJ, Britz HC. Fatal respiratory failure during a "technical" rebreather dive at extreme pressure. Aviat Space Environ Med 2007;78:81-6.

10. Wood LDH, Bryan AC. Effect of increased ambient pressure on flow- volume curve of the lung. J Appl Physiol 1969;27:4-8.

Discussion

IAN MACKNIGHT: Here's a very simple question. I understand the problem, and thank you for making it so clear, but the obvious question is what does one do about it?

SIMON MITCHELL: That's a good question. We've written a paper on this accident, which is referenced in the manuscript and which does discuss the issue in more detail. You do have to understand that David Shaw's accident occurred at an extreme depth. (Editor's note: see Technical Diving Conference DVD on DAN Website for video.) But that's where technical divers are heading, so we need to consider this issue. I think there are a couple of things that can be done. First, recognize the signs of carbon dioxide toxicity and do something about it early, which means rest early, stop doing what you're doing early. Reduce your work of breathing in some way early. So bailing out might have helped, perhaps, if David could have ventilated himself using his second stage purge button early. Once you get into effort independent exhalation though, it may be too late for that. Nevertheless, trying to stop the process early is one issue. Second, configure your equipment to make a lower work of breathing a priority. David had a fine grade CO_2 absorbent. He could have had a courser grade. There were also a few equipment configuration issues, which probably increased the resistance to breathing. But all of those are things that got him into the spiral. It's not a way of getting out of it unfortunately. Once you're in that spiral, it's very difficult to get out of it. Third, one of the issues that's been raised with me is whether flipping over onto his back and giving himself a positive static lung load (Editorial note: David Shaw's rebreather had a back-mounted counterlung) might have helped. A positive static lung load is a bit like what we refer to in medicine as constant positive airway pressure, where you provide a bit of pressure to try to keep the airway open. That may have helped, but I don't know the answer. To summarize, there's a few levels at which you can intervene, but most of them are in the lead-up to the event rather than what you do about it if you get into that spiral. Do you have any comments you want to make about that, Dan?

DAN WARKANDER: Probably he was too deep, and maybe you could have gotten shallower early, or used gas with more helium, but it's too late once you're there. It's not an easy situation.

SIMON MITCHELL: The issue of gas is interesting. I'm trying to remember, but I think it was something 4:80 he was breathing at the bottom. So he had about 16% nitrogen. His reason for having that was to try to ameliorate the high pressure nervous syndrome (HPNS), which we're going to hear about later today. With more helium his HPNS might have been worse. He might have been exchanging one problem for another.

JOHN CHATTERTON: For working surface-supplied divers who want to "stay ahead of the wave," if they start to feel a buildup of CO_2, they stop, they take a vent, recover, and then go back to work. Does the increased level of CO_2 in the body cause other effects? Nitrogen can cause narcosis. Can excessive levels of CO_2 impact judgment specifically?

SIMON MITCHELL: Absolutely, no question about that. We're going to hear about that too, I think. But carbon dioxide is a narcotic gas on its own, and will be synergistic with nitrogen. It's interesting though, isn't it, John, that literally right up until a minute before his death, David was still aware enough to be flushing fresh gas. He was still aware enough to perceive that he had a CO_2 toxic event and was flushing fresh gas into his loop. Another question for technical divers is why flushing the loop does not help in this situation. The answer is that it is probably not a matter of the loop being contaminated with CO_2. The diver just isn't breathing enough. Internet commentators would likely suggest he should have flushed the loop more but flushing the loop doesn't help if the problem is hypoventilation. You need to breathe more. It is true that we can't exclude some degree of scrubber failure, and there may have been some CO_2 contamination. We'll never know.

PAUL GERNHARDT: Your book Deeper Into Diving taught me that controlled full exhalations are important in terms of flushing the CO_2 out of your lungs,and it's possible to recognize situations like this and reduce that pressure in the cavity by controlled and slow exhalation fully to more fully and not collapse the tube.

SIMON MITCHELL: I think that the emphasis, we placed in the book on deep, slow breathing is mainly to try to combat the effect of something that I didn't talk about today, which is the effect of dead space. For example, we have about 150 ml of dead space in our airways, which is gas that's been exhaled, has been in the alveoli, but it's the first gas that gets drawn back into the alveoli. We increase the dead airspace volume whenever we put any kind of breathing apparatus on. If we assume the typical amount of gas in each typical breath is about 600 ml, then at least 150 ml of that is dead space. But if you suddenly start breathing rapidly and shallowly and each breath you take is only 300 ml, then half of every breath you take is dead space gas; it's already been in the lungs and it's already contaminated with CO_2. So a rapid, shallow breathing pattern is disadvantageous compared to a slow, deep breathing pattern. That's the main point I think that we were trying to get at in the book with the comments about the breathing pattern. The problem with CO_2 is that once it starts to rise, it tends to push you into a rapid shallow breathing pattern, and that's what you've got to try to avoid and take those long, slow breaths.

CLIFF BOEHM: Cliff Boehm from Baltimore, Maryland, sport diver and physician. It appeared to me that the grunting was akin to what our COPD patients will do in trying to stent open their airways. Obviously, under the circumstances the work cost him more than the product of airway stenting. Are there other techniques, either diver-initiated or some mechanical flow restrictor, to simulate that sort of thing and prevent that collapse of the airway?

SIMON MITCHELL: It's a good point and relates to the point I made earlier that what you saw there was "instant emphysema." The problem with emphysema is that the elasticity of the balloon (that is, the respiratory tissue) is less, but it amounts to the same problem. That was the basis for my earlier comment about flipping over on your back and giving yourself a positive static lung load (when wearing a back mounted counterlung). I don't know that anyone has ever looked at this objectively. I recall Dan Warkander did some work where he showed that positive static lung loads were better tolerated by the divers than negative static lung loads during exercise, and it may be that that's the reason; that it in some way stents the airway open. As to putting restrictions in the equipment, I don't know. I think you might be fixing one or ameliorating one problem and buying another because you'll get an expiratory resistance.

KARL HUGGINS: Can you comment on, number one, individual susceptibility to carbon dioxide retention, and, second, if there's any type of monitoring device that could be attached that would monitor internal carbon dioxide levels.

SIMON MITCHELL: Individual susceptibility is well established in that there are differences in the way individuals respond to rising levels of CO_2. Some will immediately respond by increasing their ventilation and keeping the level low. Some will tolerate a degree of increase in CO_2 without increasing ventilation. And there is some evidence that divers acquire a "CO_2 resistance" of sorts. In other words, their respiratory controller (in the brain) is happy to let the CO_2 level rise a little bit, particularly if getting it down again is going to require extra work. Now, the implication of that in this setting is that it will potentially bring you closer to the spiral. So there is individual variability. That's point number one. Point number two regarding CO_2 monitoring. There is nothing in diving, which allows that at present. The way we do it in anesthesiology is measuring the end expiratory CO_2. We sample gas, which has supposedly come from the alveolus and measure the CO_2 in that gas. That would be one potential way of doing it in a rebreather however we don't have a CO_2 monitor that goes on a rebreather yet. In theory, it could help the diver make decisions about slowing down and resting.

CENTRAL NERVOUS SYSTEM OXYGEN TOXICITY

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Central nervous system (CNS) toxicity is the most common and most serious oxygen toxicity risk in technical diving. Pulmonary toxicity (14) and ocular toxicity (vision changes) (9) can occur with long exposures but are not addressed here.

Biochemistry of Oxygen Toxicity
Digestion breaks food into simple sugars which react with oxygen to produce high energy molecules that are used to do physical work, build or repair tissue, and maintain physiological homeostasis such as body temperature and oxygen (O_2) and carbon dioxide (CO_2) levels (Fig. 1).

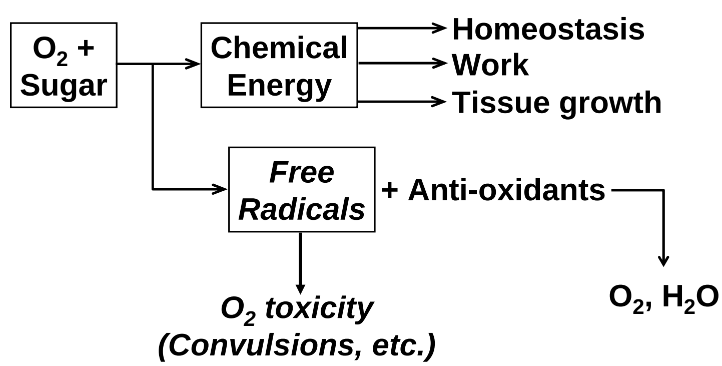


Figure 1. The biochemistry of oxygen toxicity.

As a normal part of oxygen metabolism, a small fraction of the chemical energy escapes from the proper pathways to form “free radicals” that are chemically unstable and can cause tissue damage or interfere with normal tissue function (14). Fortunately, anti-oxidant defenses have evolved that scavenge the free radicals and re-convert them into water and oxygen.

A diver who breathes elevated oxygen partial pressures, however, generates more free radicals than the anti-oxidants can deactivate. If enough free radicals accumulate, they can interfere with normal brain function and cause the signs and symptoms of O_2 toxicity such as seizures.

Physiology of Oxygen Toxicity

Cerebral blood flow (CBF) controls the rate of oxygen delivery to the brain. If CBF is high, free radicals accumulate rapidly, and oxygen toxicity occurs sooner. If CBF is low, free radicals accumulate more slowly, and oxygen toxicity is delayed. Arterial carbon dioxide is important in controlling CBF. CBF increases when the arterial CO_2 is high and decreases when the CO_2 is low. The arterial CO_2 is controlled by ventilation.

Carbon dioxide is eliminated by ventilation that reaches the alveoli. This is the alveolar ventilation. Every breath cycles one tidal volume into and out of the respiratory system (Fig. 2). The total ventilation is the breathing frequency times the tidal volume. Part of the tidal volume is trapped in the airway dead space, however, and never reaches the alveoli. Thus, the alveolar ventilation is the tidal volume minus the dead-space volume times the breathing frequency.

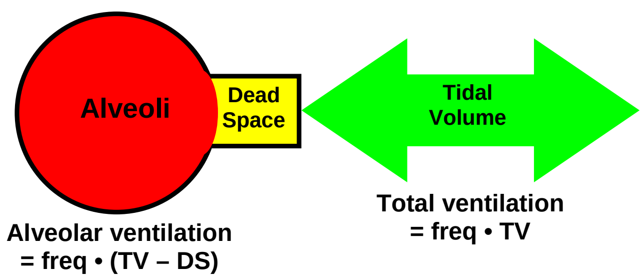


Figure 2. Total and alveolar ventilation.

Hyperventilation occurs when the alveolar ventilation is excessive and removes too much CO_2 from the alveoli so that the arterial CO_2 partial pressure falls below its normal homeostatic level of about 38 mmHg or 5 kPa.[1] Abnormally low alveolar CO_2 is known as hypocapnia and may cause numbness and tingling. Hyperventilation and hypocapnia are unusual during diving, however, because of increased breathing resistance. They are more common at sea level, particularly during anxiety, and divers who become anxious after surfacing sometimes hyperventilate leading to symptoms that can be mistaken for decompression sickness.

[1] One Pascal (Pa) is a unit of pressure equal to 1 Newton/m^2=10^{-3} kPa (kilopascal). A CO_2 partial pressure of 6 kPa is also a Surface Equivalent Value (SEV) of 6% since 100 kPa = 1 bar = 10 msw = 0.987 atmospheres.

Hypoventilation is a greater problem in diving than is hyperventilation. During hypoventilation, the alveolar ventilation is too low so that not enough CO_2 is removed from the alveoli, and the arterial CO_2 rises above its normal homeostatic level. This is hypercapnia. Hypoventilation can occur if the tidal volume is too small, the total dead space (including airways and breathing apparatus) is too large, or the breathing frequency is too low (Fig. 3). In any of these cases, the alveolar ventilation is insufficient to eliminate enough CO_2, and hypercapnia occurs even though the total ventilation may appear high. Thus, even though a diver seems to be breathing excessively, he or she is hypoventilating if the gas does not reach the alveoli. It is important to remember that the term hypoventilation really means alveolar hypoventilation.

Figure 3. Causes of alveolar hypoventilation.

CO_2 Retainers

While arterial CO_2 is a powerful ventilatory stimulus, not everyone has an equally strong ventilatory drive when presented with an increase in CO_2. Those who have relatively small increases in ventilation when CO_2 rises are called CO_2 retainers and might be susceptible to O_2 toxicity as a result of higher cerebral blood flow.

Dr. Karl Schaefer worked in submarine medicine for the German Navy during World War II, and, after the war, he did similar work for the U.S. Navy. Schaefer investigated the ventilatory response of seven breath-hold who were U.S. Navy submarine escape instructors (30). Schafer measured the ventilation of these divers before, during, and after breathing air containing 5% CO_2 (Fig. 4). The y-axis in Fig. 4 is ventilation in liters per min. The x-axis shows 15 min of ventilation on air followed by 15 min on 5% CO_2 and 15 min on air. The lower line is the increase in ventilation that occurs during CO_2 breathing during a period of intense breath-hold diving activity. The upper line represents the same seven divers after a 3-month layoff during which their sensitivity to CO_2 increased by 25% as indicated by the rise in ventilation. The point is that a CO_2 retainer today may not be a CO_2 retainer tomorrow. Variability in CO_2 response is another source of uncertainty that makes susceptibility to oxygen toxicity difficult to predict.

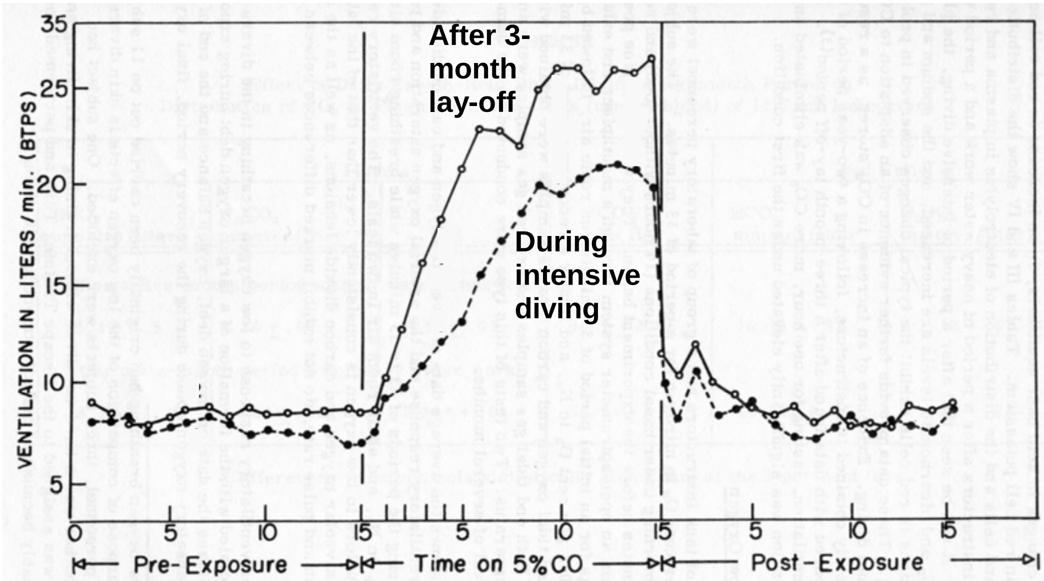
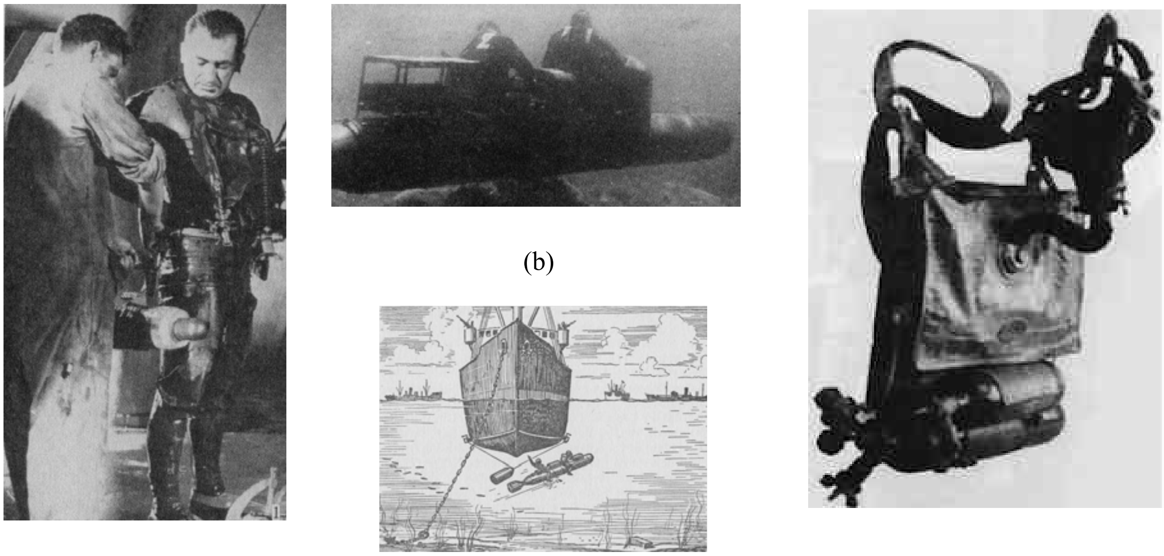


Figure 4. Ventilation while breathing 5% CO_2 during a period of intensive breath-hold diving activity and after a three month period of no diving (30).

Operational Oxygen Toxicity

The problem of operational CNS O_2 toxicity first became apparent during the Second World War. The 10th Light Flotilla of the Italian Navy used oxygen divers to sink or disable some 30 British and allied ships in the Mediterranean (8). An Italian combat diver might surface swim to within a hundred yards of a target ship before submerging for the final attack and placing a limpet mine on the bilge keel (Fig. 5a). The Human Torpedo was another method of attack for distances greater than a man could swim (Fig. 5b). Piloted by two divers, this vehicle had a large warhead that could be fastened under the target ship's hull (5c).



(a) (b) (c) (d)

Figure 5. The 10th Light Flotilla of the Italian Navy. (a) Combat diver preparing to attack a British ship in Gibraltar harbor (31). (b) "Human torpedo" piloted by two divers used for longer range attacks from outside harbors and launched from a submarine (31). (c) Placing a warhead underneath a target ship (37). (d) Closed-circuit pendulum oxygen rebreather used by 10th Light Flotilla divers (http://regiamarina.net/xa_mas/history/origin_us.htm).

The divers breathed oxygen from a pendulum rebreather (Fig. 5d) and, on occasion, would become unconscious and be lost. There was a rare story from a diver who survived an apparent episode of oxygen toxicity during an attack in Gibraltar harbor (8) (pg. 94).

"… the torpedo … began to sink at a great rate … I felt … a strange sensation of well-being, with red, yellow, and blue sparks before my eyes … more than 30 meters down and … still sinking … I felt that the strange sensation of well-being was about to turn to loss of consciousness. … I had to … swim as hard as I could … at last I reached the surface."

In the U.S., Dr. Chris Lambertsen developed an oxygen rebreather for the Office of Strategic Services (OSS; (33)). Lambertsen spent many hours in the Caribbean instructing the OSS swimmers in oxygen diving. The oxygen exposure limits at the time were 30 min at 90 fsw or 120 min at 50 fsw (18), and Lambertsen would occasionally feel signs of toxicity such as twitching and fluttering of the diaphragm. These signs resolved if he hyperventilated. At the University of Pennsylvania after the war, he confirmed the influence of ventilation, CO_2, and cerebral blood flow on O_2 toxicity (33).

Figure 6. OSS Operational Swimmer training with the Lambertsen Amphibious Respiratory Unit (LARU; CJL photo).

Figure 7 shows two World War II combat divers wearing oxygen rebreathers that pass the exhaled gas through an absorbent canister to remove CO_2. The device on the right is a British pendulum unit in which the diver inhales and exhales through the same hose into the CO_2 scrubber. The pendulum system is simple and requires no one-way valves, but CO_2 is retained in the hose, and this dead-space increases as the absorbent bed is exhausted. The device on the left (the LARU) is Lambertsen's recirculating unit in which the diver inhales from the CO_2 scrubber through one hose and exhales into the scrubber through another hose. One-way valves ensure unidirectional gas flow, but breathing resistance in the hoses and scrubber can restrict the increase in ventilation that would occur at sea level with elevated CO_2. This becomes a greater problem as depth increases.

Figure 7. The LARU-X and the Amphibian Mark II (CJL photo).

The Lambertsen unit also used a full facemask. After the War while demonstrating it to the U.S. Coast Guard, Lambertsen inadvertently found himself at a depth of 100 fsw, alone, and on the verge of oxygen toxicity. Just prior to onset of a convulsion, he inflated his counterlungs to increase his buoyancy and rose to the surface, unconscious, but where he was rescued (33). Because unconsciousness, particularly due to hypoxia or oxygen toxicity, appears common in rebreather fatalities (34), a full facemask and a nearby dive buddy might significantly improve the safety of rebreather diving.

Increased breathing resistance is a threat to adequate ventilation, particularly during exercise. This is illustrated by the effect of depth on the Maximum Voluntary Ventilation (MVV), which is the highest ventilation sustainable for 15 sec (Fig. 8). As depth increases, so does resistance to gas flow in the airways causing increased work of breathing (10). At 100 fsw, for example, the MVV is only about half of what it was on the surface. The greater work of breathing in the airways and breathing apparatus can cause respiratory muscles to fatigue sooner than they would on dry land.

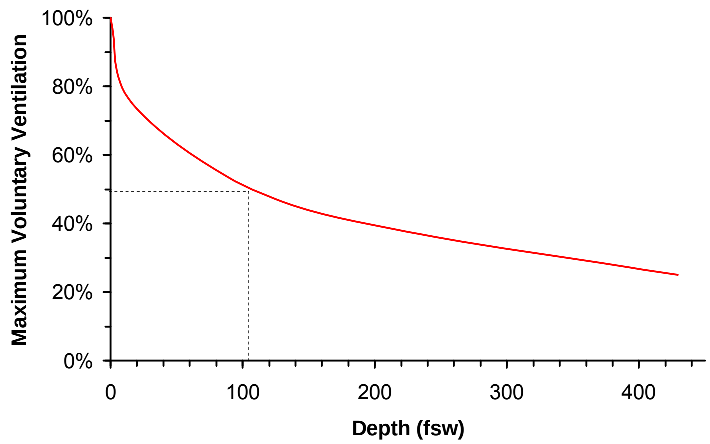


Figure 8. Maximum Voluntary Ventilation (MVV) (10).

Kenneth Donald and Oxygen Diving during World War II

The British Navy developed its own underwater attack capability during World War II including a "Human Chariot" (Fig. 9) that was modeled on captured Italian equipment (37). With U.S. Navy oxygen exposure limits of 50 fsw for 120 min and 90 fsw for 30 min, divers began to "flake out" in training and after one died, formal scientific investigation began (18).

Figure 9. British Navy Human Chariot (37; pg. 81).

Surgeon LT Kenneth Donald volunteered for ‘special service’ to study the problem of oxygen toxicity. With no research background and little hyperbaric experience, Donald found himself in charge of an experimental program that ran from 1942-45 and was the largest study of oxygen toxicity conducted to that time. Much of this work remained confidential until his 1992 book, *Oxygen and the Diver* (18).

Figure 10 is the wetpot where Donald conducted his studies. A test diver in the water was tended by a safety diver above him. Sidney Woollcott, a Human Chariot diver who won the Distinguished Service Medal for sinking the Italian liner *Sumatra* at Phuket, described his experience as an experimental subject (37) (Chapter 3).

“I had been down about 20 min (at 50 feet) when I felt the first twitching of the lips. I exercised my lips around the mouthpiece, and the twitching went off… (At 30 min,) I suddenly felt a violent twitching of my lips. I tried to wriggle them around the mouthpiece again, my mouth was blown out like a balloon … The twitching of my lips increased, and I felt a terrific tingling sensation at the side of my mouth, as if someone were touching it with a live wire. This … became a definite pain, and my lips became so distorted … as if my mouth were stretched to … near my right ear. I tried to climb the ladder, but … my whole body was convulsing … I tried to shout to the attendant to grab me before I fell back. Although my lips formed words, no sound came … blackness closed in on me – I was out.”

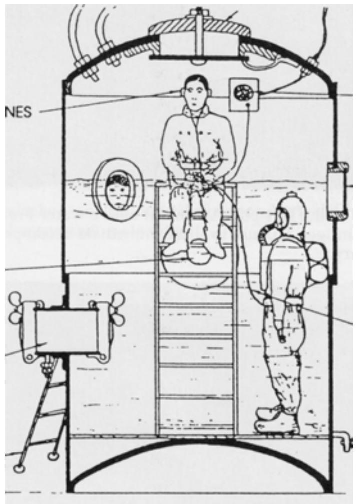


Figure 10. Admiralty Experimental Diving Unit chamber (37) (Chapter 3).

Sidney Woollcott's experiment was more spectacular than most but, otherwise, it was typical. For each depth tested, a diver would breathe oxygen until he developed signs or symptoms. Figure 11 summarizes 1,212 O_2 toxicity symptoms reported in 2,170 exposures by the U.S and British navies (21). Over half were muscular twitching, sometimes occurring several times in one exposure. Nausea was next most common followed by dizziness and vertigo, and convulsions, all at about 10%. Half the convulsions appeared to occur without premonitory symptoms (21).

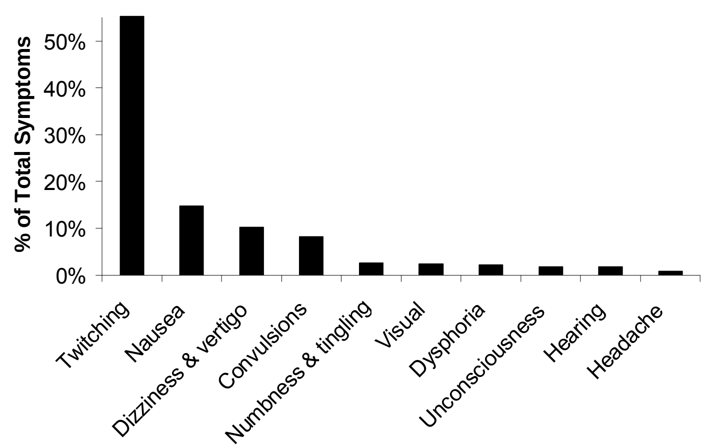


Figure 11. Reported signs and symptoms believed to have been associated with CNS oxygen toxicity (21).

After enough dives were conducted, Donald constructed a "survival curve" as shown in Fig. 12a where the percentage of divers who "survived" (did not develop symptoms) to a given time was presented as a function of time. The y-axis in Fig. 12a is the percentage of divers who developed symptoms, and the x-axis is the exposure time in minutes. In Fig. 12a, 37 dry, resting divers were exposed to 90 fsw of oxygen, and 50% developed symptoms by 22 min.

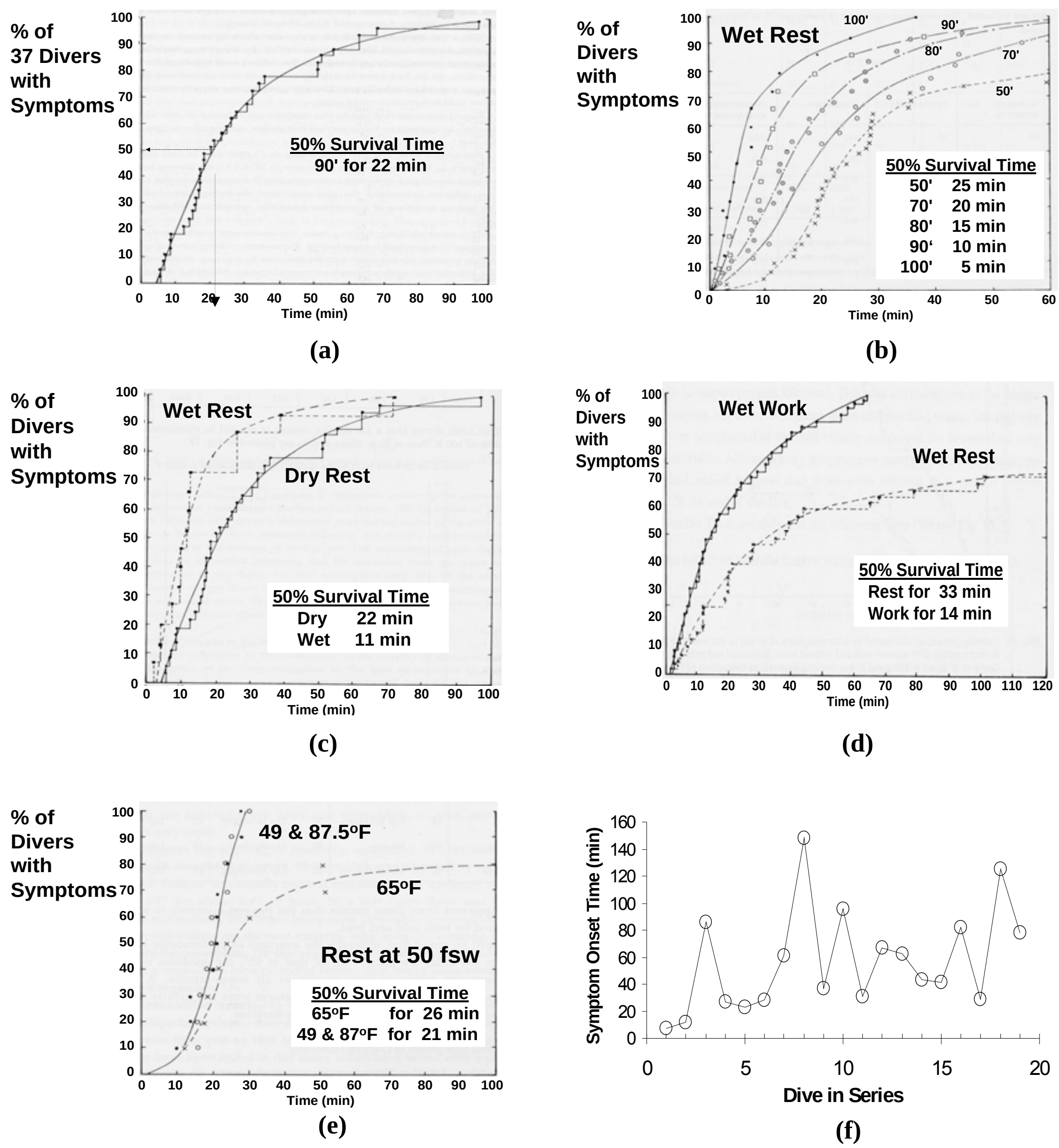


Figure 12. CNS oxygen toxicity "survival" (18).
(a) Survival curve at 90 fsw for dry, resting divers.
(b) Survival curves for 50, 70, 80, 90, and 100 fsw for wet, resting divers.
(c) Survival curves at 90 fsw for wet and dry divers at rest.
(d) Survival curves at 50 fsw for wet divers at work or at rest.
(e) Survival curves for resting divers at 50 fsw at 65ºF and at 49 or 87ºF.
(f) Symptom onset time for multiple exposures of a single diver.

Figure 12b shows the results for wet resting exposures at 50-100 fsw. The 50% survival times were short, ranging from 25 min at 50 fsw to 5 min at 100 fsw. The 50% survival time decreased by about 5 min for each 10 fsw increase in depth.

The effect of immersion on symptom onset time is shown in Fig. 12c for resting divers exposed dry and wet at 90 fsw. A wet diver survived only about half as long as a dry diver. The 50% percent survival times were 22 min dry and 11 min wet.

The difference between work and rest is shown in Fig. 12d for divers who were immersed at 50 fsw. Exercise reduced the 50% survival time from 33 to 14 min.

Water temperatures of 49, 65, 87.5^{o}F were tested at 50 fsw with resting divers (Fig. 12e). Forty-nine and 87.5^{o} F seemed to have the same effect and decreased the 50% survival time from 26 to 21 min. The differences were greater at longer times. Since the divers were thermally comfortable when the exposures began, the absence of a larger effect at the short times probably reflected the time necessary for the divers to heat or cool.

One of the most striking observations was the wide range of variability within individual divers. Figure 12f shows the onset times for one diver who made 19 resting dives to 70 fsw at two dives per week. The day in the dive series is shown on the x-axis and the symptom onset time on the y-axis. Similar variability in susceptibility from day to day was typical for most divers.

Donald conducted 611 individual exposures at depths of 25 to 100 fsw. Immersion decreased the 50% survival time by half, from 22 to 11 min, for resting divers at 90 fsw. The mechanism responsible for this decrease is uncertain although the diving response as a result of facial immersion has been observed to cause increased cerebral blood volume (29). Exercise decreased survival time by 58%, from 33 to 14 min, for wet divers at 50 fsw. Although exercise with air at sea level typically decreases arterial CO_2, experiments with graded exercise while breathing oxygen at 2 ata have found a progressive increase in arterial CO_2 (13). Temperatures above and below 65^{o}F caused a 19% decrease in survival time from 26 to 21 min for divers resting at 50 fsw. This effect was probably underestimated due to beginning from a pre-dive thermoneutral state. No human studies have investigated possible causes of the temperature effects. The 50% survival time at 50 fsw for wet resting divers was about 25 min and each additional 10 fsw decreased this about 5 min. Perhaps the most surprising finding was the extreme variability of symptom onset times, one diver having a range of onsets of 7–148 min with a mean of 57 min. No convulsions occurred, and the distribution of symptom onset times was otherwise similar to observations for other divers.

Donald concluded (pg. 78) (18),

"The variation of tolerance between individuals, the variation of tolerance of each individual, the impairment of tolerance with work and under water, all make diving on pure oxygen below 25 fsw a hazardous gamble… the complete absence of symptoms before convulsions constitute a grave menace to the independent oxygen diver."

These conclusions were based on extensive data and do not seem unreasonable. The final conclusion was more speculative, however, as it extrapolated beyond the available information.

"… exclud(ing) covert military diving … 15 fsw would now be an appropriate limit." (Pg. 100-101)

Donald's work has been criticized due to a rumor that his divers feigned symptoms to reduce their risk of oxygen convulsions. Although he denied this with vigor (pg. 195-196) (18), it has cast unfortunate uncertainty over a unique body of work that was executed in difficult times with great effort and dedication.

U.S. Navy Oxygen Exposure Trials

There are independent data from U.S. Navy studies from which quantitative risk estimations can be made. These included 773 single and multilevel working dives at 20-50 fsw in which the O_2 percentage was controlled to over 99%. Manifestations of O_2 toxicity were described as 11 convulsions, 33 definite symptoms, and 37 probable symptoms (32).

The Navy data can be modeled statistically (20, 21, 32). Suppose O_2 toxicity were caused by a toxic substance "X" as suggested by the biochemistry of free radicals reviewed earlier. High oxygen partial pressures might generate more "X." Some "X" might be deactivated by protective agents. The probability of O_2 toxicity might be modeled to increase with the concentration of "X."

A simple statistical model fit to the Navy data estimated the probability of convulsions during square dives (32). In Fig. 13, the oxygen exposure time is on the x-axis, and the dive depth is on the y-axis. The model predicted the rectangular hyperbolas that have traditionally been used to represent the relationship between time and the occurrence of oxygen toxicity (11, 12). Figure 13a shows the probability of convulsions in increments of 1% from a threshold of 0% at 19 fsw to 8% at the top of the figure. The points marked by "X" represent seven convulsions. For example, one convulsion occurred after 31 min at 40 fsw for which the estimated risk was slightly less than 2%. Four other convulsions occurred on multilevel dives and are not shown.

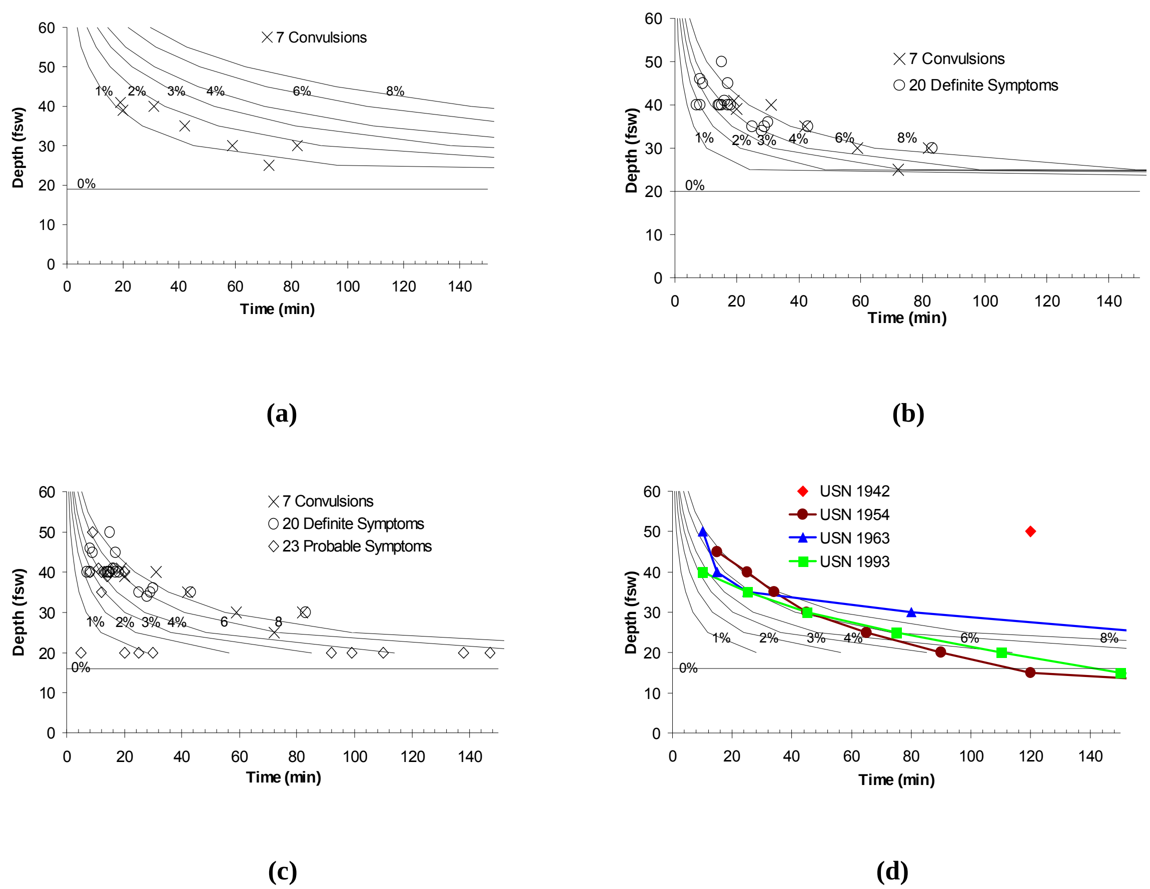


Figure 13. Statistical models of CNS oxygen toxicity (32). (a) Convulsions only. (b) Convulsions and definite symptoms. (c) Convulsions, definite, and probable symptoms. (d) U.S. Navy oxygen exposure limits, 1942 to 1993 (18).

A more conservative approach in Fig. 13b modeled the probability of either convulsions or definite symptoms (32). The circles in the figure represent 20 definite symptoms. The probability curves are shifted downwards to shallower depths, and the 0% symptom threshold was 20 fsw.

A still more conservative approach results from including convulsions, definite, or probable symptoms. The diamonds in Fig. 13c represent 23 probable symptoms. The probability curves are shifted further downwards indicating higher predicted risk as shallow depths. The 0% threshold for symptoms is 16 fsw, near Donald's recommendation of 15 fsw. Because of the unpredictable nature of O_2 toxicity, the most conservative model of convulsions, definite or probable symptoms is used in the subsequent discussion.

Figure 13d shows model predictions for convulsions, definite, and probable symptoms in comparison with the U.S. Navy O_2 Exposure Limits from 1942 to 1993 (18). The 1942 limit of 50 fsw for 120 min has an estimated risk well above 8%. The largest decrease in the limits occurred from 1942 to 1954. For the short, deep exposures, the estimated risks were about 8% and fell to below zero by 120 min. The 1963 limits were 7-8% for the short, deep dives and even higher for longer dives. The 1993 limits were more conservative than the 1963 limits but had estimated risks starting at 6% deep and falling to below threshold at shallow depths.

The finite, non-zero risks of the 1993 limits for 100% oxygen were also estimated by Navy models (20, 21, 24), but for operational diving with closed-circuit oxygen, procedures for purging the breathing apparatus counterlung are such that dives begin with about 75% oxygen rather than pure oxygen (3) which results in estimated risks of less than 1% (20, 21, 24).

Donald had reported that some divers seemed more susceptible to oxygen toxicity that others. The U.S. Navy searched for evidence of differing susceptibility among divers in their oxygen trials, but there were too few toxicity episodes to show this statistically (23).

Mixed Gas Oxygen Exposure Limits

Donald also had the task of developing equipment and diving procedures for use by Port Clearance divers (Fig. 14) whose job was to sweep European harbors of mines and booby traps after the Allied invasion in Normandy in 1945 (18). (Today, these are called explosive ordinance disposal (EOD) divers.) Because the harbor depths were too great for pure oxygen, Port Clearance Divers used semi-closed breathing apparatus as indicated by the stream of bubbles from the diver in Fig. 14. Donald believed the exposure limits were the same for pure oxygen and for oxygen in mixed gas. However, he recognized that the risk of CO_2 retention was greater at the deeper depths with mixed gases, and this might increase the O_2 toxicity risk.

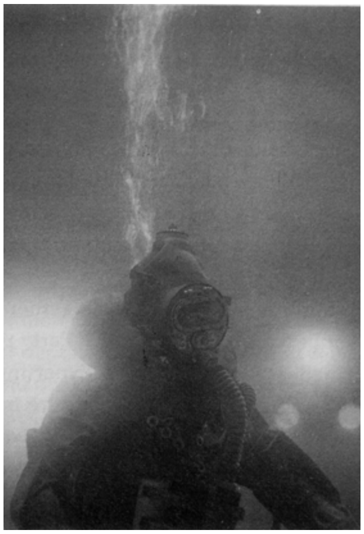


Figure 14. Port Clearance diver with a semi-closed circuit rebreather (18).

Figure 15 shows risk estimates for mixed gas diving using the same values as in Fig. 13 but expressed in terms of O_2 partial pressure in atmospheres rather than in fsw. The 0% threshold is at 1.5 atm. Figure 15 also shows the 1959 U.S. Navy (1) and 1991 NOAA (2) mixed-gas limits for comparison. For short, Navy exceptional exposure limits, estimated risks are on the order of 4-6% and decrease to 0% at 1.5 atm for longer exposures. For normal limits, the maximum risk is 1% and below the 0% Navy threshold at 60 min. The 1991 NOAA exceptional exposure limits are similar to the 1959 USN Exceptional Exposure limits while the normal exposure limits decrease from 2% to below the 0% threshold.

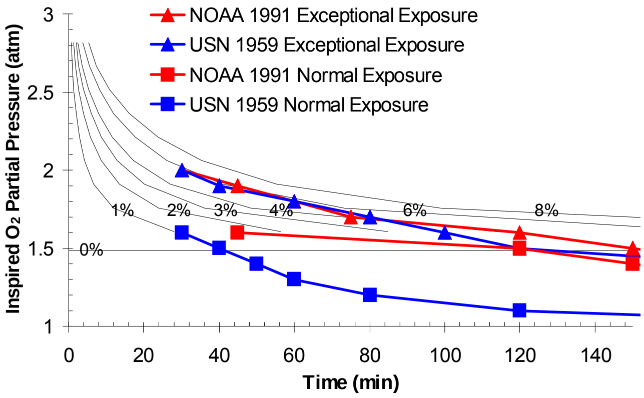


Figure 15. Statistical model of the probability of convulsions, definite symptoms, and probable symptoms expressed in terms of oxygen partial pressure rather than depth (32).

The constant risk isopleths for the Duke model are about 2% lower than for the Navy model, but the 0% risk isopleth of 1.5 atm for the Duke model is greater than the 0% risk isopleth of 1.3 atm for the Navy model (24). This was the basis on which the Navy selected a maximum O_2 partial pressure setpoint of 1.3 atm for closed-circuit mixed gas diving, but the Navy also imposed an arbitrary time limit of 240 min at 1.3 atm because of potential onset of pulmonary oxygen toxicity (personal communication, CAPT E.T. Flynn, MC, USN (ret)).

Both the Duke and Navy models were calibrated with dives of 20 fsw (1.6 atm) or deeper, and there was only one probable, dive-stopping event in 93 dives at 20 fsw (20). With one event in 93 exposures, the 95% binomial confidence interval includes all incidences of oxygen toxicity between 0.03% and 5.8%. Thus, while oxygen toxicity models are useful for illustrating principles, predictions for partial pressures of 1.6 atm or less are unreliable at best. For this reason, we shift our attention to observational studies and case reports, which although more ambiguous and less desirable than controlled trials, are the only other sources of information bearing on the problem of CNS toxicity at low oxygen partial pressures.

Observational Studies

Leitch reviewed 1,301 dives conducted at the British Navy Deep Trials Unit to investigate why exposures below 155 fsw (46.5 msw) were aborted (26). Incidents leading to dive termination included respiratory distress, disturbed consciousness, panic, nausea, malaise, mood or sensory disturbances. When categorized by O_2 partial pressure, there were 0% incidents in 319 dives at partial pressures of 0.9-1.2 atm, 2% in 299 dives at 1.3 atm, 8% in 155 dives at 1.4-1.6 atm, and 5% in 530 dives at 1.7-2 atm (Fig. 16). These findings do not address oxygen toxicity directly, but the absence of incidents below partial pressures of 1.3 atm was consistent with a threshold for oxygen-related problems of 1.2-1.3 atm.

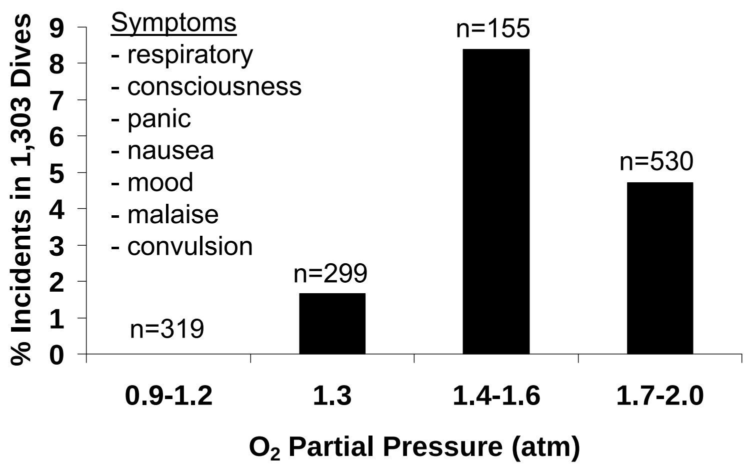


Figure 16. Inspired oxygen partial pressures in effect during dives that were aborted (26).

In 2006, Arieli and coworkers reported on signs and symptoms in 2,527 closed-circuit oxygen training dives by 473 Israel Navy combat swimmers (6). The mean O_2 fraction was 91±5% so the actual O_2 exposure was less than indicated by the dive depth. No symptoms were reported at 7 fsw (2 msw) or less in 61 dives, 2.7% of 711 dives had symptoms at 10 fsw (3 msw), 3.3% of 269 dives had symptoms at 13 fsw, 3.9% of 1108 dives had symptoms at 17 fsw (5 msw), and 6% of 164 dives had symptoms at 20 fsw (6 msw). Eight divers (0.4% of 2,500 dives) lost consciousness after 3-4 hrs although the depths were not specified.

While the Arieli paper refers to CNS oxygen toxicity (6), the most common signs and symptoms (e.g., 4.5% headache, 2.6% hyperventilation, 2.4% heavy breathing) were attributable to CO_2 retention while signs and symptoms attributable to oxygen poisoning (e.g., 2.6% nausea, 1.6% dizziness, 0.9% tinnitus, 0.6% disorientation, 0.4% tingling, 0.4% hearing disturbances, 0.32% loss of consciousness) were less common and might also reflect CO_2 retention. Indeed, loss of consciousness after 3-4 hrs was consistent with the breakthrough of a depleted CO_2 scrubber, and the increase in symptom incidence with depth could reflect CO_2 retention due to increased gas density.

In a second publication, the same authors investigated the relationship of inspired CO_2 to unconsciousness (5). CO_2 scrubber performance was tested in 18 of 36 divers who developed symptoms. Only rebreathers that had remained sealed after the incident were tested. The divers peddled a bicycle ergometer for 10 minutes while the inspired CO_2 was monitored. When the results were categorized as high or low inspired CO_2, 11 divers in the high CO_2 group had a mean 4.2% surface equivalent value (SEV), and four of these (36%)

had become unconscious. Seven divers in the low CO_2 group had a mean 0.2% SEV, but none of these divers lost consciousness. The causes of the high CO_2 were poor canister packing, strenuous activity, or water leaking into the canister. A study in 2008 found that both under and over-packing a canister with absorbent reduced the duration to effectively remove CO_2 (7).

While unconsciousness due to CO_2 poisoning is no less hazardous that from O_2 poisoning, differentiating between the two based only on signs and symptoms may not always be obvious, and of course, CO_2 retention also potentiates oxygen toxicity.

"Shallow Water Blackout"

During his oxygen toxicity investigations, Donald identified a phenomenon he called "shallow water blackout (SWBO)" in which closed-circuit oxygen divers became unconsciousness at depths of less than 20 fsw (17, 18). (Donald's shallow water blackout was different from, and predated, the shallow water blackout associated with breath-hold diving today.) Symptoms reported by SWBO survivors included feeling "muzzy, hazy, confused, distant, out of touch, and everything went in waves." During recovery, the divers often had marked tremor.

Two groups of divers were at risk for SWBO: (a) "Human Chariot" pilots whose risk was associated with inspired CO_2 due to faulty scrubbers (Fig. 9). (b) Landing Craft Obstruction Clearance Divers, a secret unit that cleared obstacles from Sword and Gold beaches prior to the D-Day invasion in Normandy (Fig. 17). Their risk was associated with CO_2 retention during bouts of extreme anaerobic exercise (17, 18).

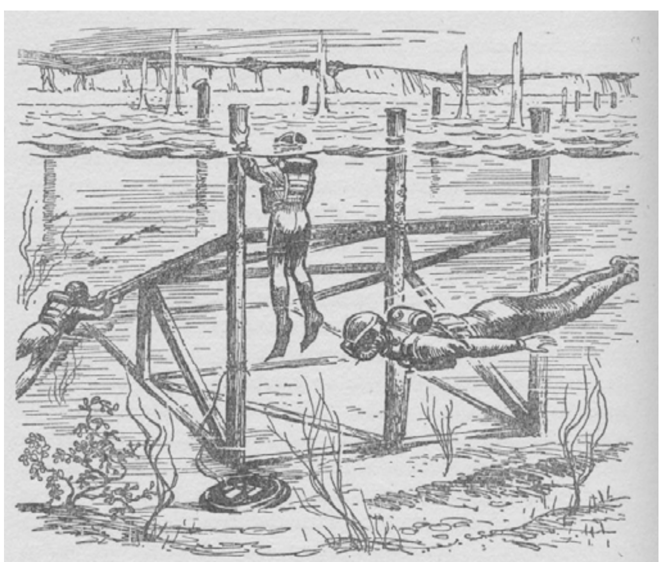


Figure 17. Landing Craft Obstruction Clearance Divers, pg. 116 (37).

Donald ruled out CNS oxygen toxicity because he had not observed it at less than 25 fsw. CO_2 retention seemed a possible candidate, but the respiratory distress associated with CO_2 was uncommon even though the CO_2 levels were high. Donald's investigations led him to conclude that the normal ventilatory response to CO_2 was diminished in hyperoxia thus allowing arterial CO_2 to rise to narcotic levels without stimulating the usual respiratory symptoms.

The signs and symptoms reported by Arieli in the Israeli combat divers also occurred at depths too shallow for CNS oxygen toxicity, and excess CO_2 was also implicated (5, 6). There is certainly no question that CO_2 narcosis is a significant hazard to divers. Whether CO_2 narcosis is a greater risk with hyperoxic gases and whether Arieli's divers were affected by SWBO remain to be determined.

Modern technical divers commonly breathe inspired oxygen partial pressures of 1.3-1.6 kPa, can have physiological CO_2-retention due to breathing resistance, and sometimes use closed-circuit mixed gas breathing apparatus with the potential for inspired CO_2 from faulty scrubbers. These divers are occasionally subject to a phenomenon called "deep water blackout," which appears similar to Donald's observations at shallow depth (28). Whether the mechanisms of the two phenomena are similar also remains to be determined.

Case Reports

Case 1. A DAN member reported a series of dives including the profile shown in Fig. 18 which was for about 27 min to 200 fsw on trimix 18/45 (18% oxygen, 45% helium). At 120 fsw, he shifted to trimix 35/25, and at 80 fsw, he took a low PO_2 break on 18/45 trimix before switching to 50% nitrox at 70 fsw. After another low PO_2 break at 30 fsw on 35/25 trimix, he switched to 100% O_2 at 20 fsw. After about 7 min at 20 fsw, he noted involuntary contractions of his diaphragm and switched to 18/45 trimix. The contractions lasted for less than 1 min, and he completed the dive on 50% nitrox without further incident. Having made many dives with these gases, he passed this off as an interesting experience and continued using the same procedures until similar episodes of diaphragmatic contractions at 20 fsw and 70 fsw on 50% nitrox (both with 1.6 atm PO_2) got his attention. He has since switched to a rebreather and uses a constant 1.25 atm PO_2 setpoint to avoid the oxygen partial pressure spikes that occur when switching open-circuit gas mixes. A comparison between oxygen partial pressures for open-circuit and rebreather diving is presented in Assessing the Risk of Decompression Sickness (35) relative to the balance between the risks of decompression sickness and CNS oxygen toxicity.

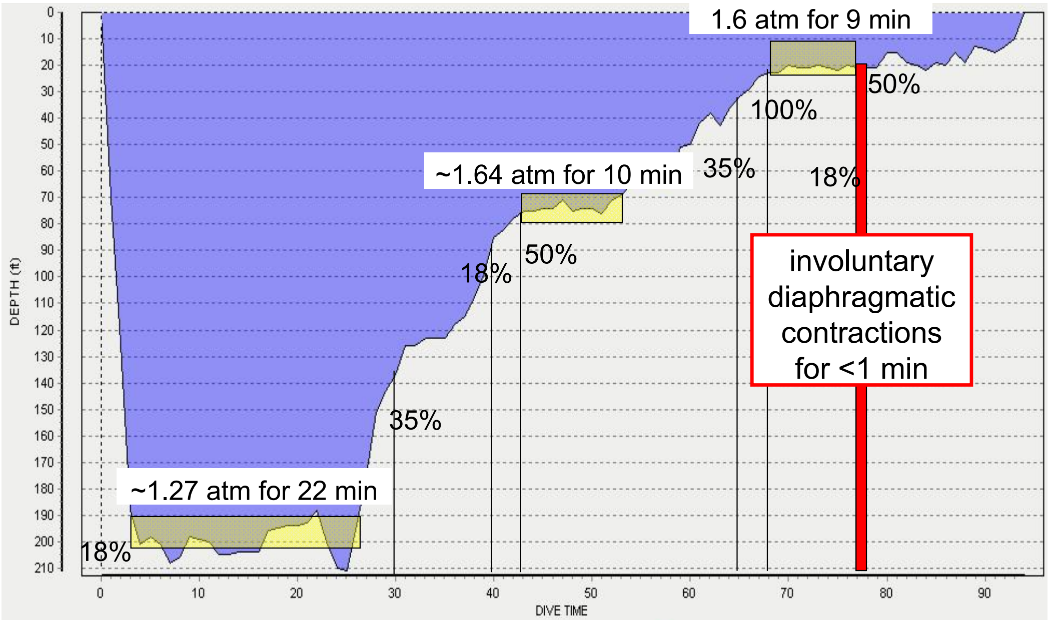


Figure 18. Apparent CNS oxygen toxicity reported to DAN by a diver who frequently changed gases using open-circuit breathing apparatus.

Case 2. Another report to DAN concerned a diver using a rebreather with a 1.3 atm oxygen setpoint had made a 247 fsw dive and was finishing his 40 fsw decompression stop when he noted diaphragmatic contractions that began like cold shivers and strengthened over 30-60 sec before ending as a convulsion. (His 'CNS O_2 clock' – see below – was less than 50%. During a dive 28 hrs earlier, his 'clock' had reached nearly 100%.) He had enough time to close his mouthpiece valve and was preparing to breathe 50% nitrox by open circuit when the convulsion occurred. An attentive dive buddy took charge and returned him to the surface where he was recompressed despite the absence of DCS symptoms. While breathing oxygen during recompression, diaphragmatic contractions occurred 6-7 times suggesting continued sensitivity to oxygen, but he breathed air to avoid convulsions.

Cases 1 and 2 are important anecdotes regarding CNS oxygen toxicity but would have been more useful had they been accompanied by computer-recorded depth, gas switch, and time profiles (Case 1) and O_2 sensor and time recordings from the rebreather "black-box" (Case 2). For the future, divers are encouraged to send full recordings and symptom descriptions to DAN for analysis. Problem-free dives are just as important as dives on which problems occur.

Case 3. This case occurred in the Duke wetpot with a Mk 15 rebreather, an air diluent, and 1.6 atm O_2 setpoint (36). A Navy diver had a seizure after 40 min of heavy work at

100 fsw (30 msw). The original Scott mouthpiece in the Mk 15 was found to be a major source of breathing resistance and was replaced with a low resistance design. After reducing the setpoint to 1.4 atm, 156 dives were completed without further oxygen incident.

Case 4. This was a fatal dive to 180 fsw on air with an oxygen partial pressure (PO_2) of 1.36 atm. Decompression was conducted at 20 fsw and 10 fsw on 100% O_2 where a seizure was witnessed. The diver was reported to have been taking multiple medications including epinepherine, darvocet, ventolin inhaler, lomotil, marax, transdermscop, decongestants, mylanta, tylanol, and sudafed.

Case 5. This was a fatal cave dive to 95 fsw on 39% nitrox with a PO_2 of 1.51 atm. The diver was witnessed to have a seizure and was later reported to have been taking pseudoephedrine, phenylpropanolamine and antihistamine.

Case 6. This was a fatal open-circuit cave dive on 24.3/26 trimix with a PO_2 of 1.4 atm. The diver appeared uncertain after 25 min at 156 fsw and aborted the dive. At 147 fsw, she fell sideways and convulsed. She dropped her regulator which could not be reinserted as her jaws were locked. A post-dive investigation found no problems with her equipment and gas. She had taken a decongestant and birth control medication.

Case 7. This was a non-fatal training dive for 15 min at 90 fsw on air (0.8 atm PO_2). The diver made a 10 min safety stop at 20 fsw on 82% O_2 (1.3 atm PO_2). On ascending from 20 fsw, his visual field became orange, and he had two violent spasms during which his back arched and head snapped rearwards. Upon reaching the surface, he had 10-15 additional spasms on the swim platform but remained conscious. There were no further symptoms.

This case occurred after a short exposure to a low O_2 partial pressure. The case was remarkable in that the diver had recently taken Cialis whose active ingredient, tadalifil, is known to increase blood flow. We tested the hypothesis that tadalifil might increase susceptibility to oxygen toxicity in rats (16). Tadalafil caused no change in cerebral blood flow (CBF) in air at 1 ata, but CBF increased at 6 ata of oxygen through nitric oxide dependent pathways, and the onset of O_2 toxicity was accelerated. These experiments do not prove that tadalafil will accelerate O_2 toxicity in humans, but they suggest caution. Moreover, Cases 4-6 involved other medications and occurred at apparently low O_2 partial pressures suggesting further investigation of other medications is warranted.

The "O_2 Clock"

In the 1980s, the National Oceanic and Atmospheric Administration (NOAA) found that the existing oxygen exposure limits did not address the oxygen exposures in its undersea habitat program where divers might be saturated on nitrogen-based atmospheres at depths of 30 to 100 fsw and make long excursions to depths as great as 300 fsw on air. The Navy oxygen limits of Fig. 13 were easily exceeded during these excursions. NOAA asked Dr. Lambertsen if he would develop exposure limits that might be more appropriate for habitat excursion diving.

Table 1 shows the Lambertsen limits that were published in the 1991 NOAA Diving Manual (2). These limits were based on best judgment from extensive experience, not on the statistical analysis of quantitative data. Indeed, the NOAA limits apply not just to CNS oxygen toxicity but also to pulmonary toxicity and to symptoms such as finger numbness that have been described as "whole-body" oxygen toxicity (19, 25).

Table 1. NOAA oxygen partial pressure and exposure time limits (2).

Oxygen partial pressure (atm)	Normal exposure mits (min)	Exceptional exposure limits (min)
2.0	--	30
1.9	--	45
1.8	--	60
1.7	--	75
1.6	45	120
1.5	120	150
1.4	150	180
1.3	180	240
1.2	210	--
1.1	240	--
1.0	300	--
0.9	360	--
0.8	450	--
0.7	570	--
0.6	720	--

Figure 15 showed the limits of Table 1 in the context of a model of CNS oxygen toxicity that suggested the NOAA normal exposure limits were between zero and 1%. Because the data on which the model was based were practically non-existent at these low partial pressures, all that can be stated about the limits of Table 1 is that the risks of CNS toxicity are probably small. The risks of pulmonary or "whole-body" toxicities were not examined here.

The time limit for each oxygen partial pressure in Table 1 assumes a "square" dive, i.e., the partial pressure is constant throughout the exposure. Technical dives, however, typically change gas mixes multiple times (Fig. 18) to keep the oxygen partial pressure as high as possible in order to reduce decompression time.

The purpose of "O_2 clock" was to track oxygen exposure using the NOAA limits through a series of gas mixes. (The term "O2 clock" appears to have been initiated by Dick Rutkowski (personal communication). See http://www.iantd.com/articles/95-2gurr.html for a more complete discussion.) The concept associates a percentage of the allowable oxygen exposures in the NOAA table with each minute of exposure time (%CNS/min). For example, 45 minutes at 1.6 atm is equivalent to 2.22% per minute (100%/45 min), and 180 min at 1.3 atm is equivalent to 0.56% per minute (100%/180 min). The total O_2 clock percentage is found by multiplying the %CNS/min by time for the partial pressure of each mix and summing these products for all mixes. A diver who breathes 1.3 atm for 60 min accumulates 33% of his or her O_2 clock. An additional 80 min at 1.5 atm is 67%, which would bring the total to 100%, and in theory, further oxygen exposure would be unsafe.

Another concept sometimes used in O_2 clock calculations holds that the CNS O_2 risk can be reduced by breathing low oxygen partial pressures. This is the principle of "intermittency" is used in the U.S. Navy Oxygen Treatment Tables 5 and 6 by alternating between oxygen (2.82 atm) and air (0.59 atm) at 60 fsw. Intermittency has been demonstrated experimentally for pulmonary oxygen toxicity in animals and humans, but little work has tested its validity for CNS toxicity (15, 22).

Applying the O_2 clock to the dive of Fig. 18 (Case 1 of the Case Reports) suggests that the diver reached approximately 80% of his allowable CNS exposure, but this does not include the 3 min periods on 18% (about 0.6 atm) and 35% (about 0.7 atm) oxygen which by intermittency theory, should allow some reduction of risk. Nonetheless, the diver developed definite signs of CNS oxygen toxicity. The diver of case 2 appeared to have an oxygen convulsion at 50% of his O_2 clock.

The O_2 clock is a logical tool for applying square dive exposure limits to multilevel exposures, but its foundation is uncertain, and as indicated by cases 1 and 2 above, obeying its principles it does not guarantee freedom from CNS toxicity. The value of the O_2 clock as a predictor of CNS toxicity probability might be better assessed if technical divers recorded their depth, time, and O_2 partial pressure profiles and sent them to DAN (with medical outcomes) for analysis.

CNS Oxygen Toxicity Safety

Safety is acceptable risk where risk depends on the probability and severity of injury (27). If the injury is mild, the acceptable probability might be higher. If the injury is serious, the acceptable probability should be lower. If the probability is unpredictable as in CNS oxygen toxicity, the acceptable probability should be lower still.

What oxygen partial pressures are safe? The question does not have an unequivocal answer. The Navy is responsible for the safety of Navy divers and publishes its safety guidelines in the U.S. Navy Diving Manual (4). DAN attempts to provide the best information available and offers to assist the diving community in formulating its own safety guidelines. At present, the available information seems sufficient to say that the risk of oxygen may be worrisome at or above 1.3 to 1.6 atm, but even this non-specific conclusion is tempered by the possibility that intra- and inter-individual variability, environmental effects, pharmaceutical influences and O_2-CO_2 interactions could reduce the threshold to less than 1.3 atm.

If the technical diving community wants more specific answers, technical divers should contribute specific information about their practices and experience. Contact DAN for details.

References

1. U.S. Navy Diving Manual: U.S. Navy; 1963 July 1963. Report No.: NAVSHIPS 250-583, July 1963.

2. NOAA Diving Manual: Diving for Science and Technology. 3 ed. Silver Spring, MD: Office of Undersea Research, National Oceanic and Atmospheric Administration 1991.

3. U.S. Navy Diving Manual: U.S. Navy; 1993 15 Feb 1993. Report No.: Revision 3, 0927-LP-001-9110, 15 Feb 1993 (SUPERSEDES NAVSEA 0994-LP-9010, REVISION 2, 15 DEC 1988).

4. U.S. Navy Diving Manual. Wash., D.C.: Naval Sea Systems Command 2008.

5. Arieli R, Arieli Y, Daskalovic Y, Eynan M, Abramovich A. CNS oxygen toxicity in closed-circuit diving: signs and symptoms before loss of consciousness. Aviation, space, and environmental medicine. 2006 Nov;77(11):1153-7.

6. Arieli R, Shochat T, Adir Y. CNS toxicity in closed-circuit oxygen diving: symptoms reported from 2527 dives. Aviation, space, and environmental medicine. 2006 May;77(5):526-32.

7. Arieli R. The effect of over- or underfilling the soda lime canister on CO2 absorption in two closed-circuit oxygen rebreathers. Undersea Hyperb Med. 2008 May-Jun;35(3):213-8.

8. Borghese J. Sea devils. Chicago: Regnery 1954.

9. Butler FK, Jr., White E, Twa M. Hyperoxic myopia in a closed-circuit mixed-gas scuba diver. Undersea Hyperb Med. 1999;26(1):41-5.

10. Camporesi E, Bosco G. Ventilation, gas exchange, and exercise under pressure. In: Brubakk A, Neuman TS, eds. *Bennett and Elliott's Physiology and Medicine of Diving*. Edinbrugh: Saunders 2003:77-114.

11. Clark J, Lambertsen C. Pulmonary oxygen tolerance in man and derivation of pulmonary oxygen tolerance curves. Philadelphia: Institute for Environmental Medicine, University of Pennsylvania; 1970. Report No.: IEM Report No. 1-70.

12. Clark J, Lambertsen C. Rate of development of pulmonary O2 toxicity in man during breathingat 2.0 ata. J Appl Physiol. 1971;30:739-52.

13. Clark J, Gelfand R, Lambertsen C. Human tolerance and physiological responses to exercise while breathing oxygen at 2.0 atm. Aviation, Space, and Environmental Medicine. 1995;66:336-45.

14. Clark J, Thom S. Oxygen under pressure. In: Brubakk A, Neuman TS, eds. *Bennett and Elliott's Physiology and Medicine of Diving*. Edinbrugh: Saunders 2003:358-418.

15. Clark J. Extension of oxygen tolerance by interrupted exposure. Undersea Hyperb Med. 2004;31(2):195-8.

16. Demchenko I, Ruehle A, Allen B, Vann R, Piantadosi C. Effects of phosphodiesterase-5 inhibitors on cerebral blood flow and seizures in rats exposed to HBO2. J Appl Physiol (January 29, 2009). doi:10.1152/japplphysiol.91407.2008

17. Donald K. Oxygen poisoning in man: Admiralty Experimental Diving Unit; 1945. Report No.: AEDU Report XVI.

18. Donald K. Oxygen and the diver: Best 1995.

19. Hamilton R. Tolerating exposure to high oxygen levels: Repex and other methods. Marine Tech Soc J. 1989;23(4):19-25.

20. Harabin A, Survanshi S. A statistical analysis of recent naval experimental diving unit (NEDU) single-depth human exposures to 100% oxygen at pressure. Bethesda: Naval Medical Research Institute; 1993. Report No.: NMRI 93-59.

21. Harabin A, Survanshi S, Homer L. A model for predicting central nervous system toxicity from hyperbaric oxygen exposure in man: effects of immersion, exercise, and old and new data. Bethesda: Naval Medical Research Institute; 1994. Report No.: NMRI 94-03.

22. Harabin AL, Survanshi SS, Weathersby PK, Hays JR, Homer LD. The modulation of oxygen toxicity by intermittent exposure. Toxicology and applied pharmacology. 1988 Apr;93(2):298-311.

23. Harabin AL, Survanshi SS, Homer LD. A test for variations in individual sensitivity to hyperbaric oxygen toxicity. Undersea Hyperb Med. 1994 Dec;21(4):403-12.

24. Harabin AL, Survanshi SS, Homer LD. A model for predicting central nervous system oxygen toxicity from hyperbaric oxygen exposures in humans. Toxicology and applied pharmacology. 1995 May;132(1):19-26.

25. Kenyon D, Hamilton R. Managing oxygen exposure when preparing decompression tables. In: Bitterman N, Lincoln R, editors. Diving and hyperbaric medicine; 1989; Haifa: EUBS; 1989. p. 72-6.

26. Leitch D. A study of unusual incidents in a well-documented series of dives. Aviation, space, and environmental medicine. 1981;52(10):618-24.

27. Lowrance W. Of acceptable risk. Science and the determination of safety. Los Altos, CA: William Kaufmann 1976.

28. Menduno M. Safety first: an analysis of recent diving accidents. aquacorps technical diver. 1992;3.2:3-10.

29. Natoli M. The effects of PIO2 and PICO2 on CNS oxygen toxicity as assessed by near infrared spectroscopy and ventilatory response. Durham, NC: Duke University; 1991.

30. Schaefer K. Adaptation to breath-hold diving. In: Rahn H, Yokoyama T, editors. Physiology of breath-hold diving and the Ama of Japan; 1965; Tokyo: NAS NRC; 1965. p. 237-52.

31. Schofield W, Carisella P. Frogmen: first battles. Boston: Branden 1987.

32. Vann R. Oxygen toxicity risk assessment: final report; 1988. Report No.: ONR Contract N00014-87-C-0283.

33. Vann R. Lambertsen and oxygen: beginnings of operational physiology. Undersea Hyperbaric Med. 2004;31:21-31.

34. Vann R, Pollock N, Denoble P. Rebreather fatality investigation. In: Pollock N, Godfrey J, editors. Proceedings of the American Academy of Underwater Sciences 25th Symposium; 2007; Dauphin Island, AL; 2007. p. 98-107.

35. Vann R, Denoble P, Doolette D. Assessing the risk of decompression sickness. In: Vann R, Mitchell S, Anthony G, Denoble P, eds. Technical Diving Conference; 2009 January 18-19, 2008; Durham, NC: Divers Alert Network; 2009: 158-177.

36. Vann RD. Decompression theory and application. In: Bennett PB, Elliott DH, eds. *The physiology of diving and compressed air work.* 3 ed. London: Bailliere Tindall 1982:352-82.

37. Waldron T, Gleeson J. The frogman: the story of the wartime underwater operators. London: Evans Brothers 1955.

Discussion

SIMON MITCHELL: A comment to make sure none of you are confused between my message and the message we've just heard about hyperventilating to lower CO_2. That will work when you're near the surface and your gas isn't dense. It may not work if you're down on the bottom and your gas is more dense.

BILL HAMILTON: Especially if you're in the effort independent zone.

SIMON MITCHELL: That's right. In addition I thought Bill raised an important point about diver rescue. I completely agree with Bill. This idea that during the clonic phase of a convulsion (alternate contractions and relaxations), your airway is spasmed shut is not correct, or only partially so. The airway is not spasmed shut, as has been demonstrated in animal studies. So I agree that the risk of embolism is very small. If you hold an unconscious diver under water, the risk of drowning is very high.

PETER BENNETT: It's a comment about the symptoms. I've seen a lot of oxygen convulsions in the chamber in front of me. I didn't see anything happen first; they just went very pale and they convulsed right in front of my face. With regard to premonitory facial twitching, a lot of that came out of Donald's work. Recruitment of divers was on the basis of “you, you and you,” and when Jim sat there he was told you're going to get lip twitching before you convulse. And he sat there, and poor old Joe convulsed in front of him so he started his lips twitching. He didn't want to convulse, so he started lips twitching. He was then pulled back to the surface for having a symptom. And that was the talk in all the pubs. Donald would say that's not quite true, you know, Peter, but, in fact, the sailors said it was true.

DICK VANN: Twitching was observed in the U.S. Navy studies as well.

JEFF BOZANIC: Several people have recommended the use of an antioxidant regime to reduce the problems that we talked about with free radicals. Is that effective or likely to be effective in diving scenarios?

DICK VANN: That's been looked at. And some were shown not to be effective. There are some potential drugs that might be useful, and I think that work may still be ongoing. Jake, can you comment on that?

JAKE FREIBERGER: There's work ongoing, but no, antioxidants have not helped with pulmonary toxicity.

HAL WATTS: I'd like to see a show of hands on how many divers in here has had a symptom of O_2 hit. (Editor’s note: many hands.) That's pretty interesting, isn't it?

SIMON MITCHELL: We've got to stop. There's a lot of technical divers in here who have spent a lot of time sitting at their last decompression stop, 10 feet, three meters, breathing 100 percent oxygen and the oxygen clock is way up over 100 percent. What should they do to reduce their risks of a seizure?

BILL HAMILTON: If you can switch periodically to bottom mix, switch off the pure oxygen every 20, 25 minutes for 5 minutes, that will allow you to go all day. The hyperventilation business is a quick and immediate thing, and you pointed out that it doesn't always work. But the intermittency is something that you'll find in Lambertsen's work and it seems always reliable.

DICK VANN: How do you know?

BILL HAMILTON: That's what's in the literature.

SIMON MITCHELL: If I had to pick the question that most of the technical divers had brought to this session today, that's the one because it really worries them to do these calculations and sit there at that last deco stop with the oxygen clock way up over 100 percent.

JEFF BOZANIC: The question is if you're going to be intermittent and switch to a lower PO_2 how low is effective?

BILL HAMILTON: The conventional wisdom is below 0.5 atmospheres of oxygen is what it will take. To get below 1 or anything like that will be helpful if you're up at 1.6 the rest of the time.

BILL HAMILTON: Now, if you do have to rescue, there's one last point here, and that is if a diver needs to be rescued, you may not be able to replace the mouthpiece. You may be able to hold it in if it's still in his mouth, but if it's not, the conventional wisdom is not to try to put it in. If the diver doesn't have an airway, get him out of the water, because there's nothing else you can do. There's a small, very small chance of embolism. We heard a good lecture on that in the workshop on breath-hold diving a year or so ago. You're not likely to have embolism, but if you stay in the water trying to breathe the water, you're going to drown, that's for certain, for sure. So this is what you have to do if you've got to rescue someone, get them out of the water.

NITROGEN NARCOSIS, OXYGEN NARCOSIS AND THE HIGH PRESSURE NERVOUS SYNDROME

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Nitrogen Narcosis

Extensive reviews of all aspects of nitrogen narcosis are available in the literature (18, 25, 35, 46, 57). This paper will restrict itself to specific aspects of nitrogen narcosis which may be pertinent to deep compressed air and technical diving.

Signs and Symptoms

Behnke et al. (6) were the first to prove that the nitrogen of compressed air was responsible for signs and symptoms of narcosis, characterized as “euphoria, retardation of the higher mental processes and impaired neuromuscular coordination.” This is accompanied by limitation of the powers of association and a tendency to fixation of ideas. Errors may be made in arithmetic calculations, reaction time is slowed and fine manipulations are more difficult. Intellectual functions are affected to a greater extent than manual dexterity.

Mild signs and symptoms are common at 100 fsw with a wide individual variability and day-to-day variability, as shown by objective psychometric tests. This is due to natural biological variability and possibly, in regard to the latter, to such factors as fatigue, apprehension, cold, work etc., much as seen with alcohol or the early stages of hypoxia. At 100 fsw Behnke et al. found that the narcosis is not sufficient to be a problem (6), but at 300 fsw the signs and symptoms may be severe and amount to stupefaction or in some cases loss of consciousness (32). There are many factors which will potentiate the signs and symptoms, including alcohol (36, 52), fatigue and hard work (1, 2), apprehension and anxiety (Davis et al. 1972), and any increase in carbon dioxide (49, 50). Frequent exposure may afford some adaptation (35) but this may require five days of saturation exposure, as discussed later.

Importantly, for those who maintain they do not experience nitrogen narcosis, even at great depths, there is significant post-dive amnesia and memory loss. Everybody is affected at some depth and denial, as with alcohol and driving, has the same association.

Effects of Depth

The depth-dependent effect of nitrogen narcosis on psychometric performance was well illustrated (Table 1) as long ago as 1937 by Shilling and Willgrube (72). They noted the greatest severity immediately on reaching depth and that rapid compression potentiated the narcosis. Acclimatized subjects showed some improvement.

Table 1. Effect of compressed air on psychometric tests (72).

Depth (m)	0	27.5	30.5	38	46	53.5	61	68.5	76	84	91.5
Depth (ft)	0	90	100	125	150	175	200	225	250	275	300
Mean extra time to Solve problem(s)	0.35	11.09	6.89	7.65	9.74	11.95	13.98	17.17	26.07	26.53	31.42
Mean extra errors in solving problems	0.18	0.86	0.49	0.42	0.72	0.84	1.22	0.88	2.18	2.66	3.02
Mean decrease in numbers crossed out	--	-0.59	-0.09	-2.26	-2.30	-2.49	-2.55	-4.24	-5.85	-6.43	-8.74
Average reaction time	0.214	--	--	--	0.237	--	0.242	--	0.248	--	2.257
Mean extra time to solve problems (acclimatized subjects)	1.64	2.55	3.42	3.91	4.66	8.00	11.75	15.73	16.33	17.09	24.36

Case and Haldane (27) found that at 250 fsw manual skills showed little deterioration. At 300 fsw, however, the narcosis was severe with marked impairment of practical ability and judgment. Rashbass (67) also used an arithmetic test at 250 fsw in which 26 divers showed a deterioration of 30.3% from surface results. At 200 fsw with the same arithmetic test, Bennett and Glass (15), measured a mean decrement of 23%.

Adolfson et al. (1, 2) emphasized even greater severity at 400 fsw. At this depth, the arithmetic test indicated the number of sums correct was reduced by 61.6% with 25% more errors. Manual dexterity was affected to a much less degree (Fig. 1). Orders were recognized but ignored, there was a sense of impending loss of consciousness, euphoria and dizziness, manic or depressive states, catalepsy and a disorganization of the sense of time. Again, frequent exposure produced some adaptation.

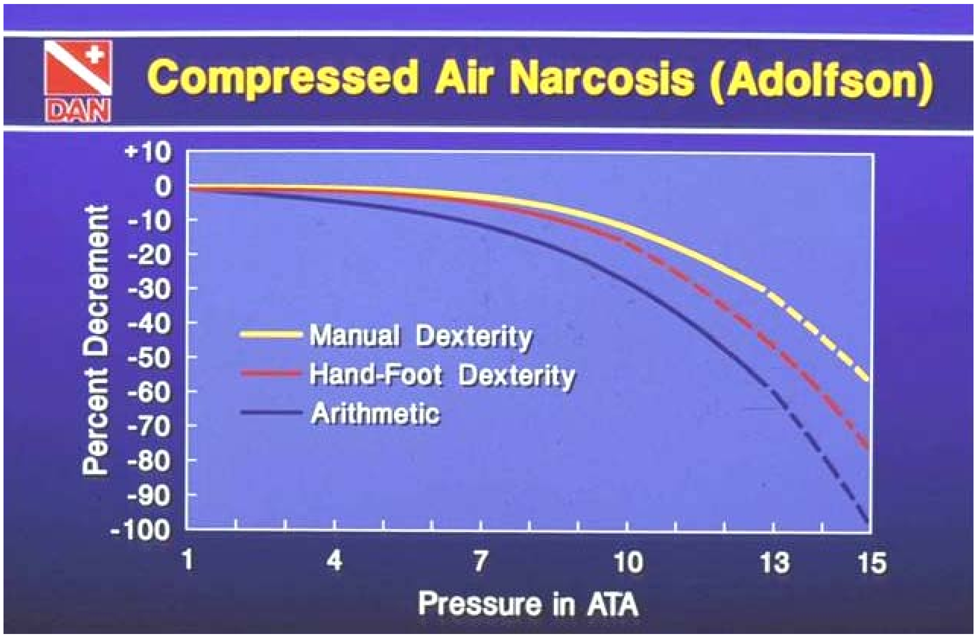

Figure 1. Effects of compressed air narcosis to 400 fsw

Individual Differences and Variations in Tolerance

There is no question that there is an individual susceptibility to the effects of nitrogen narcosis (25). This may be due to individual accommodation or "learning to cope" with a reduction in anxiety and recognition by the individual of his own signs and symptoms. Thus highly trained and experienced deep divers may be able to function much more effectively at depths which would incapacitate less experienced divers. Such experienced deep divers will pace themselves, be slow and methodical and exert extra effort and concentration to try to mitigate the narcosis compared to an individual, for example, experiencing 300 fsw narcosis for the first time. However, normal biological variability due to different individual physiological susceptibility, as in alcohol, is also a factor.

Another form of accommodation is supported by deep diving record holders such as Dr. Dan Manion who in 1994 reached 491 fsw for a brief time. These divers start by diving relatively shallow, and then make each dive progressively deeper until the record dive itself, thereby gradually accommodating to some extent to the increasing nitrogen narcosis. Lambertsen and Wright (55) suggested "that by careful choice of highly intelligent young men in excellent condition, one can select individuals who can acclimate very adequately to conditions which others might be seriously incapacitated as a result of nitrogen narcosis." While all subjects can accommodate to 100 fsw compressed air only, some, but not all, can compensate for 200 fsw during extended sojourns (74).

Adaptation

Adaptation to nitrogen narcosis has been well reviewed by Hamilton (42). This is not the accommodation effect discussed earlier, but an improvement seen best in saturation nitrox diving. Thus in Predictive Series II at the University of Pennsylvania (33) divers breathing normoxic nitrogen at 4 ata (100 fsw) were slightly narcotic initially but soon returned completely to normal. A similar effect was reported in the NOAA OPS experiments in Tarrytown at 120 fsw (45).

The adaptation effect, however, was not so prevalent at deeper saturation depths as reported during the US Navy Nisat 1 dive in 1976 to 200 fsw (43, 47) and the Nisahex ocean dive at 7 ata (200 fsw) for 6 days by the Swedish Navy in 1982 (62). The divers were reported to be quite affected by narcosis and although many functions improved after 4-6 days, the divers were not without some signs or symptoms of narcosis until the shallower depths of decompression. Hamilton, in the 1983 UHMS workshop on nitrogen narcosis, reports that the divers felt "mildly drunk and pleasantly high" and stayed that way for 5 days (42). "They were fumbly and could only do one thing at a time. If given three tasks, they would complete the first, and then ask again "what was the second thing?" They could do learned things quite well, but new tasks required careful thought and a slow and methodical approach, or mistakes were made.

The most stoic diver, a professional, tried to cover his narcosis by being "formal and straight" but later admitted he did, in fact, feel narcotic. The results were very similar to the US Navy Nisat dive (43).

Again, adaptation was reported by Coler et al. (30) in the AMES crews. Simulators, where divers were exposed to 100 fsw of normoxic nitrogen for two weeks with repeated tests for short term memory, EEG changes etc., adaptation started after 5 days and by the 8th or 9th day, had returned to surface values.

Recommended Compressed Air Limits

Suggested limits to avoid nitrogen narcosis as much as possible during any deep diving operations must be very varied. For recreational diving the suggested OSHA limit is 130 fsw, but many European divers dive routinely to 150 fsw or deeper. In 2007, the Department of Labor and OSHA have proposed the limit for scientific divers in 1982 and 1985 as 190 fsw. According to Hamilton (46), British and Norwegian sectors of the North Sea for offshore commercial diving using compressed air is limited to 165 fsw.

A recommended limit for everyone is difficult due to wide individual variability, synergistic action of carbon dioxide with nitrogen, hard work and diver experience. Certainly 200 fsw is probably too deep for the majority of divers most of whom certainly will experience narcosis. Routine exposures of divers to 165 fsw in a pressure chamber to allow them to acquaint themselves for the first time to nitrogen narcosis has usually resulted in uncontrolled laughter and loquacity. Egstrom noted that scientific divers holding the 200 fsw certification have to make 6 such dives per year to maintain the certification (46). At 200 fsw, however, all will be affected to various degrees (even if they deny it) and at 250 fsw, the narcosis becomes marked and a definite threat to safe diving.

There is no clear overall limit, as it will eventually depend on the individual susceptibility, the level of experience and the conditions of the dive itself. Perhaps all that can be said is that at 100 fsw the narcosis is minimal, but becomes progressively worse with increasing depth and by 200 fsw can be a real issue as regards safety. In practice, virtually all of the technical diving training agencies encourage the use of helium mixtures for dives beyond 150 feet, and some suggest air should not be used deeper than 100 feet.

Rate of Compression or Descent

It is widely held that rapid compression potentiates nitrogen narcosis. The effect is believed due to an increase in alveolar and cerebral carbon dioxide (2-5, 7, 72). However, narcosis depends on a critical molar concentration of nitrogen being reached in the brain. If the rate of compression is very rapid, as in British submarine escape research, then this concentration may not be reached and narcosis may be ameliorated for a brief time (9, 14).

Thus, compression of 10 divers to 400 and 500 fsw at a rate of 500 fsw in 20 seconds, followed by decompression 40 seconds later showed only a significant decrement in two choice reaction times at 500 fsw. One subject reported a hallucination of drinking a glass of beer and most reported dizziness. In later escape trials from 600 fsw, subjects reported “an overwhelming wave of narcosis” during the rapid ascent at about 100 fsw. This was because the nitrogen from the lungs to the brain did not reach sufficient concentration for narcosis until then. However, on the surface, this quickly waned and in 30 seconds they felt fine again (34).

It is pertinent that the US and UK navies did some experiments compressing subjects from 400 fsw to 450 fsw with non-narcotic oxygen-helium and then took off the masks in air. In 2½ minutes they lost consciousness.

Given the usual limitations on gas supply and bottom time during technical diving, and the consequent imperative for a rapid descent, it is unlikely that varying the descent rate is likely to represent a practical strategy for ameliorating nitrogen narcosis.

Carbon Dioxide Effects

Carbon dioxide increase is reputed to increase susceptibility to nitrogen narcosis, oxygen toxicity and decompression sickness. In regard to carbon dioxide, Case and Haldane noted this as early as 1941 and reported that the combined effects of nitrogen and carbon dioxide in studies at 300 fsw with inspired CO_2 percentages from 3.6 to 4.3% were much more severe than either gas alone. At higher partial pressures of carbon dioxide, loss of consciousness resulted.

Another somewhat hidden effect of CO_2 is the enhancement of the effects of nitrogen narcosis by exercise or work during diving as shown again by the work of Adolfson (1). This indicated significant increases in decrements of psychometric tests in working divers compared to resting divers at 100, 200 and 300 fsw breathing compressed air (Table 2).

Table 2. Additional decrements in manual dexterity and arithmetic tests (differences in number correct) at 4, 7 and 10 ata air due to leg exercise compared to resting divers (1).

	Manual Dexterity	Arithmetic
4 ata	- 1.9	- 0.9
7 ata	- 3.0*	- 4.5*
10 ata	-3.7*	-15.0*

*statistically significant < 0.001

This is considered due to increase of arterial and tissue carbon dioxide levels and the synergistic actions of this very narcotic gas to the narcotic effect of nitrogen. This endogenous increase in CO_2 can be very serious for some "CO_2 retainer" divers (56). With air at 7.8 atm exertion, with restriction of breathing, can produce a marked rise in CO_2 such that the individual may go from mild narcosis to coma within only three minutes. Lanphier (56) maintained that "some of the best divers for some reason are most prone to such problems. Increased work of the breathing apparatus or added external dead space in the equipment can produce further elevations of arterial PCO_2."

Alteration of arterial PCO_2 due to exertion while breathing air on the surface is shown by Lanphier (56) in CO_2 retainers below (Fig. 2). This has caused a number of deaths in divers who experienced what came to be called "shallow water blackout (SWBO)" – a loss of consciousness due to the combined effect of raised partial pressure of oxygen in CO_2 retainers. (Note that this was the original meaning of the term SWBO. In more recent usage, SWBO is applied to breath-hold divers.)

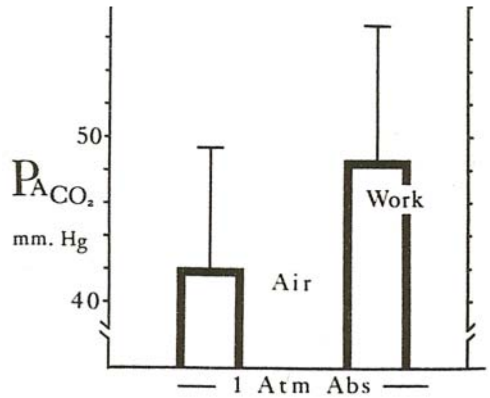

Figure 2. Alteration of arterial PCO_2 by exertion with air at normal pressure in CO_2-retaining divers (56).

Oxygen Effects

With respect to oxygen Frankenhauser et al. (37) and Hesser (48) studied the effect on psychometric tests of varying oxygen pressures at a constant nitrogen partial pressure at a depth of 100 fsw. The results (Figure 3) showed a significant potentiation by the raised oxygen pressure. However, they did not attribute this to oxygen narcosis, but to the raised oxygen partial pressures blocking the carbon dioxide carrying capacity of the blood (41) and therefore carbon dioxide synergism.

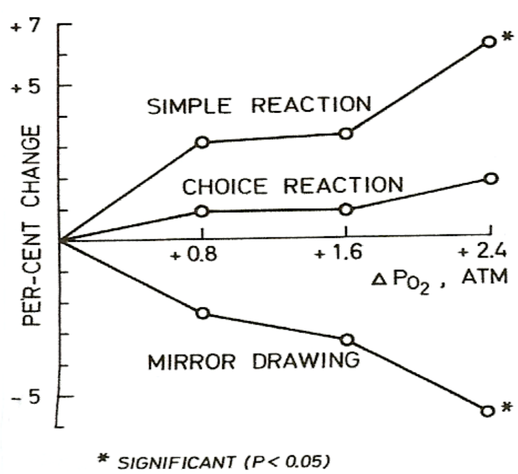

Figure 3. Changes in performance induced by increasing the oxygen pressure at a constant high nitrogen pressure (3.9 atm) (mean values for 12 subjects) (37, 48).

On the other hand, Albano et al. (4) found that 7 divers at 300 fsw breathing 96% nitrogen and 4% oxygen were quantitatively more narcotic at an arithmetic test than those breathing air (Table 3).

Table 3. Comparison of N_2 narcosis breathing air or 96/4 N_2/O_2 at 300 fsw in an arithmetic test (4). Each line represents an individual diver.

Sums Attempted			% Errors		
Control (surface air)	10 ata Air	10 ata 96/4 N_2/O_2	Control (surface air)	10 ata Air	10 ata 96/4 N_2-O_2
23	18	12	4.4	22.2	41.6
24	19	15	4.3	79.0	86.6
50	43	33	0.0	23.0	21.8
40	20	14	10.0	30.0	42.8
36	32	28	28.0	53.6	71.4
27	24	20	7.4	50.0	60.0
45	34	30	0.0	26.4	30.0
*35	*27	*22	*7.7	*40.6	*50.6

**Mean; P = < 0.01*

Similar results were seen by Surg Lt Barnard RN at 300 fsw in subjects breathing either air or 5% O_2/95% N_2. The issue of the practical relevance of a narcotic effect for oxygen is further discussed later in this paper.

Oxygen Narcosis

Since technical diving involves use of nitrox and other mixed gases, there is considerable interest, if not controversy, on whether oxygen is a narcotic. Clearly from the mechanisms based on lipid solubility discussed later, it should be, but is this more important than its convulsant properties?

Oxygen is different from the inert gases as it is metabolized in the body. Nevertheless, oxygen narcosis has indeed been reported in humans and animals. Elliott (34) describes research on HMS Reclaim in the UK where a BIBS (Built in Breathing System) error meant that two divers in a diving bell ended up breathing pure oxygen at 120 fsw and became unconscious due to oxygen anesthesia.

With animals, mice at 13 ata (400 fsw) oxygen or more will become anesthetized as shown by Paton (66). The author has a film showing this in the rat, too. The technique relies on rapid compression to high pressures of oxygen. Under these conditions the anesthesia occurs before convulsions can occur. Since, however, no diver is likely to do this, is oxygen narcosis of any relevance to technical divers?

The work of Frankenhauser et al. (37), Hesser (48), discussed earlier, showed in divers that at a constant nitrogen partial pressure of 3.92 atm increasing the oxygen partial pressure from 0.2 to 2.6 atm did indicate small and insignificant increases in narcotic effect for simple reaction time from 0.243 sec to 0.256 sec and for choice reaction time from 0.67 sec to 0.70 sec, which is of no concern to technical divers.

Bennett and Ackles (13) reported a similar narcotic effect measuring neurological responses to auditory stimuli (N_1P_2) and arithmetic in divers exposed to 1, 2 and 3 atm oxygen (Table 4). Clearly those effects are too small to be of concern as at these pressures, especially at 3 atm, as the convulsant effects are much more relevant. As mentioned, no technical diver will breathe oxygen at such pressures.

Table 4. Effect of increased pressures of oxygen on the mean amplitudes of the N_1P_2 wave of the auditory evoked response in 5 subjects compared with their efficiency at an arithmetical task (percentage change during first 5 minutes (13)).

	Air at surface 0.2 atm O_2 0.8 atm N_2	Oxygen at surface 1.0 atm O_2	Oxygen at 33 ft 2.0 atm O_2	Oxygen at 66 ft 3.0 atm O_2
Spike height N_1P_2	-3.4 ± 8.2	-11.8 ± 5.2	-27.8 ± 8.0	-21.5 ± 4.9
Arithmetic correct	+8.5 ± 5.6	-1.0 ± 5.7	+1.0 ± 5.7	-6.1 ± 5.3
Arithmetic attempted	+12.8 ± 4.2	-2.6 ± 4.6	+1.3 ± 5.7	-5.9 ± 4.5

At any event, its narcotic potency does not seem to comply with its lipid solubility of 0.11 for oxygen compared to 0.067 for nitrogen (Table 5). In a human study by Hesser, Fagraeus and Adolfson (49) oxygen was found to be only 0.26 as potent as nitrogen. The lower effect is no doubt due to its being metabolized and much lower levels actually occurring in the brain compared to the lungs.

<u>EAD/END (Equivalent Air Depth/Equivalent Nitrogen Depth)</u>

A succinct example of the irrelevance of oxygen narcosis in calculating END is available from Smithers on the website http://masa.net/trimixnarcosis.html. "At 130 fsw on air, the PO_2 is about 1.0 atm and the PN_2 about 3.9 atm for a total narcotic "partial pressure" of 4.9 atm (assuming O_2 is narcotic). With a max PO_2 of 1.4 atm and a max of PN_2 of 3.9 atm, the difference at any depth in narcotic potential for an END of 130 fsw is 0.4 atm (total narcotic gas) or about 10 fsw of EAD". Smithers comments that most divers would opt for the decompression advantage of the additional 0.4 atm PO_2.

Recent work in Israel in fulfillment of a MSc degree at the University of Haifa was carried out by Heilweil (53). This involved evaluation of the "alleged" narcosis reduction when diving with nitrox mixtures. Comparison was made in 35 divers of EAN36 (i.e. Nitrox36) compared to air at a depth of 100 fsw for 20 mins in the sea. The experiments were double-blinded and sensitive cognitive tests and tools were used to quantify the quality of self-judgment and self-confidence along with actual performance. No significant differences were found between nitrox and air. This in spite of many claims by divers breathing nitrox that they feel less narcosis – a possible placebo effect.

So in conclusion, in regard to oxygen narcosis, yes, oxygen can exert a narcotic effect, but it is less than predicted by its lipid solubility, almost certainly because oxygen is metabolized and tissue PO_2 does not equilibrate with the PO_2 in the lungs at the oxygen pressures that can be safely used in diving. Thus, in practical terms, oxygen narcosis is much less of a problem for technical diving than would arise from the use of nitrogen at significant depths. To overcome the potential for nitrogen narcosis, deep divers do use oxygen-helium mixtures as an alternative. However, this then introduces the problem of the high pressure nervous syndrome (HPNS; see below).

Mechanisms of Nitrogen Narcosis

It is not proposed to discuss here the extensive literature on the possible mechanisms responsible for nitrogen narcosis; they are covered extensively elsewhere (18). Briefly, it is considered to be similar to general anesthesia by gaseous anesthetics. This is based on the Meyer-Overton hypothesis (59, 60, 65), which states "All gaseous or volatile substances induce narcosis if they penetrate the cell lipids in a definite molar concentration (0.03-0.06 moles of drug per kg of membrane)". In this regard there is still a strong relationship between solubility in lipids (fat) and narcotic potency as shown below (Table 5).

Table 5. Correlation of narcotic potency of the inert gases, hydrogen, oxygen and carbon dioxide with lipid solubility and other physical characteristics.

Gas	Molecular weight	Solubility in lipid	Temperature (°C)	Oil-water solubility ratio	Relative narcotic potency
					(least narcotic)
He	4	0.015	37	1.7	0.2
Ne	20	0.019	37.6	2.07	0.3
H_2	2	0.036	37	2.1	0.6
N_2	28	0.067	37	5.2	1
Ar	40	0.14	37	5.3	2.3
Kr	83.7	0.43	37	9.6	2.5
Xe	131.3	1.7	37	20.0	25.6 *(most narcotic)*
O_2	32	0.11	40	5.0	1.7
CO_2	44	1.34	40	1.6	20.0

Helium, neon and hydrogen are weak narcotics compared to air. Argon is about twice as narcotic and xenon is used as a general anesthetic in Russia and Germany. Carbon dioxide is a known strong narcotic, and oxygen, according to this hypothesis, should be somewhat more narcotic than nitrogen, but, as discussed later, its convulsant properties are far more important to divers.

Pressure Reversal and Critical Volume Theory

In 1950 Johnson and Flagler (51) observed an unusual effect, known as "Pressure Reversal." Tadpoles anesthetized by alcohol or an anesthetic would wake up and appear normal when exposed to a very high hydrostatic pressure of 140 ata (4,480 fsw) (Fig. 4).

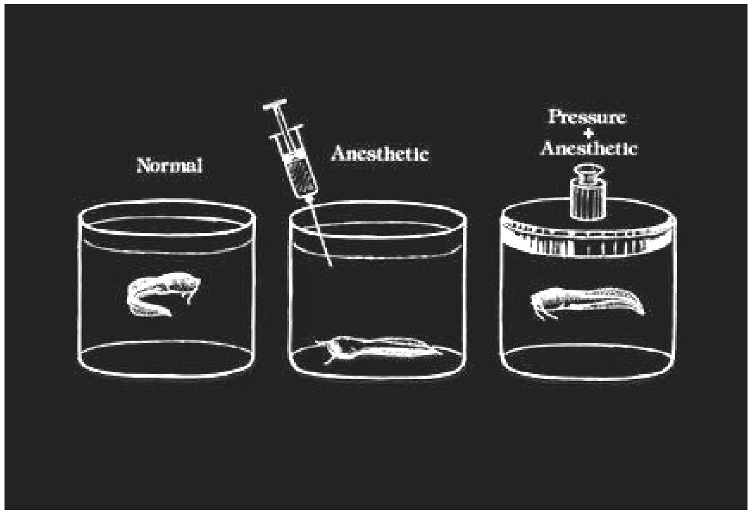

Figure 4. Tadpoles became unconscious when an anesthetic is added to the water and wakes up to addition of 140 ata hydrostatic pressure (51).

This was later confirmed in mice, newts and isolated nerves. This led Keith Miller (61) at Harvard to propose the "Critical Volume Theory," i.e., "Anesthetics expand a critical hydrophobic molecular site and pressure contracts this." In simple terms, a "critical hydrophobic molecular site" represents structures in cell membranes that are important for conduction of the nerve impulses upon which normal function of our nervous system depends. If these structures are physically distorted by absorption of large numbers of gas molecules, then conduction of nerve impulses can be impeded, manifesting as the cognitive impairment we call narcosis. This distortion can be reversed, i.e. the membrane structures can be returned to their original size or configuration by the application of high pressures; hence the fascinating phenomenon of "pressure reversal." Interestingly, this theory also implies that the application of pressure in the absence of membrane expansion by a narcotic gas would compress those same important membrane structures below their normal size or configuration, once again producing an interruption of normal function that will be discussed below under HPNS. For example, olive oil and carbon disulphide would behave as below (Table 6).

Table 6. An increase in volume causes narcosis and a decrease leads to the high pressure nervous syndrome (HPNS) (61).

Solvent	Effect	Critical Volume Change (%)	Correlation Coefficient
Olive Oil	Anesthesia Convulsions	+0.035 ± 0.03 -0.039 ± 0.12	0.85 0.91
Carbon Disulfide	Anesthesia Convulsions	+0.060 ± 0.04 -0.060 ± 0.16	0.84 0.92

Clements and Wilson (29) agreed that a lateral expansion of cell membranes does occur in the presence of a narcotic agent such as nitrous oxide. They concluded that inert gases sufficient to bring about such a standard effect will cause a decrease in surface tension at the lipid-water interface. Once again, in simple terms, this is because the expansion in the membrane forces the lipid molecules further apart. If the "membrane expansion" theory of how these inert gases produce narcosis was correct, such a decrease in surface tension should be measurable.

This effect was studied with the inert gases at increased pressures by Bennett et al. (16) by measurement of changes in the surface tension of a lipid monolayer inside a pressure chamber (Fig. 5). The results endorsed the theory. Nitrogen, argon, oxygen and carbon dioxide all showed a fall in surface tension indicating the potential for expansion of nerve cell membranes and narcotic properties. Interestingly, when helium was introduced (therefore replacing the more soluble gases that would expand the lipid layer), there was an increase in the tension, which supported the notion that constriction of nerve cell membranes might result in the symptoms (including convulsions) of the High Pressure Nervous Syndrome (Fig. 6). Narcosis and HPNS were therefore opposites as discussed later.

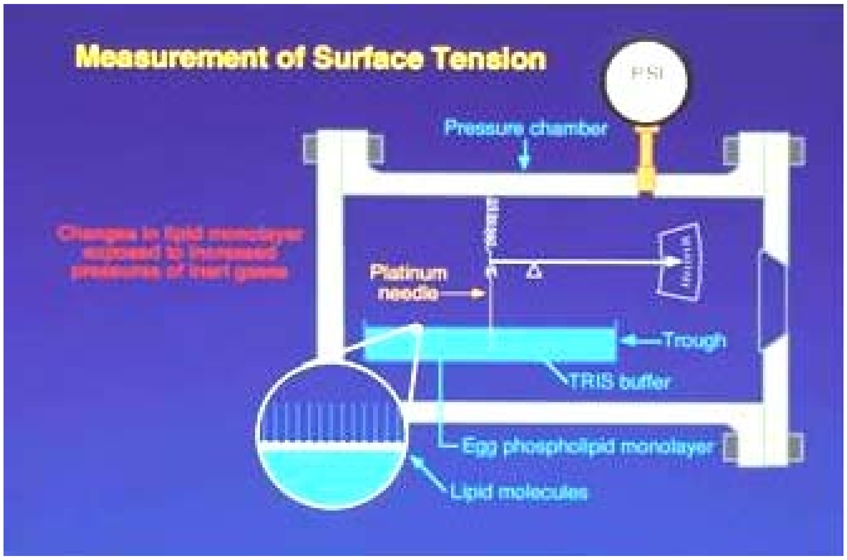

Figure 5. Equipment for measuring changes in surface tension on a phospholipid monolayer exposed to various gases at raised pressure (16).

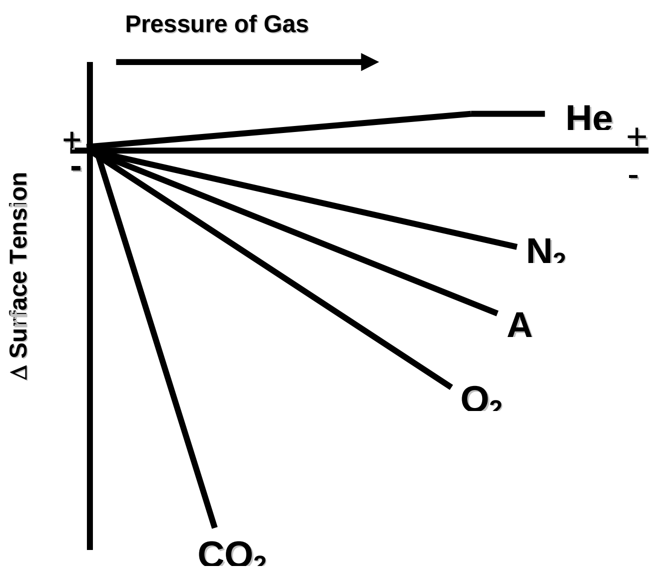

Figure 6. Penetration of a lipid monolayer of egg phospholipid by inert gases, oxygen and carbon dioxide at increased pressures. An increase in surface tension indicates a constriction (HPNS) of the model membrane, whereas a fall in surface tension indicates expansion of the membrane and potential narcosis (16).

There has been debate about exactly which structures within a nerve cell are the primary targets for the disruptive mechanisms described above. A cell membrane is composed of both lipids and protein, and Franks and Lieb (38) considered that the protein was more important than the lipid. Whatever the case, one of the critical functions of nerve cells is to pass information from one to another. This is achieved at so-called "synaptic junctions" (Fig. 7) and much research points to these as the site of action for narcosis and HPNS in the brain. Electrical impulses must pass across a very small gap from one nerve cell to another. This is done by the synaptic vesicles releasing chemical neurotransmitters across the gap. These neurotransmitters alter membrane function on the other side of the synapse in a way that potentially results in the continuation of the nerve impulse along the downstream nerve cell.

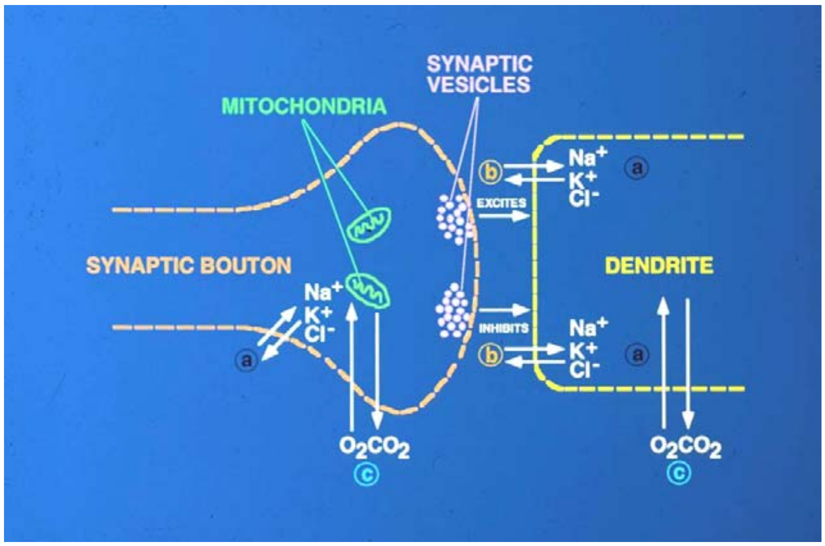

Figure 7. Diagram of a synapse.

Both nitrogen narcosis and HPNS affect the release of these neurotransmitters in opposite ways to affect conduction, in one case, depression, (narcosis) and the other increased excitability (HPNS).

High Pressure Nervous Syndrome (HPNS)
Extensive reviews of HPNS are available elsewhere (18, 70). This paper will concentrate on specific issues that may be of interest to technical divers.

The occurrence of HPNS was first reported by Bennett (8, 10) during research to overcome nitrogen narcosis in connection with submarine escape from British submarines. Volunteers were compressed with oxygen-helium at 100 ft/min to depths of 600 fsw and 800 fsw for 4 hrs.

Based on the lipid/narcosis relationship, helium should be 4 or 5 times less narcotic than nitrogen and there should be no helium narcosis. Instead, there were significant decrements in performance at psychometric tests (Table 7).

Table 7. Subjects compressed at 100 fsw/min to 600 fsw and 800 fsw breathing oxygen-helium (8, 10).

	600 ft (6)	800 ft (4)
Sums correct	-18%	-42%
Sums attempted	-4%	-6%
Number of ball bearings	-25%	-53%

This was accompanied by non-narcotic signs and symptoms such as dizziness, nausea, vomiting and a marked tremor of the hands. Surprisingly, unlike nitrogen narcosis in the 600 fsw exposure, the tests showed evidence of adaptation after 1½ hr (Fig. 8).

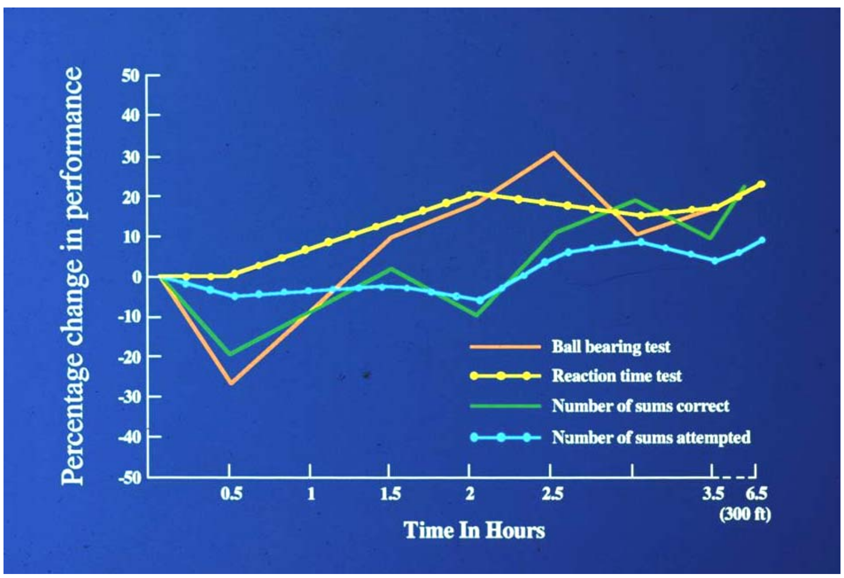

Figure 8. Performance decrements in subjects compressed at 100 fsw/min to 600 fsw for 4 hr. Psychomotor decrements are seen with recovery in 1 ½ hr (8, 10).

The decrements in performance at 800 fsw were equivalent in severity to those seen with nitrogen narcosis at 300 fsw and so attempts to dive to 1000 fsw seemed unlikely. However, the U.S. Navy in the Duke University Medical Center's new pressure chambers made a 24-hr compression to 1000 fsw which resulted in few of these unusual signs and symptoms first called "helium tremors" but later HPNS (64, 71, 75).

The French Comex commercial diving company "Physalie" dives (39) followed with four dives which exceeded 1000 fsw to 1189 fsw with compression time of 2 to 3 hr. In the latter case, especially with two divers compressed in some 2 hr to 1189 fsw, the signs and symptoms of HPNS were severe, including extreme fatigue, somnolence, tremors and a big increase in the slow (theta 5-7 hz) electrical activity of the brain which were considered likely precursors of convulsions, so the dive was aborted after 4 mins. In fact, convulsions have been reported in monkeys at depths only 35% deeper than helium tremors at 50 ats (1650 fsw) (24) and so 1200 fsw was suggested as the limit of deep helium diving. Convulsions were also reported in mice at 90-100 ats (3000 fsw) and lethal limits occurred at 5100-5450 fsw (58).

Signs and Symptoms

The signs and symptoms of HPNS therefore are:

Table 8. Signs and Symptoms of HPNS.

Tremors of the hands	Animals – convulsions
Myoclonic jerking of the limbs	EEG theta (3-7 hz) ↑
Increased reflexes	EEG alpha (8-13 hz) ↓
Nausea and vomiting	Evoked Potentials ↑
Loss of appetite, weight loss	Decrement in performance
Dizziness	Poor sleep, vivid dreams
Fatigue and somnolence (microsleep)	Visual/auditory hallucinations
Dyspnea	

They are initiated by rapid descent and start to appear at 600 fsw becoming increasingly more severe the greater the depth. HPNS is increasingly important today, as it is starting to affect breathhold divers who have now reached such depths. Technical divers using mixed gas are now diving wrecks and caves deeper than 600 fsw, and also attempting to break depth records deeper than 1000 fsw with fast rates of compression.

The tremors are affected both by rapid compression and the overall increase in depth as shown below using a tremor accelerometer (22, 23). Subject JB's normal resting tremor of 8-12 hz (not like Parkinson's disease at 3-4 hz) rises with each compression phase and there is an overall increase in tremor with each stage of increased depth. On the other hand, subject PS is unaffected (Fig. 9), implying a significant difference in individual susceptibility to this effect.

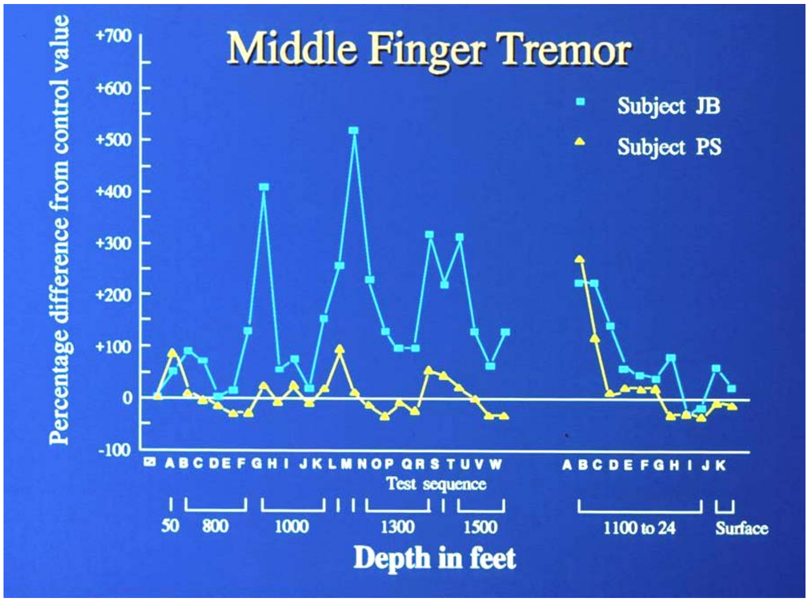

Figure 9. Tremors during a dive to 1500 fsw at RNPL.

A similar individual susceptibility is seen with all of the signs and symptoms of HPNS. As a result, in the extensive Duke/GUSI dives to 600 m (2132 fsw) in Germany (21, 22) divers beforehand were compressed to 100 ft/min to 600 fsw with tests of performance, tremor measurement, electroencephalogram with frequency analysis, signs and symptoms scores etc. to determine their individual sensitivity. Very sensitive individuals will also likely experience the nausea and vomiting and not wish to continue. However, none of the GUSI divers were excluded due to these tests.

Methods to suppress these signs and symptoms of HPNS were reviewed in 1975 (12) at a UHMS workshop "Strategy for Future Diving to Depths Greater than 1,000 ft" and this reviewed a number of methods accumulated from more than 23 experimental deep dives from 1965 to 1975. Nineteen more deep dives were later reviewed in 1980.

These methods were:
Selection of the least susceptible divers.
Choice of a suitable compression rate involving a slow exponential profile with stages during compression.
Excursions from saturation depth.
Use of a narcotic agent such as nitrogen or hydrogen in the mix (oxygen-helium-nitrogen or Trimix).
Allowing 24 hours on reaching saturation depth for adaptation.

Individual susceptibility was discussed above. The other methods will be covered below.

Choice of Compression Rate

Clearly, as already described, compression rates of 100 fsw/min (a rate typical of that adopted for many deep technical dives) will produce HPNS at 600 fsw and deeper with increasing severity. On the other hand, a slow 24-hr compression will enable reaching 1,000 fsw without HPNS (75).

It is not possible to review here all the many compression schedules from 1967-1975 and later, but the 1500 fsw deep oxygen-helium saturation dive at RNPL in 1970 extended the 1968 depth of 1,189 fsw with severe HPNS to 1,500 fsw (22, 23). The divers did have some signs and symptoms of HPNS but were functional and spent 10 hr at this depth. The secret was the introduction of a slower descent with stages requiring 3½ days. Very many deep dives followed using these slow often exponential methods of compression rate (17) with longer and longer stages with increasing depth.

However, a dive with oxygen-helium to 1800 fsw (73) with this slow philosophy of compression taking 3½ days resulted in severe HPNS. Signs and symptoms included fatigue, dizziness, nausea, vomiting, aversion to food, 8% weight loss, stomach cramps, diarrhea, myoclonic jerking and dyspnea or a sensation of not able to get enough breath. The U.S. Navy then restricted oxygen-helium saturation diving to 1,000 fsw.

Nevertheless, in recent years a number of technical divers have tried to reach the 1000 fsw depth with open circuit Trimix breathing apparatus. The official record at writing was by Nuno Gomes, 52, with a descent time of only 14 minutes but with Trimix (helium, nitrogen and oxygen). The unofficial record is by Pascal Bernabe, 41, with a compression time of only 10 minutes and again on Trimix. Little information is available as to how much HPNS was present in the short time at depth, but it would be very unlikely they did not experience some HPNS and could have been very dangerous. Indeed, the widely publicized video of David Shaw's fatal dive which involved a 900-foot descent in 12 minutes clearly shows a significant tremor. At least some of the subsequent problems leading to his death related to difficulty with the manual dexterity at the bottom.

Excursions from Saturation

Excursions from a saturation depth to a greater depth appear to be of value (12, 26, 44, 54). Thus in the Buhlmann team dive to 1,000 fsw (26) with a fast compression time of 1 hr 10 min by 3 divers, the signs and symptoms of HPNS had ameliorated in 2½ hr and excursions to 1,189 fsw were made 1 day later in a large wet pot using closed circuit Draeger breathing apparatus. There was no HPNS and the divers swam and lifted heavy weights.

Further, the University of Philadelphia dives Predictive Series IV (54) included a 3½ hr compression to 1200 fsw which produced serious HPNS signs and symptoms. After a 22-hr hold, excursions from 1,200 to 1,600 fsw produced less HPNS and useful underwater work.

It appears that once HPNS has occurred and there is recovery, it will never be so bad again on the same dive. Conversely, if severe HPNS has been prevented, then rapid compression excursions may still precipitate HPNS.

Trimix

A further method for ameliorating HPNS was initiated in 1973 by Bennett et al. (1974), based on the tadpoles, pressure reversal and membrane surface tension research on nitrogen narcosis discussed earlier. Thus, if helium showed a rise in surface tension (excitability), and nitrogen a decrease (narcosis), the correct mix of the two might well end up with no change and no HPNS or narcosis (i.e. pressure reversal).

Four divers were therefore compressed in 33 mins in 3 stages to 1,000 fsw, first breathing 18% nitrogen and in a later dive 10% nitrogen in helium-oxygen. A comparison was made between helium-oxygen use and 10% nitrogen Trimix, which clearly ameliorated HPNS (12). Similar dives were made by COMEX in their CORAZ dive series (28, 68). Three dives were made to 1,000 fsw with a compression total time of 4 h with either 0%, 4.5% or 9% nitrogen. These found that 4.5% appeared best for ameliorating the HPNS.

Similarly the Duke Medical Center Atlantis dive series (18) in 1979, 1980, 1981 and 1982 was designed to examine the effect of compression rate and either 5% or 10% nitrogen (Trimix) on HPNS. Extensive physiological and psychological measurements were made including work on an ergometer and arterial blood gases to study the dyspnea at such depths. The results identified slow compression (5 days) and 5% nitrogen in heliox as most effective at controlling HPNS to depths as great as 2,250 fsw. The best profile was from Atlantis IV and this was selected for an extensive series of 5% Trimix dives in Germany during the 1980's (Table 9).

Table 9. Duke/GUSI compression profile to 600 msw (1968 fsw) with Trimix 5 (N_2 5%/50 kPa (0.5 atm) O_2/He rest).* From Bennett & Schafstall (21).

Travel 0 – 180 msw	=	5 m/min (36 min)
Stop at 180 msw	=	2 hr
Travel 180-240 msw	=	3 m/min (20 min)
Stop 240 msw	=	6 hr
Travel 240-300 msw	=	1.5 m/min (40 min)
Stop at 300 msw	=	2 hr
Travel 300-350 msw	=	0.5 m/min (1 h 40 min)
Stop at 350 msw	=	9 hr
Travel 350-400 msw	=	0.25 m/min (3 h 30 min)
Stop at 400 msw	=	2 hr
Travel 400-430 msw	=	0.125 m/min (4 h)
Stop at 430 msw	=	2 hr
Travel 430-460 msw	=	0.125 m/min (4 h)
Stop at 460 msw	=	12 hr
Travel 460-490 msw	=	0.1 m/min (5 h)
Stop at 490 msw	=	2 hr
Travel 490-520 msw	=	0.1 m/min (6 h 40 min)
Stop at 520 msw	=	13 hr
Travel 520-550 msw	=	0.075 m/min (6 h 40 min)
Stop at 550 msw	=	13 hr
Travel 550-575 msw	=	0.05 m/min (8 h 20 min)
Stop at 575 msw	=	16 hr
Travel 575-600 msw	=	0.05 m/min (8 h 20 min)

* For clarification, and to avoid confusion, note the difference in trimix nomenclature from that usually utilized by technical divers.

With this profile and mix, the performance decrements were smallest under these conditions with little or no effect of the compression rate. At 10% nitrogen, there was more performance decrement. The EEG showed little or no change in the slow theta activity. One of the divers performed 240 watts work for sustained 5 minutes with the arterial carbon dioxide no higher than 53 mmHg. Some dyspnea or breathlessness was still present, however, but not with the 10% nitrogen mixture.

From 1983 to 1986 the German (GUSI) organization made 14 deep Trimix 5 dives at depths between 300-600 msw and carried out certified welds. Further from 1986-1990 there were seventeen more deep dive Trimix 5 dives made to 450 msw with 13 divers for

2662 man days of saturation and 983 days of welding. The divers were able to work and function well, and there were no permanent neurological after affects.

Mechanism of HPNS

The mechanism of HPNS is complex and is covered in more detail elsewhere (18). However, as described earlier, it is essentially an effect of the pressure itself on nerve junctions (i.e. synaptic) propagation in the brain. It is not due to helium breathing *per se*. Indeed, the main problem with helium is that it does little to alleviate the problem. As with nitrogen narcosis, there is altered release of neurotransmitters. However, the effects are opposite as shown below; causing an excitatory effect for HPNS and depressive effect for narcosis. Trimix affords a balance between these effects. The more soluble nitrogen does what the helium fails to do; "expanding" the membrane structures against the effects of pressure.

Table 10. Opposite Effects of Narcosis and HPNS.

Narcosis Neuronal Membrane Expansion	HPNS Neuronal Membrane Contraction
Hyporeflexia	Hyperreflexia
Fall in surface tension (monolayer)	Rise in surface tension (monolayer)
Protected by LiCl (rats)	Enhanced by LiCl (rats)
Acetylcholine receptor binding increased in electroplaque (fish)	Acetylcholine receptor binding decreased in electroplaque (fish)
Reverses suppression dopamine sensitive cyclic AMP response	Suppressed dopamine sensitive cyclic AMP response
Facilitates GABA mediated transmission DECREASED SYNAPTIC EXCITEMENT	Reduces GABA mediated inhibition INCREASED SYNAPTIC EXCITABILITY
TRIMIX	

Hydreliox

The use of hydrogen as a narcotic gas instead of nitrogen in Trimix to ameliorate HPNS is reviewed at length elsewhere (18). Extensive research and dives have been done by the French Comex dive company. Most of these used a Trimix of 54% H_2/45% He/1% O_2

which would mostly control HPNS but with some narcosis. However, in two of the dives tremor was seen and this was followed by psychotic disorders even at only 984 fsw. It was concluded that the use of hydrogen at partial pressures higher than 25 atm may cause psychotic problems in some susceptible subjects. Nevertheless, subsequent deep dives with hydrogen led to the further conclusion that a fraction of 50% hydrogen in helium-oxygen appears effective to some 1500 fsw since most of the neurological symptoms of HPNS, including tremors, are reduced or suppressed.

In confirmation, Comex performed ocean dives with 49% H_2 to 1640 fsw with six excursions to 1,706 fsw and one to 1,739 fsw with 26 hr of underwater work in a satisfactory condition. In 1992, using Hydreliox, three divers were compressed over 13 days to 2,132 fsw with one making an excursion for a few hours to 2,300 fsw (40, 69). Tremors were present at 2,132 fsw, the slow theta EEG waves increased 200 to 300% and there were sleep disturbances but HPNS was reduced.

<u>Options for Reducing HPNS with Fast Descents</u>

As has been shown, fast descents will potentiate the onset and severity of HPNS. Rates of 100 fsw/min have clearly illustrated this. On the other hand, compression in the region of 30 fsw/min to 1000 fsw with 5 or 10% nitrogen is effective in ameliorating HPNS. The lower nitrogen will probably allow control of HPNS, but sensitive divers may still be affected. If 10% nitrogen or even higher levels are chosen, there may be some euphoria of nitrogen narcosis and performance decrement but maybe less chance of HPNS. Some of the deep record divers to 1,000 fsw have chosen nitrogen levels as high as 14% equivalent to 150 fsw presumably because they feel they can handle nitrogen narcosis at that depth. However, there is no data to show whether HPNS at this rate of compression can be controlled even with 14% nitrogen certainly with any duration at that depth.

Perhaps the fastest rate of compression to 1000 fsw without HPNS was 33 min (30 ft/min) in the 1974 Duke-Oceaneering dives (12) using 10% nitrogen in He/O_2. Five divers showed little or no HPNS with no nausea, tremors or significant performance decrements. Work was carried out in 56°F water for one diver wearing a heated suit who reported mild euphoria.

For comparison, the compression table used extensively in Germany with great success at ameliorating or preventing HPNS (Table 7) with 5% nitrogen-heliox involved 15 fsw/min to 600 fsw a 2 hr stage, and compression from 600 fsw to 768 fsw at 10 fsw/min, 6 hr at 768 fsw and compression to 1,000 fsw at 5 fsw/min.

There is little else that can be done other than eliminate divers sensitive to HPNS. The cause is the increased hydrostatic pressure and the faster the rate the worse the symptoms.

Unfortunately, the descent rates on deep technical dives are driven by the need to minimize bottom time because the length of decompression increases markedly as bottom time increases at these extreme depths. Decreasing the descent rate from 66-100 fsw / minute to 33 fsw / minute for a 1,000 fsw dive would be associated with a need for hours of extra decompression on top of an already punishing schedule. Nitrogen is very effective in Trimix in ameliorating HPNS, but it is not a cure-all and at fast rates of compression even Trimix may not prevent HPNS.

References

1. Adolfson J (1967). Human performance and behavior in hyperbaric environments. Acta Psychologica Gothoburgensia. VI Ed. John Elmgren, Almqvist and Wiksell. Stockholm.

2. Adolfson J, Muren A (1965). Air breathing at 13 atmospheres. Psychological and physiological observations. Sartryck ur Forsvars Medicin 1:31-37.

3. Albano G (1970). Principles and observations on the physiology of the scuba diver (translation from Italian). Office of Naval Research Report DR-150. Arlington, VA.

4. Albano G, Criscudi PM (1962). La syndrome neuropsichica de profondita. Ball Soc Ital Biol Sper 38:754-756.

5. Bean JW (1950). Tensional changes of alveolar gas in reactions to rapid compression and decompression and question of nitrogen narcosis. Am J Physiol 161:417-425.

6. Behnke AR, Thomas RM, Motley EP (1935). The psychologic effects from breathing air at 4 atmospheres pressure. Am J Physiol 112:554-558.

7. Bennett PB (1965). Psychometric impairment in men breathing oxygen-helium at increased pressures. RN Personnel Research Committee, Underwater Physiology Subcommittee. Underwater Physiology Subcommittee. Report No. 251, London, Medical Research Council.

8. Bennett PB (1965). The narcotic action of inert gases. In OG Edholm, AL Bachrach, eds. The Physiology of Human Survival. Academic Press, London, pp 164-182.

9. Bennett PB (1966). The aetiology of compressed air intoxication and inert gas narcosis. International Series of Monographs in Pure and Applied Biology: Zoology Division. Vol 31, Oxford. Pergamon Press.

10. Bennett PB (1967). Performance impairment in deep diving due to nitrogen, helium, neon and oxygen. CJ Lambertsen, ed. Underwater Physiology. Proceedings of the 3rd Symposium Nat Acad Sci, Nat Res Council, ONR, Williams and Wilkins, Baltimore pp 327-340.

11. Bennett PB (1970). Potential methods to prevent the HPNS in human deep diving. In Techniques for Diving Deeper than 1500 feet. EB Smith, MJ Halsey, S Daniels, eds. Undersea Medical Society, Bethesda, pp 36-47.

12. Bennett PB (1975). A strategy for future diving. In 8th workshop: The Strategy for Future Diving to Depths Greater than 1,000 ft. Report No WS6-15-75. Undersea Medical Society, Bethesda.

13. Bennett PB, Ackles KN (1970). The narcotic effects of hyperbaric oxygen. In J Wada, T Iwa, eds. Proceedings of the 4th International Congress on Hyperbaric Medicine. Tokyo. Igaku Shoin, pp 74-79.

14. Bennett PB, Dossett AN, Ray P (1964). Nitrogen narcosis in subjects compressed very rapidly with air to 400 and 500 fsw. RN Personnel Research Committee Report. UPS 239. Medical Research Council, London.

15. Bennett PB, Glass A (1961). Electroencephalographic and other changes induced by high partial pressures of nitrogen. Electroenceph Clin Neurophysiol 13:91-98.

16. Bennett PB, Papahadjopoulos D, Bangham AD (1967). The effect of raised pressures of inert gases on phospholipid model membranes. Life Sci 6:2527-2533.

17. Bennett PB, Rostain JC (1994). The High Pressure Nervous Syndrome. In The Physiology and Medicine of Diving. PB Bennett and DH Elliott, eds. Saunders, London, pp 194-237.

18. Bennett PB, Rostain JC (2003). Inert gas narcosis. In Bennett and Elliott’s Physiology and Medicine of Diving. Saunders, pp 300-322.

19. Bennett PB, Rostain JC (2003). The High Pressure Nervous Syndrome. In Bennett and Elliott’s Physiology and Medicine or Diving. Saunders, pp 323-357.

20. Bennett PB, Schafstall H (1990). The value of TRIMIX 5 to control HPNS. In Lin Yu Chong, K Shida, eds. Man in the Sea, Vol 1. San Pedro, CA. Best Publications, pp 101-115.

21. Bennett PB, Schafstall H (1992). Scope and design of the GUSI International Research Program. Undersea Biomed Res 19:123-241.

22. Bennett PB, Towse EJ (1971a). Performance efficiency of men breathing oxygen-helium at depths between 100 feet and 1500 feet. Aerospace Med 42:1147-1156.

23. Bennett PB, Towse EJ (1971b). The High Pressure Nervous Syndrome during a simulated oxygen-helium dive to 1500 fsw. Electroenceph Clin Neurophysiol 31:383-393.

24. Brauer R (1975). The High Pressure Nervous Syndrome: animals. PB Bennett and DH Elliott, eds. The Physiology and Medicine of Diving and Compressed Air work. Williams and Wilkins, Baltimore, pp 231-247.

25. Brauer R (1983). Acclimation to nitrogen narcosis. A review. In 29th Undersea Medical Society Workshop, Nitrogen Narcosis. RW Hamilton and KW Kizer, eds. UHMS Publication 64 WS (NN) 4-26-85), pp vii, 1-17.

26. Buhlmann AA, Matthys HJ, Overrath G (1970). Saturation exposures of 31 ats in an oxygen-helium atmosphere with excursions to 36 ats. Aerospace Med 41:394-2773.

27. Case EM, Haldane JBS (1941). Human physiology under high pressure. J Hyg (Camb) 41:225-249.

28. Charpy JP, Murphy E, Lemaire C (1976). Performances psychométriques après compressions rapides a 300 m. Med Subaq Hyperbare 15:192-195.

29. Clements JA, Wilson KM (1962). The affinity of narcotic agents for interfacial films. Proc Nat'l Acad Sci 48:1008-1014.

30. Coler CR, Paton RM, Lampkin EC (1971). Effects of prolonged confinement in a hyperbaric environment on short term memory. Proc 41st Annual Meeting Aerospace Med Assoc. Washington, DC, pp 151-152.

31. Davis FM, Osborne JP, Baddely AD (1972). Diver performance: nitrogen narcosis and anxiety. Aerospace Med 43:1079-1082.

32. Edmonds C, Lawry C, Pennefather J, Walker R, eds. (1992). Diving and Subaquatic Medicine, IV edition, Arnold, London.

33. Elcombe DD, Teeter JH (1973). Nitrogen narcosis during a 14 day continuous exposure to 5.2% O2 in N2 at pressure equivalent to 100 fsw (4 ata). Aerospace Med 44 (7); 864-869.

34. Elliott DH (2007). In Naval Forces Under the Sea. The Rest of the Story. J Joiner, J Russell, Lasky. Best Publishing Co, Flagstaff, AZ, pp 354-355.

36. Fowler B, Ackles KN, Porlier G (1985). Effects of inert gas narcosis on behavior – a critical review. Undersea Biomed Res 12:369-402.

36. Fowler B, Hamilton K, Porlier G (1986). Effect of ethanol and amphetamine on inert gas narcosis in humans. Undersea Biomed Res 13:345-354.

37. Frankenhauser M, Groff-Lonnevig V, Hesser CM (1963). Effects on psychomotor functions of different nitrogen-oxygen mixtures at increased ambient pressures. Acta Physiol Scand 59:400-409.

38. Franks NP, Lieb WR (1978). Where do anesthetics act? Nature 274:339-342.

39. Fructus XR, Brauer RW, Naquet R (1971). Physiological effects observed in the course of simulated deep chamber dives to a maximum of 36.5 atm in helium oxygen atm. In CJ Lambertsen, ed. Proceedings of the 4th Symposium on Underwater Physiology. Academic Press, New York, pp 545-550.

40. Gardette B., Massimelli JY, Comet M (1993). Hydra 10. A 701 m on shore dive on hydreliox. In RE Reinertsen, AO Brubakk, G Bulstad, eds. Proceedings of the EUBS Congress, Trondheim, Norway, pp 32-37.

41. Gesell R (1923). On the chemical regulation of respiration. Am J Physiol 66:5-

42. Hamilton RW (1983). Nitrogen narcosis: its significance in modern diving. In 29th Undersea Medical Society Workshop, Nitrogen Narcosis. RW Hamilton and KW Kizer, eds. UMS Publication 64 WS (NN) 4-26-86, pp II 1-11.

43. Hamilton RW, Adams GM, Harvey CA, Knight DR (1982). A composite study of shallow saturation diving. NSMRL Report 985. Naval Medical Research Laboratory, Groton, CT.

44. Hamilton RW, Fructus XR (1971). Saturation – excursion diving: Operation LUDION III. In CJ Lambertsen, ed. Proceedings of the 4th Symposium on Underwater Physiology. Academic Press, Yew York, pp 537-544.

45. Hamilton RW, Kenyon DJ, Frietag M, Schriener HR (1973). NOAA Ops I and II: Formulation of excursion procedures for shallow undersea habitats. UCRI-731. Union Carbide Corporation, Tarrytown, NY.

46. Hamilton RW, Kizer KW, eds. (1985). Proceedings 29th Undersea Medical Society Workshop, Nitrogen Narcosis. Undersea Medical Society Publication 64 WS (NN) 4-26-85.

47. Harvey CA (1977). Shallow saturation hyperbaric exposures to nitrogen-oxygen environments and isobaric switches to helium-oxygen. Undersea Biomed Res 4(1):A15.

48. Hesser CM (1963). Measurement of inert gas narcosis in man. In CJ Lambertsen, LJ Greenbaum, eds. Proceedings 2nd Symposium on Underwater Physiology. Washington DC, National Acad Sci, Nat Res Council.

49. Hesser CM, Adolfson J, Fagraeus L (1971). Role of CO2 in compressed air narcosis. Aerospace Med 42:163-168.

50. Hesser CM, Fagraeus L, Adolfson J (1978). Roles of nitrogen, oxygen and carbon dioxide in compressed air narcosis. Undersea Biomed Res 5:391-400.

51. Johnson FH, Flagler EA (1950). Hydrostatic pressure reversal of narcosis in tadpoles. Science 12:91-92.

52. Jones AW, Jennings RD, Adolfson J (1979). Combined effects of ethanol and hyperbaric air on body sway and heart rate in man. Undersea Biomed Res 6:15-25.

53. Heilweil E (2007). Evaluation of the alleged reduced narcosis of nitrox mixtures. M.Sc. Thesis, University of Haifa. Faculty of Humanities. Departmenbt of Maritime Civilisations.

54. Lambertsen CJ (1976). Predictive Studies IV. Physiological effects and work capability in He-O2 excursions staged to depths of 400-800-1200 and 1600 feet. In Proceedings of the Symposium: The Work Diver. The Marine Technology Society, Washington DC, pp 156-173.

55. Lambertsen CJ, Wright WB (1973). Multiday exposure of men to high nitrogen pressure and increased airway resistance at natural expired oxygen tension: A 14 day exposure to 5.2% O2 in N2 at 4.0 ats abs pressure. Aerospace Med 44:826-833.

56. Lanphier EH (1963). Influence of increased ambient pressure upon alveolar ventilation. In Proceedings 2nd Symposium on Underwater Physiology. Eds CJ Lambertsen, LJ Greenbaum. National Academy of Sciences Publ 1181. National Research Council. Washington pp 124-133.

57. Lemaire C, Rostain JC (1988). The High Pressure Nervous Syndrome and Performance. Octaves, Marseille, France.

58. Lever MJ, Miller KM, Paton WDM (1971). Effects of hydrostatic pressure on mammals. In CJ Lambertsen ed. Proceedings of IV Symposium on Underwater Physiology. New York. Academic Press, pp 101-108.

59. Meyer HH (1899). Theoris der alkolnarkose. Arch Exp Path Pharmak 42:109.

60. Meyer KH, Hopff H (1923). Narcosis by inert gases under pressure. Hoppe-Seyler's Z Physiol Chem 126:288-298.

61. Miller KW, Paton WDM, Smith RA (1973). The pressure reversal of general anesthesia and the critical volume hypothesis. Mol Pharmacol 9:131-143.

62. Muren AM, Adolfson J, Ornhagen HG, Gennser M, Hamilton RW (1984). Nisahex. Deep nitrox saturation with nitrox and trimix excursions. In Underwater Physiology VIII, AJ Bachrach and MM Matzen, eds. Undersea Medical Society, Bethesda.

63. Nitrogen Narcosis. A bibliography with abstracts. Undersea Medical Society Publ No 61 (NN) 6-1-83.

64. Overfield EM, Saltzman HA, Salzano JV (1969). Respiratory gas exchange in normal men breathing 0.9% oxygen in helium at 31.3 ats. J Appl Physiol 27:471-475.

65. Overton E (1901). Studien uber die narkose. Jena Fischer.

66. Paton WDM (1967). Experiments on the convulsant and anesthetic effects of oxygen. Br J Pharmacol Chemother 29:350-366.

67. Rashbass C (1955). The unimportance of carbon dioxide in nitrogen narcosis. RN Report. RN Personnel Research Committee 153. Medical Research Council, London.

68. Rostain JC, Gardette MC, Naquet R (1980). HPNS during rapid compression of men breathing He-O2 and He-N2-O2 at 300 m and 180 m. Undersea Biomed Res 7:77-94.

69. Rostain JC, Gardette-Chauffour MC, Gardette B (1994). HPNS during a deep hydrogen-oxygen dive up to 701 meters. Undersea Hyperb Med 21:40.

70. Rostain JC, Martinez E, Lemaire C, eds. (1989). High Pressure Nervous Syndrome. 20 years later. Proceedings 1st Meeting International Group on High Pressure Biology. ARAS Publications, Marseille, France.

71. Salzano J, Rausch DC, Saltzman H (1970). Cardiorespiratory responses to exercise at a simulated seawater depth of 1000 ft. J Appl Physiol 28:34-41.

72. Shilling CW, Willgrube WW (1937). Quantitative study of mental and neuromuscular reactions as influenced by increased pressure. US Nav Med Bull 35 (4):373-380.

73. Spaur W (1979). Personal communication.

74. Stringer J (1983). Euphoria at 200 ft. Skin Diver Magazine 32:126-129.

75. Summit JK, Kelly JS, Herron JM, Saltzman H (1971). 1000 ft helium saturation exposure. In CJ Lambertsen, ed. Proceedings of the 4th Symposium on Underwater Physiology. New York, Academic Press, pp 519-527.

Discussion

SIMON MITCHELL: Peter, you spoke about two broad strategies for reducing HPNS. One is reducing compression rate and one is introducing nitrogen into the mix. Obviously, for most of the group here who are technical divers, changing the compression range isn't an option because of bottom time constraints. The question then defaults to the optimum strategy for use of nitrogen? Obviously, the amount of nitrogen we can put in the mix depends upon how narcotic it's going to be. Do you have a sense, say if we were going on a 300-meter dive for example, how much nitrogen would you want us to put in the mix to ameliorate HPNS? Is it simply a case of the more the better?

PETER BENNETT: No. As you're going very fast,there is no guarantee that the Trimix is really going to prevent the HPNS. It may prevent it for a while. You may feel you're okay. But it will break through with a big bang; you'll have all the symptoms coming in a rush. I think the work we did shows you can use 10 percent. It's OK. Some of these guys are going to 1,000 foot now are using 16 percent. That's a bit heavy. They're getting some narcosis, I'm sure. The question is this: Is it better to have some narcosis that you know, rather than HPNS that you may not? That is a very individual choice. But I think you can take 10 percent as an average, and you would be OK. Sixteen percent is getting on the high side because you're getting on the narcosis side of the coin. You're trying to decide which you want; HPNS or narcosis, and trying to hit the limit point.

RICHIE KOHLER: You drew a line at 600 feet where HPNS becomes a problem. Before that, for divers using closed circuit technology, is there any advantage to introducing small amounts of nitrogen in their mix where HPNS is not a problem?

PETER BENNETT: Again, it's going to depend on your sensitivity. What we did was do 600-foot trials to select people who were most sensitive. We would compress them at 100 feet a minute to 600 feet, and you see how they react. Do they get nauseous, do they vomit and so on. If they do, then you've got to worry whether you're going to use them or not. Or you can try Trimix then and say we're going to use 5 or 10 percent nitrogen for the 600-foot dive which can control it reasonably well. HPNS may be a problem if you start going deeper. We've got this biological variability, which is always with you, and it is a problem. I don't think less than 600 foot you have to worry a great deal, but again, it's tied to the rate of compression. You're going fast so in a sense every time you go to 600 foot without Trimix or with Trimix you are testing what we would do with another individual to find out whether he is sensitive to HPNS. If you haven't had HPNS in doing those dives, you're not going to get it. So you've already done the test to show you're not sensitive.

UNIDENTIFED SPEAKER: First of all, looking around the room, I notice that the mean age in the room is a little bit higher than I would have expected. No offense to anyone. But you have mentioned that to control HPNS the selection of divers is important, and on several of your slides you mentioned age of the divers. Have you found that age is related or correlated in any way?

PETER BENNETT: We didn't have a lot of older divers to experiment on, so I can't say definitely. There was certainly a feeling among the commercial diving groups that younger was better, and that the older divers didn't appear to do so well in the very deep dives.

DICK VANN: What about the use of hydrogen in a rebreather where you can switch to a gas if you're going very deep with a low enough oxygen percentage?

PETER BENNETT: Why use hydrogen instead of nitrogen, which is much safer? You won't blow yourself up.

DICK VANN: Because of the increased density. I think Lou Nuckols indicated –

PETER BENNETT: No. Remember what I said about dyspnea. In fact, they felt much better when the density was higher. Less dyspnea at 10 percent than 5 percent. So density wasn't the problem.

DICK VANN: It's not a question of the density on the HPNS. It's the work of breathing. That's a big issue, or a big disadvantage of Trimix is that work of breathing.

PETER BENNETT: I understand. Steve was still able to do a heavy workload with that amount of nitrogen in the mix. I'm a bit leery of hydrogen. While it's below 4 percent you're not going to get an explosion, but what about the guy smoking a cigarette and throwing it over the side and it blows up. You can't be sure. People handling hydrogen in general, I don't know. It's up to you guys whether you want to do that.

THERMAL CONCERNS IN COLD WATER DIVING

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Introduction

Hypothermia is defined as a lowering of body core temperature to a stressful level (3). The central core, including the brain, spinal cord, chest organs, abdomen and pelvis can tolerate only a narrow temperature variation before their normal functions become impaired. Even a small reduction in core temperature of only 0.5-1^{o}C can result in a loss of mental capacity (10-20%) and up to 40% loss of memory. Core temperatures below 35^{o}C, a temperature which is normally considered the onset of mild hypothermia, produce diminished heart rate, blood pressure and basal metabolic rate. Reports on the notorious Nazi Dachau experiments during World War II show that exposures, which cause central core temperatures to fall between 24.2-25.7^{o}C, are fatal (1). These gruesome experiments showed that death in hypothermia is most certainly due to arrest of the heart, even at a time when respiration is continuing.

Thus, it can be said that the most important effects of cold exposures are on the heart. The most obvious effect is slowing of the heart's pacemaker as heart temperature drops, leading to a progressive decline of the rate at which the heart beats accompanied with a decline in cardiac output, followed by cardiac arrest. Human patients cooled to 30.5-32.5^{o}C prior to surgery have been shown to have 31% reduction in cardiac outputs (11). Fortunately, protection for the hypothermic brain exists during this cardiac output reduction due to its diminished oxygen uptake.

While there seems to be a universal acceptance of the effects that hypothermia has on the human body, the scientific literature contains a wide range of seemingly conflicting recommendations for how hypothermic victims should be treated; many recommending rapid rewarming by complete immersion in a 40-44^{o}C water bath (5), others taking the position that rewarming in field conditions is unacceptably dangerous and should not be practiced if avoidable (2). Unfortunately, the latter recommendation is frequently not practical due to the remote settings where a hypothermic victim might be found, difficult weather conditions, or problems with communications and transportation. Additionally, it is commonly accepted that the most important step in the treatment of hypothermia is to start rewarming as soon as possible. Indeed, the speed with which treatment can be started is critical, since the brain is unlikely to survive following cardiac arrest much more than an hour, even at low body temperature (6).

Although there appears to be a sizeable controversy over the best methods to treat hypothermic victims, there seems to be a general consensus of the most common causes of post-rescue death (10). These causes must be considered critical physiological elements in the design of any emergency hypothermia treatment system, including:

a) Further fall of central core temperature caused by continued exposure, particularly to wind chill, must be avoided. This makes it imperative that the hypothermic victim be wrapped in a warm, impermeable enclosure to minimize further loss of body heat via convection or evaporation.

b) Further fall of central core temperature must be avoided which is caused by "afterdrop," a condition in which the core temperature continues to drift downward when surface cooling has ceased due to an influx of cold peripheral blood into the core as a result of vaso-dilatation of the extremities during active rewarming. This afterdrop is seen most markedly in those hypothermic victims who have been rapidly cooled because greater temperature differentials will exist between the central core and the extremities.

c) Mechanical stimulation of the hypothermic heart leading to ventricular fibrillation must be avoided. At heart temperatures below 33^{o}C, atrial fibrillation can develop in some patients; below 28^{o}C, ventricular fibrillation has been shown to occur if the heart is irritated mechanically (6). Whereas atrial fibrillation has a negligible effect on the function of the heart, ventricular fibrillation completely destroys the heart's ability to pump blood. It is imperative that the hypothermic victim be handled and moved as little as possible to avoid such stimulations of the heart.

d) Shock caused by hypovolemia must be avoided. During cold exposures, a loss of circulating volume will occur due to diuresis. This results from blood pooling from the peripheral blood vessels into the central core of the body due to vaso-constriction in the extremities. It can also occur in the case of immersion exposures due to blood pooling caused by elevated hydrostatic pressures in the lower extremities. In either case, the increased blood volume in the central core triggers the kidneys to increase urine secretion. Subsequent rewarming techniques which do not limit vaso-dilatation in the extremities can result in a rapid drop in blood pressure as the reduced blood volume leaves the central core.

The concerns for afterdrop expressed in b) and d) above indicate that emergency rewarming of divers suffering from hypothermia should concentrate on applying heat in localized regions of the body, including the head and torso. The extremities should be avoided until the central core temperature has been elevated above its cold-sensitive region where ventricular fibrillation and/or shock due to hypovolemia are a concern. It has been suggested that those patients not susceptible to hypovolemic shock should be rewarmed by surface warmth augmented by airway rewarming to achieve a rise in core temperature of 1-2^{o}C per hour (10). A physiological algorithm used to control the rewarming procedure must take into account the patient's body weight, surface area, central core and skin temperatures and ambient temperature. These parameters can be used to identify the rate at which heat should be supplied to various regions of the body surface and through the respiratory tract.

Thermal Exposure Limits

Producing a state of complete thermal comfort in all diving modes is an extremely difficult, if not impossible, task. Researchers have proposed thermal limits to protect divers against the dangers implicit in hypothermia and hyperthermia (7, 12). These limits were established to give design guidelines for the development of thermal protective systems and give estimates of safe exposure limits for divers in severely harsh environments. Note that these limits were designed to ensure that mental, motor and sensory functions will be minimally impaired so as not to jeopardize the performance and safety of the diver. These limits will not ensure that the diver will always be comfortable.

a) The diver net body heat loss should not exceed 200 kcal. (This has also been given as 3 kcal per kg of body mass to account for the range of diver body sizes.)

b) The diver body core temperature should not drop by more than 1^{o} C.

c) Mean skin temperature should not go below 25^{o}C, and individual skin temperatures should not go below 20^{o}C, except that of the hands, which should not go below 15^{o}C.

d) The diver's metabolic response from shivering should not exceed an incremental increase in oxygen consumption rate of 0.5 liters/minute above the metabolic cost of the diver's activity.

Thermal Endurance Limits

Based on the guidelines given above for cold exposures, acceptable cold exposure durations have been estimated (9) using the expression

$$t, hrs = \frac{-837}{\left(\dot{M} - \dot{q}_{resp}\right) - \dfrac{22.04\left(77 - T_{amb}\right)}{CLO_{suit}}} \qquad (1)$$

where $\dot{M}$ is the metabolic heat production of the diver, given in Btu/hr; $\dot{q}_{resp}$ is the respiratory heat loss from the diver, Btu/hr, T_{amb} is the surrounding water temperature, ^{o}F; and CLO_{suit} is the insulation value of the diver's suit.

Figures 1 and 2 show estimated mission durations based on Eq. (1) for a resting and lightly working diver, respectively, who are wearing garments with passive insulation levels varying between 0.4 and 1.8 CLO[2]. These estimates indicate that, theoretically, a resting diver (defined in this analysis as metabolic heat generation minus respiratory heat loss equal to 117 watts (400 Btu/hr)) in 34°F water could be expected to function properly for greater than 6 hr with a garment having an insulation level between 1.7 to 1.8 CLO. The diver who increases his activity only slightly, as shown in Figure 2, with metabolic minus respiratory heat rates equal to 176 watts (600 Btu/hr), could function adequately with a suit insulation reduced to approximately 1.3 CLO in the same water temperature.

[2] CLO as a unit of thermal protection can be characterized as the insulation inherent in a business suit when worn in air. It can be quantified as 1.136 divided by the suit conductance, where suit conductance is measured in BTU/ft2-hr-oF; ie

$$CLO = \frac{1.136}{\left(Suit\,Conductance, \dfrac{Btu}{ft^2 - hr - {}^{o}F}\right)}$$

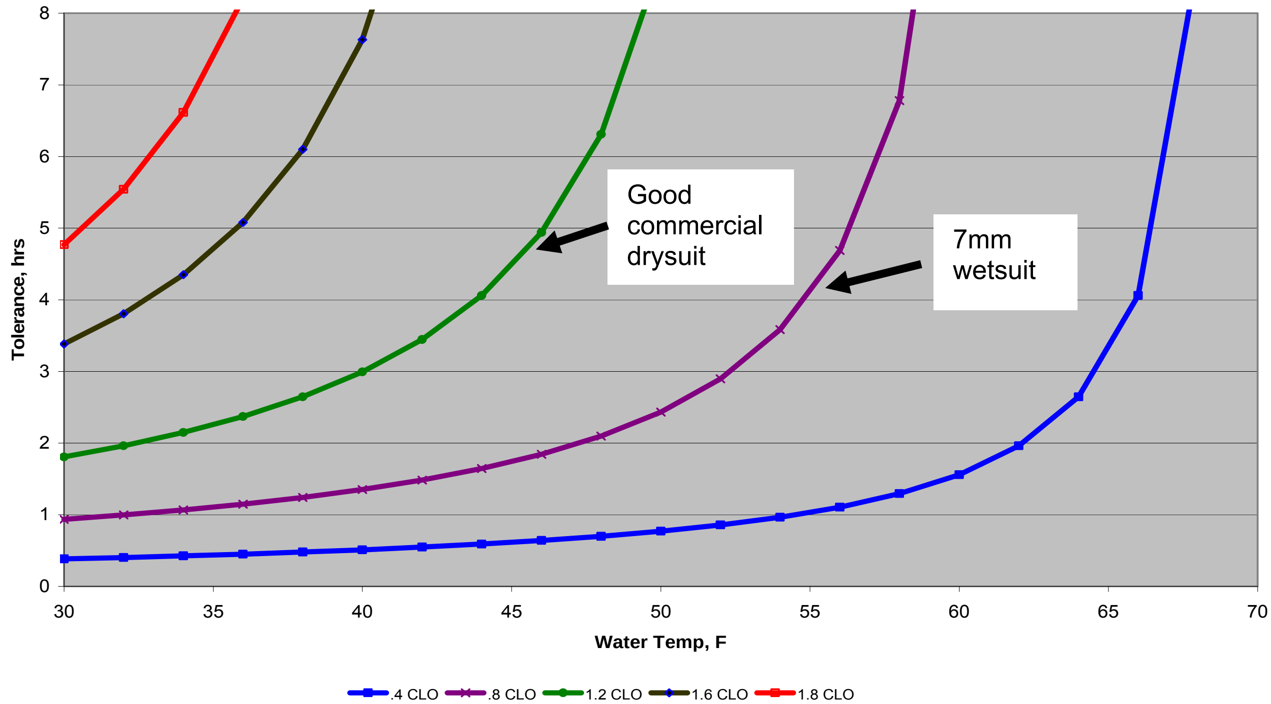

Figure 1. Estimated thermal tolerance limits for a resting diver (117 watts) in cold water with various suit insulation values.

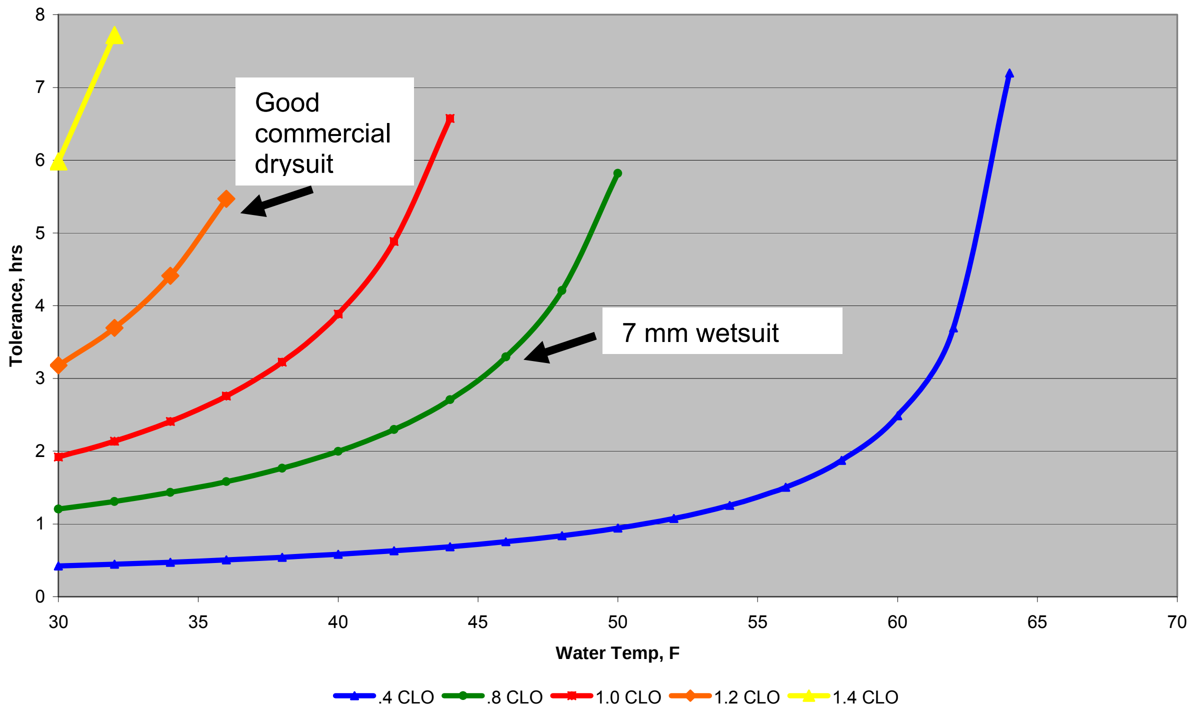

Figure 2. Estimated thermal tolerance limits for a lightly working diver (176 watts) in cold water with various suit insulation values.

New Diving Garment Technologies

An area of primary interest in diving safety and effectiveness is improving the ability of free-swimming and tethered divers to operate in thermal extremes (both hot and cold) through improved suit materials, insulating materials, heat exchangers and heat-storage devices. Current efforts are under way in a joint effort between Southwest Research Institute in San Antonio, Texas, and Duke University to identify and characterize thermal and physical characteristics of recently developed materials and to identify the integration

Figure 3a: Aspen Aerogel Cloth Super-Insulation

Figure 3b: Aspen Aerogel Cloth Super-Insulation

of several of these materials into the design and construction of composite cold water diving suits to best utilize their superior thermal properties. A composite is deemed necessary since materials offering the highest thermal resistance are often the most compressive and/or offer the least tolerance to moisture. A new diving suit is being developed under funding from the U.S. Navy Office of Naval Research (ONR) that integrates various suit materials to best take advantage of their desirable properties to maximize thermal protection while minimizing the undesirable features of each.For instance, super-insulation materials (based on flexible aerogel composites) have been incorporated into diving suits to meet the demanding thermal protection needs of a diver in the most extreme environments. Aspen Systems of Marlborough, Mass. has developed a flexible, drapeable aerogel composite insulation which has the thermal performance equal to the best solid insulation known (brittle monolithic aerogels) in a much more practical form, as shown in Fig. 3. Originally funded by the National Astronautics and Space Administration (NASA) for next generation spacesuit insulation development for extra-vehicular activity (EVA) on Mars, flexible aerogel composites are presently being developed suitable for submerged conditions as well. The new insulation currently comes in a thin blanket form that is amenable to conventional cutting and shaping techniques common to the clothing industry. The blankets have a measured thermal conductivity of 10 - 14 mW/m-K (R-value of 14-10 per inch) in ambient conditions, a specific gravity of around 0.1, excellent flexibility without loss of thermal performance over many tens of thousands of bending cycles, and superior acoustical absorption capability compared to conventional rubber insulations used in diving suits. The flexible aerogel-based insulation shows great promise to satisfy the thermal and mechanical requirements for a high performance diving suit insulation material.

Another promising material, developed by NASA and recently introduced commercially, is a vacuum packaged super-insulation material called Nanogel™. This material is a low-cost silica and carbon powder that is made rugged by incorporating polymer binders and vacuum packing the powder with ultra thin layers of Mylar. The developers of this material report that it provides 10 times the insulation of a comparable thickness of stagnant air, is water resistant, and is resistant to compression under hydrostatic pressure. While less flexible than the Aspen aerogel, a marriage of these two materials into a composite could potentially take advantage to the best properties in each of these materials. The Nanogel™ super-insulating material can potentially show insulations over 4 times greater than Thinsulate even in a wet, high-pressure environment.

A new composite cold water diving garment is being developed to integrate these super-insulators with insulating liquids to take advantage of the incompressible, neutrally or negatively buoyant liquids previously used with liquid-filled divers' gloves (4) and liquid-filled suit liners (8). One such liquid liner material, halocarbon oil mixed with glass micro-balloons at approximately 45% by volume, has already been shown to give an insulation quality equivalent to uncompressed foam neoprene yet incompressible and neutrally buoyant. A negatively buoyant liquid insulation, already identified, could potentially be integrated with one or both of the aerogels in a suit composite to counteract their buoyancy while maximizing the suit thermal properties. Prototype garments have been designed to give inherent insulation values of approximately 1.8 Clo, 50% greater insulation than current commercial drysuits with no additional suit bulk. Additionally, the prototype suits are equipped with aerogel glove liners, boot liners, and skull caps to protect diver extremities.

References

1. Alexander, L. (1946), "Treatment of Shock From Prolonged Exposure To Cold, Especially in Water," Combined Intelligence Objectives Sub-Committee, Item No. 24, File No. 26-37.

2. Doolittle *et al* (1982), "State of Alaska Hypothermia and Cold Water Near Drowning Guidelines," Emergency Medical Services Section, Division of Public Health, Alaska Dept of Health and Social Services, Juneau, Alaska.

3. Heine, J.N. (1996), Cold Water Diving, Best Publishing Co., Flagstaff, AZ.

4. Henkener, J.A., Nuckols, M.L., (2000). Maximizing thermal performance of divers' gloves by use of insulating liquids, Proceedings of Oceans 2000, Providence, RI, Sept 11-14, 2000, pp 1375-138.

5. Jenkins, W.T. (1976), A Guide To Polar Diving, Naval Coastal System Laboratory, Panama City, FL.

6. Keatinge, W.R. (1978), Survival in Cold Water, Blackwell Scientific Publications, Oxford.

7. Kuehn L, Ackles K. Thermal exposure limits for divers. Hyperbaric Diving Systems and Thermal Protection. American Society of Mechanical Engineers OED-6. New York, 1978:39-51.

8. Nuckols, M.L., Henkener, J.A. (2002), "Liquid-Insulation Garments For Long-Duration, Cold Water Diving," Proceedings of Underwater Intervention 2002, Feb 27-March 2, 2002, New Orleans, LA, (CD-ROM Paper G-2-3).

9. Nuckols M, Tucker W, Sarich A. Life Support Systems Design. Needham Heights, MA: Simon & Schuster, 1996.

10. Rey, L., ed (1985), Arctic Underwater Operations, Graham & Trotman, London.

11. Rose, D.N. (1957), "Problems Associated With The Use of Hypothermia in Cardiac Surgery," Proc. Royal Soc. Medicine, 50, pp 76-78.

12. Webb P, Beckman E, Sexton P, Vaughan W. Proposed thermal limits for divers. Office of Naval Research contract N00014-72-C-0057, 1976.

Discussion

SIMON MITCHELL: Are there any questions for Lou? Actually, I'll start with one. Where do I get one of those aerogel suits?

LEW NUCKOLS: We're actually working with a vendor who is very interested in commercializing them. We've been working very closely with Diving Unlimited out of San Diego; I'm sure you're all familiar with them. I'm sure they could build you a suit right now, but the cost is going to be the factor. I would say a good 400-weight Thinsulate custom-made liner for your drysuit it's going to be upwards of about $1,000. Until they are selling larger numbers, the aerogel suits will probably be double that. So you would expect to pay at least $2,000, I'm sure.

SIMON MITCHELL: There are some people in this room like Jarrod who would have to be interested. Some of these guys who are doing the incredibly long exposures, 12, 13, 14 or more hours in moderately cold water, what an extraordinary step forward for them. So there is an expectation we're going to see them?

LEW NUCKOLS: Absolutely. There is great interest from Diving Unlimited. I'm not in cahoots with Diving Unlimited whatsoever, and I'm sure there are other manufacturers out there that could likewise get into this. I will say that there's a learning curve on the actual fabrication of the panels themselves that can be properly put into a drysuit.

DECOMPRESSION WORKSHOP: CHAIRMAN'S SUMMARY

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By its nature, technical diving mandates the need for decompression stages, and not unusually, in durations of several hours. To maintain health, the technical diver must be familiar with the art of decompression and, perhaps, the science as well. While knowledge of both remains incomplete, appreciation of what is known of the mechanisms of decompression sickness (DCS), of DCS therapy, and of physiological factors affecting decompression and DCS risk can be of practical value as well as serving to satisfy the curiosity.

Richard Moon reviews the objective signs and subjective symptoms that DCS can cause with reference to affected tissues. Two mechanisms for serious spinal DCS suggested by animal experiments include obstruction of the venous circulation of the spinal cord and autochthonous (*in situ*) bubbles that form in the cord substance. Mechanisms underlying mild spinal manifestations are less certain. Arterial gas emboli (AGE, exclusive of lung barotrauma) might occur when venous gas emboli (VGE) pass through the pulmonary capillaries or around the lung filter, such as through a patent foramen ovale (PFO), and enter the arterial circulation of the brain. Direct evidence linking such mechanisms to DCS is lacking, but vascular bubbles can damage endothelium (lining of the blood vessels) causing reduced blood flow, inflammation, clotting, and fluid leakage into surrounding tissue. Thus, bubbles have secondary biochemical effects in addition to mechanical effects of distorting tissue or impeding blood flow. The importance of these effects across the spectrum of DCS manifestations is under investigation.

David Doolette discusses environmental and demographic factors associated with increased or decreased DCS risk. The most important, for which strong evidence exists, are thermal state, exercise, and acclimatization (decreased DCS risk with repeated exposures). There is weaker evidence for smaller effects due to sex, age, dehydration, and body mass index (BMI). VGE are useful measures of decompression stress but not of DCS. A diver's thermal state as determined by water temperature, exercise, and thermal protection strongly affects peripheral blood flow which controls inert gas uptake at depth and elimination during decompression. The dive phase (pre-dive, at depth, decompression, post-dive) in which exercise or thermal exposure occurs is a determinant of DCS risk and can have a greater effect on risk than the dive profile itself. Understanding the effects of dive conditions is essential for minimizing DCS risk.

Wayne Gerth and David Doolette describe a U.S. Navy decompression trial that investigated the optimal depth for the first and deepest decompression stop to achieve the lowest possible DCS risk. For an air dive of 30 min at 170 fsw with 174 min of decompression time, two different decompression models were used to compute decompression schedules with first stop depths of 70 or 40 fsw. The DCS incidence was significantly greater for the deeper schedule (5.6%; 11 DCS in 198 dives) than for the shallower schedule (1.6%; 3 DCS in 192 dives). The deeper schedule also had significantly more VGE. For the schedules tested, these results indicated that deeper decompression resulted in less effective nitrogen elimination. One can argue that the deeper stops were not optimal, but this is the only deep stops study to date with DCS as the end-point. Care is cautioned in the use of decompression stops deeper than those usually prescribed until contrary evidence based on DCS (not VGE) is available.

Richard Vann discusses the probabilistic nature of DCS and decisions regarding decompression safety including managing mild and serious DCS risk. The effects of dive conditions were shown to affect DCS risk by a factor of 10 or more. Helium-oxygen diving without switching to oxygen or nitrox was shown to have a greater risk of VGE and Type II DCS than diving with nitrox alone. DCS risks of open-water technical dives resulting in DCS were estimated at 2.9-5.1%. For 168 laboratory dives to 500 for 30 min, the DCS incidence was 14% with an estimated probability of 15%. Risk estimates suggested lower DCS probabilities with an oxygen partial pressure of 1.3 atm compared with constant oxygen fraction gases that resulted in an oxygen convulsion. No DCS was reported for 20 *Britannic* dives (343 fsw mean depth, 4:40 mean total dive time) despite a mean estimated DCS probability of 28%. Possible explanations for the discrepancy include: (a) inaccurate risk estimation; (b) unreported DCS; and (c) diver self-selection.

Simon Mitchell and Richard Pyle discuss possible DCI therapies with emphasis on in-water recompression. Surface oxygen is well-accepted as primary first aid with head-out immersion suggested as a possible (but untested) adjunct to take advantage of accelerated nitrogen elimination. Adequate hydration was recommended to avoid shock due to low blood volume. Non-steroidal anti-inflammatory drugs were recommended for accelerated pain relief. Recompression on 100% oxygen is the definitive therapy for DCI with 2.8 ata (60 fsw) the most common depth and deeper depths (e.g., 6 ata) an option for severe or unresponsive cases. Delayed recompression appeared less important for mild than for serious cases although complete recovery might be delayed. Early recompression is a priority for serious cases if chamber facilities and medical support are adequate. This raised the issue of whether in-water recompression (IWR) is ever advisable and under what conditions. Available data on IWR efficacy are generally positive although usually anecdotal rather than reported by trained medical observers. A decision tree to assist in choosing whether IWR might be attempted is provided as well as discussions of necessary equipment and procedures.

PATHOPHYSIOLOGY OF DECOMPRESSION ILLNESS

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Terminology

The term *decompression illness* refers to either *decompression sickness (DCS)* or *arterial gas embolism (AGE)*, or both. These two entities have completely different causes. DCS is due to evolution of bubbles within in tissues due to supersaturation of inert gas (usually nitrogen or helium). AGE is due to rupture of the alveolar-capillary barrier due to expansion to gas with in the lung during ascent, typically due to breath holding or regional gas trapping with in the lung. These entities are discussed below.

Decompression Sickness (DCS)

Inert gas, such as helium and nitrogen, is taken up in tissues to a degree that depends primarily on blood flow and gas solubility. During inert gas uptake, its partial pressure rises. It reaches a peak at the end of the bottom time and then falls during decompression. As long as its partial pressure is less than the external pressure acting on the tissue, the inert gas will remain in solution. This external pressure is the sum of several pressures:

Atmospheric pressure

Hydrostatic pressure due to the water column
Elastic tissue pressure

If the rate at which the external pressure declines allows tissue inert gas partial pressure exceeds the sum of the pressures listed above, supersaturation occurs, theoretically allowing gas bubble formation to occur. In practice, there is a degree of “allowable supersaturation,” or a fudge factor, which increases the threshold for bubble formation. Once this threshold has been exceeded, bubbles can form, just as carbon dioxide bubbles are generated when a can of carbonated beverage is opened. At that point surface tension tends to reduce bubble volume, while further diffusion of dissolved inert gas into the bubble tends to make them grow.

Although clinical manifestation of DCS can occur in different types of tissues, the most common manifestations consist of pain around the joints and neurological signs and symptoms. Numbness, tingling, weakness and even frank paralysis can occur. Joint pain is believed to be caused by tissue distortion from bubble formation within relatively rigid tissue such as tendons, cartilage or perhaps bone. The most severe neurological manifestations are caused by damage to the spinal cord. Why the spinal cord should be involved more commonly than other tissues is not understood. However, one theory advanced by John Hallenbeck (1) is that spinal cord blood flow can be impeded by bubble formation within the veins that drain the spinal cord (epidural venous plexus). Hallenbeck observed this in experimental animals after a provocative chamber exposure. He argued that a reduction in blood flow due to obstruction of the veins would further impede inert gas washout and amplify the process of bubble formation. This explanation was later criticized on the grounds that it could not explain the frequently observed mild sensory abnormalities or weakness. An alternative hypothesis was proposed by James Frances (2), who suggested that bubbles could form within the substance of the spinal cord (autochthonous bubbles). He felt that autochthonous bubbles could be reduced in size by recompression, and this could explain why spinal cord DCS often responds to treatment even hours or sometimes days after onset. On the other hand, to demonstrate autochthonous bubble formation in experimental animals, extremely severe decompression profiles are required. Thus, whether either the Hallenbeck or Francis models could explain the frequent mild symptoms experienced by recreational and other divers is in question.

Other manifestations of DCS include skin rash and vertigo (sensation of spinning, associated with difficulty with balance, nausea and vomiting). The latter is caused by damage to the vestibular apparatus, the balance organ. Theoretical calculations suggest that the vestibular apparatus maybe susceptible to DCS by virtue of either formation of bubbles within tiny spaces in the bone surrounding the inner ear (3) or due to the slow gas washout (long halftime) of the fluids within the inner ear (4).

Arterial Gas Embolism (AGE)

AGE consists of direct “injection” of air from the gas containing spaces in the lung into the blood. This can occur during ascent if the alveolar pressure exceeds the elastic limit of the alveolar-capillary interface. It can occur either due to breath holding or mechanical obstruction of the airways. AGE can then enter the arteries that supply the vital organs, including the heart and brain. Because the brain receives approximately one-fifth of the resting cardiac output AGE frequently causes neurological manifestations similar to stroke. Divers with AGE may lose consciousness or develop sudden weakness or numbness in one arm or in half of the body. Visual symptoms can also occur. The original notion was that AGE caused abnormalities by occluding blood vessels. While this sometimes occurs, small amounts of gas can pass through the arterial circulation of the brain (5), but in the process of doing so damage the lining of the blood vessels (endothelium) and due to secondary effects caused a reduction in blood flow.

Secondary Effects of Bubbles

The presence of bubbles by themselves may not cause clinical decompression sickness. It is recognized that the body is capable of withstanding a certain bubble load without symptoms of DCS. In a recent study in recreational divers, on the first day of diving up to 80% of divers had venous bubbles detectable by Doppler, but none developed DCS (6). For clinical symptoms to develop, secondary effects must occur.

Arterial bubbles by themselves can initiate secondary effects, either by damaging the blood vessel endothelium or lining (7, 8), by occluding the vessel to reduce flow or by "seeding" additional bubble formation (4). Bubbles in the bloodstream are most commonly observed in the veins. Small quantities of bubbles are therefore filtered by the capillaries of the lung, where the inert gas is exhaled. However, large quantities of venous bubbles (venous gas embolism, VGE) can overwhelm the pulmonary capillary filter and enter the arterial blood (9, 10). This can also occur either via a patent foramen ovale, an opening between the right and left aria in the heart (11-14)).

Bubbles entering the arterial circulation by this mechanism then behave like AGE. In addition to direct inclusion of blood vessels, the lining (endothelium) can be damaged or stripped by circulating bubbles. The endothelium is in important for regulating arterial diameter (and hence resistance) and also to maintain liquids within the blood. When the endothelium is damaged, control of blood vessel diameter is impaired and plasma can leak from the blood stream into the surrounding tissue. The effects of this are similar to those of dehydration or blood loss: hypotension, tissue hypoperfusion and cellular hypoxia. Loss of plasma has been documented using radioactive tracer techniques (15). This causes the proportion of the blood volume that is made up of red blood cells (hematocrit) to increase (referred to as hemoconcentration). This is manifested by an increase in hematocrit. Indeed, elevated hematocrit in DCS or AGE is associated with more severe disease (16).

Gas bubbles interacting with the endothelium can initiate a reduction brain blood flow due to other mechanisms, including deposition of white blood cells (leukocytes) on the lining of the blood vessels, possibly causing mechanical obstruction of blood flow. In addition, platelets may interact with gas bubbles by adhering to the surface of the bubble and initiating clot formation. A reduction in circulating platelet numbers has been observed in asymptomatic dives (17-20), providing at least indirect evidence for platelet activation and clot formation.

While reduced blood supply to tissue via blood vessel occlusion, tissue distortion or endothelial effects can cause cellular hypoxia, there are several other mechanisms by which cells can die. First, if blood supply is reduced to a critical value, cells may die directly due to lack of oxygen (anoxia). Alternatively, a moderate reduction in blood flow can cause a phenomenon known as ischemia-reperfusion syndrome. This refers to the effects of a period of transient reduction in blood supply followed by its re-establishment. When this happens, oxygen free radicals are generated in excess. These molecules can then react with various components of the cell and tissue to cause direct injury. Third, in neurological tissues such as the brain, reduced blood flow can cause an increase in excitatory neurotransmitters, which include glutamate and aspartate. These substances can facilitate entry of calcium into the cell, which then initiates formation of reactive molecules such as superoxide anion and nitric oxide. These two molecules can react to form yet another toxic compound, peroxynitrite, which can cause damage to DNA and other cell components. As a result of DNA damage, repair mechanisms are activated, which themselves require a large amount of energy. As a result, the cell can literately burn itself up. Finally, there is a phenomenon in which injured cells appear to work appropriately for a period of time, sometimes days, and then abruptly die, a process known as *apoptosis*.

While these mechanisms have been studied extensively in other vascular occlusive diseases such as stroke and myocardial infarction, our understanding of their importance in the context of decompression illness is still in its infancy. It is conceivable that increased knowledge of these mechanisms may lead to new avenues for treatment of DCI.

Summary

It is generally agreed that DCI occurs as a result of bubbles, either in the blood or in the tissues. Secondary effects of bubbles include lose of plasma, endothelial deposition of leukocytes, platelets, ischemia-reperfusion injury, excitatory neurotransmitter release and apoptosis. A better understanding of these processes may lead to methods of treatment of DCI that could improve the outcome now achieved by recompression with oxygen.

References

1. Hallenbeck JM, Bove AA, Elliott DH. Mechanisms underlying spinal cord damage in decompression sickness. Neurology. 1975;25:308-16.

2. Francis TJ, Pezeshkpour GH, Dutka AJ, Hallenbeck JM, Flynn ET. Is there a role for the autochthonous bubble in the pathogenesis of spinal cord decompression sickness? J Neuropathol Exp Neurol. 1988;47:475-87.

3. Fraser WD, Landolt JP, Money KE. Semicircular canal fractures in squirrel monkeys resulting from rapid decompression. Interpretation and significance. Acta Otolaryngol. 1983;95(1-2):95-100.

4. Mitchell SJ, Doolette DJ. Selective vulnerability of the inner ear to decompression sickness in divers with right-to-left shunt: the role of tissue gas supersaturation. J Appl Physiol. 2009 Jan;106(1):298-301.

5. Helps SC, Parsons DW, Reilly PL, Gorman DF. The effect of gas emboli on rabbit cerebral blood flow. Stroke. 1990;21:94-9.

6. Dunford RG, Vann RD, Gerth WA, Pieper CF, Huggins K, Wachholz C, et al. The incidence of venous gas emboli in recreational diving. Undersea Hyperb Med. 2002 Winter;29(4):247-59.

7. Levin LL, Stewart GJ, Lynch PR, Bove AA. Blood and blood vessel wall changes induced by decompression sickness in dogs. J Appl Physiol. 1981;50:944-9.

8. Nossum V, Koteng S, Brubakk AO. Endothelial damage by bubbles in the pulmonary artery of the pig. Undersea Hyperb Med. 1999;26(1):1-8.

9. Butler BD, Hills BA. Transpulmonary passage of venous air emboli. J Appl Physiol. 1985;59:543-7.

10. Vik A, Brubakk AO, Hennessy TR, Jenssen BM, Ekker M, Slordahl SA. Venous air embolism in swine: transport of gas bubbles through the pulmonary circulation. J Appl Physiol. 1990;69(1):237-44.

11. Moon RE, Camporesi EM, Kisslo JA. Patent foramen ovale and decompression sickness in divers. Lancet. 1989;1:513-4.

12. Wilmshurst PT, Byrne JC, Webb-Peploe MM. Relation between interatrial shunts and decompression sickness in divers. Lancet. 1989 Dec 2;2(8675):1302-6.

13. Germonpré P, Dendale P, Unger P, Balestra C. Patent foramen ovale and decompression sickness in sports divers. J Appl Physiol. 1998;84:1622-6.

14. Wilmshurst P, Bryson P. Relationship between the clinical features of neurological decompression illness and its causes. Clin Sci (Lond). 2000 Jul;99(1):65-75.

15. Brunner F, Frick P, Bühlmann A. Post-decompression shock due to extravasation of plasma. Lancet. 1964;1:1071-3.

16. Boussuges A, Blanc P, Molenat F, Bergmann E, Sainty JM. Haemoconcentration in neurological decompression illness. Int J Sports Med. 1996;17:351-5.

17. Martin KJ, Nichols G. Observations on platelet changes in man after simulated diving. Aerosp Med. 1972 Aug;43(8):827-30.

18. Philp RB, Ackles KN, Inwood MJ, Livingstone SD, Achimastos A, Binns-Smith M, et al. Changes in the hemostatic system and in blood and urine chemistry of human subjects following decompression from a hyperbaric environment. Aerosp Med. 1972;43:498-505.

19. Philp RB, Freeman D, Francey I, Ackles KN. Changes in platelet function and other blood parameters following a shallow open-sea saturation dive. Aerosp Med. 1974 Jan;45(1):72-6.

20. Jacey MJ, Gonzales A, Tappan DV. Hematologic changes after two exposures to 6.7 ATA air at three-day intervals. J Appl Physiol. 1977 Jun; 42(6):838-44.

Discussion

DICK VANN: Richard, suppose I just had a cerebral incident of decompression sickness and I discover I have a fairly large PFO? Should I have that repaired?

RICHARD MOON. Yeah. First, when you talk about describing cause and effect in medicine, we have - you look for the smoking gun and hopefully you see the bullet going through whatever it was shooting at. In this case, all we really have is the smoke. We have a relationship between the presence of a PFO and people with certain types of neurological decompression illness. We do not have the cause-and-effect relationship. And it's not impossible. In fact, this represents simply an association. For example, if anybody in this room has red hair, you know very well that you're at increased risk of sunburn. But dying your hair black will not affect that risk. So I think it's very much an open question. And certainly placement of an occluder to repair a PFO is not without its risks and some of which can be severe. So at the present time I would say not to do it.

RISK FACTORS FOR DECOMPRESSION SICKNESS

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Introduction

Traditionally, decompression schedules have been based only on the depth/time/breathing gas profile of a dive. There is a rich folklore about other factors that contribute to risk of decompression sickness (DCS), both real and imaginary, but recent experimental evidence indicates some risk factors may be almost as important as depth and time. If a decompression algorithm does not account for such risk factors, and most do not, it may produce acceptable decompression schedules under some diving conditions but inadequate decompression under diving conditions were important risk factors are elevated.

To illustrate this point consider the DCS risk of dives conducted under three diving conditions. As discussed in Assessing the Risk of Decompression Sickness in these proceedings (1), depth/time/breathing gas profiles and DCS outcome were analyzed for three different dive conditions: Navy decompression trials, recreational wreck dives in Scapa Flow, Scotland, and recreational dives in the Caribbean. Figure 5 in (1) shows the model-estimated risk of DCS for different no-stop bottom times for the three dive conditions. For a 60 fsw air dive, a 60-minute no-stop bottom time was estimated to have 1.6% risk of DCS for the Navy decompression trials, a 0.7% risk in Scapa Flow wreck dives and 0.05% in the Caribbean dives. No attempt was made to identify specific risk factors in that analysis, but there are obvious differences in the diving conditions. The Navy dive trials were conducted predominantly in cold water with subjects wearing wetsuits, the wreck dives were conducted predominantly in drysuits, and the Caribbean dives were in warm water. The Navy dive trials were generally conducted with divers working on the bottom and resting during decompression and were probably more strenuous than

Table 1. Some DCS risk factors.

Strong evidence
Temperature
Exercise
Acclimatization
Weaker evidence
Sex
Age
BMI
Dehydration

the recreational dives. Exercise and temperature are listed in Table 1 among the factor that influence the risk of DCS for which there is strong scientific evidence. Evidence for a potential risk factor was considered strong if, on balance, reports are consistent, show a strong association with DCS, and control for confounding variables (in particular the dive profile). This section examines factors for which there is strong scientific evidence of an alteration in the risk of DCS following diving in humans.

DCS and venous gas emboli (VGE) as decompression outcome measures

When conducting experiments on the risk of DCS, the primary goal is to measure how manipulation of some experimental condition influences the incidence of DCS. However, it is not always practical to use DCS itself as an endpoint and many studies instead measure venous gas emboli (VGE). VGE are bubbles in the venous circulation and can be detected by measuring reflected ultrasound and the extent of VGE graded on an ordinal scale. VGE occur after most dives whereas DCS is rare. VGE grades are used as an endpoint for decompression studies under the assumptions that VGE: (a) may directly cause some forms of DCS, and (b) are formed by the same stresses that form the bubbles that do cause DCS. DCS rarely occurs if there are no VGE following diving, but the detection of VGE does not indicate that DCS will occur for an individual dive. However, if VGE are measured following large numbers of dives an association between VGE grade and the incidence of DCS emerges. Figure 1 shows the incidence of DCS versus ultrasonic Doppler detected VGE grades from six studies (2-5). Following dives with no detectable VGE (Grade 0), the incidence of DCS is near zero, and following dives with the maximum detectable VGE (Grade 4), the incidence of DCS was around 15%. This association is not strong enough to use VGE grades to predict DCS incidence, but VGE scores are used to as an indicator of decompression stress to compare dives conducted under different experimental conditions when DCS is not expected or cannot be identified.

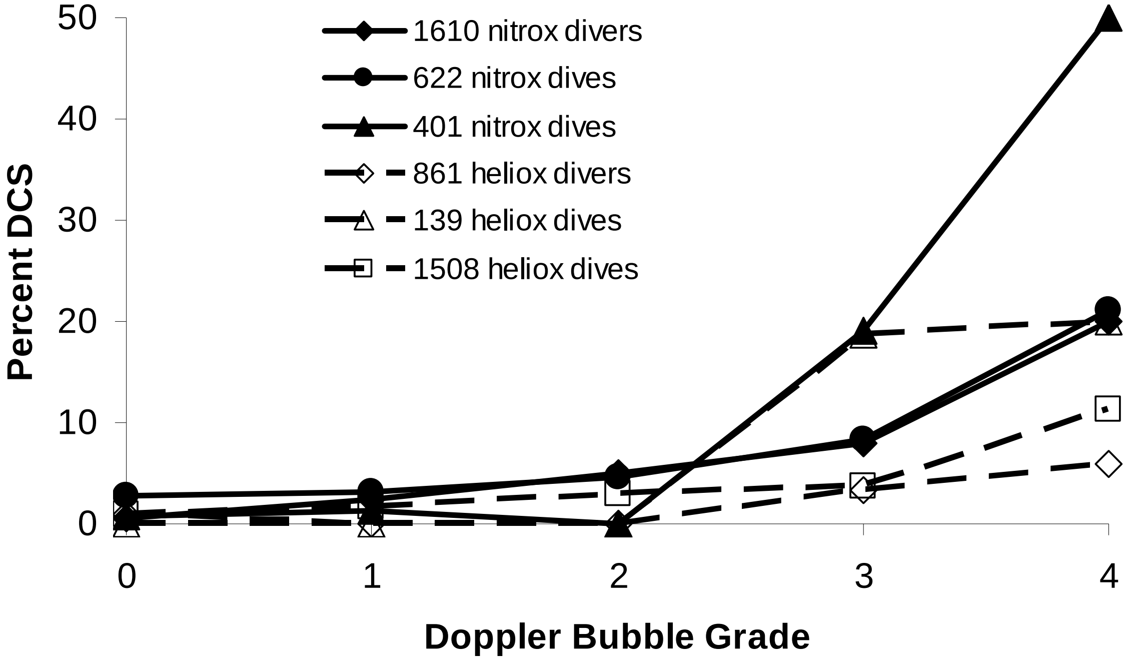

Figure 1. Relationship between DCS incidence and VGE scores (2-5).

Temperature

It is firmly entrenched in diving lore that that prolonged exposure to cold water puts a diver at increased risk of DCS. For instance, U.S. Navy Diving Manuals provided the advice that, "If the diver was exceptionally cold during the dive…the next longer decompression schedule than the one he would normally follow should be selected (6)." In 1993, Revision 3 of the U.S. Navy Diving Manual (6) also included speculation that increased DCS risk results primarily from cold during decompression. A 2004 critical literature review concluded there was weak evidence that divers may be at greater risk of DCS if warm on the bottom and cold during decompression and on the surface (7). This review summarized studies of altitude DCS, most from the World War II era, the majority of which found a greater incidence of DCS during cold exposure at altitude than during warm exposure at altitude. During development of the (recently replaced) U.S. Navy air with surface decompression on oxygen (air SURDO2) tables, a significantly greater incidence of DCS was observed in divers wearing standard dress in 73°F (23°C) water than in 45°F (7°C) water (8). In air SURDO2 operations in the U.K. North Sea oil sector, a higher incidence of DCS was observed for divers using hot water suits than for divers using dry suits (9). Similarly, during the U.S. Navy Air SURDO2 salvage operation on the TWA flight 800 crash site, a higher incidence of DCS was observed in divers using hot water suits than in divers using wetsuits (10). This diving evidence does not come from experiments designed to test temperature effects but from observations of diving operations with many confounding variables including no control of dive profiles.

Some background physiology

A physiologically plausible mechanism by which temperature could alter DCS risk is by altering peripheral blood flow and thereby altering tissue gas uptake and washout. This in turn would alter the magnitude and duration of supersaturation, bubble formation and growth, and therefore DCS risk for an otherwise identical dive profile. Temperature has been shown to alter whole body nitrogen washout (11). Figure 2 shows the cumulative washout of nitrogen from seated subjects either dry or immersed to the neck in water at various temperatures. Immersion itself increases nitrogen washout but warmer water results in greater nitrogen washout.

In an experiment to test temperature effects on VGE (12), 10 divers conducted four open-water, 38-minute, working bottom times at 78 fsw in 10°C (50°F) water followed by a no-stop ascent to the surface. On two occasions divers wore drysuits and insulation (warm) and on two occasions divers wore 1/8" neoprene wetsuits (cold), cold divers had a substantial drop in skin and core temperatures compared to the warm divers. Cold and warm dive conditions were crossed with passive (insulated sleeping bag) or active (hot water bath) rewarming on the surface following the dive. At the first measurement after surfacing, warm divers had higher VGE scores than cold divers. VGE scores declined more quickly in actively rewarmed divers than in passively re-warmed divers. A plausible explanation of these results is that cold diving conditions reduced inert gas uptake into tissues and active rewarming on the surface accelerated inert gas washout, both resulting in less supersaturation and therefore VGE formation.

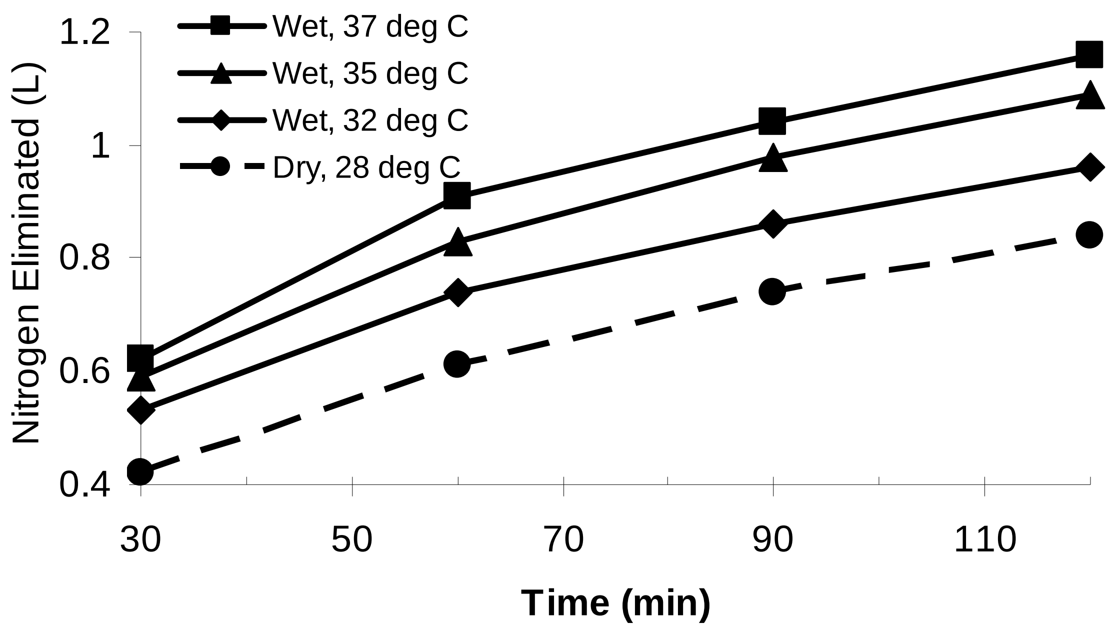

Figure 2. Nitrogen washout dry and immersed at different temperatures, drawn from data in Balldin and Lungren (11).

The results of these experiments suggest a possible explanation for the apparent opposite effects of temperature on DCS incidence between altitude and diving evidence. In the altitude studies, temperature was manipulated only at altitude (i.e. while subjects are decompressing) whereas in the Air SURDO2 operations divers were either warm or cold in the water (i.e., on the bottom and early in decompression) but the majority of decompression occurs in a chamber where conditions similar irrespective of water temperature or diver dress. If DCS risk is influenced by a temperature effect on inert gas uptake and washout, it would be expected that DCS risk would be increased by being warm on the bottom and cold during decompression.

<u>DCS incidence and temperature on the bottom and during decompression</u>

The importance of diver thermal status during different phases of the dive on the incidence of DCS was conclusively established in a recent series of experimental air decompression dives (13). Divers wore full-face masks, swimsuits, T-shirts, gloves and booties and were fully immersed in water that was controlled independently for the bottom time and decompression at either 97 °F (36.1°C, warm) or 80°F (26.7°F, cold). All dives were to 120 fsw and had 91 minutes total in-water decompression, according to the (recently replaced) U.S. Navy 1957 Standard Air table 120 fsw/ 70 min schedule, but the bottom times were varied. Divers worked on the bottom and rested during decompression. Some of the results are shown in Table 2

It can be seen in Table 2 that keeping divers cold during the bottom time and warm during decompression sharply reduced the DCS risk compared to dives conducted warm during the bottom time and cold during decompression or cold throughout the dive. Logistic regression modeling returned similar odds ratios for DCS for a 50°F (10°C) increase in water temperature during bottom time or a doubling of bottom time, and larger odds ratio for a 50°F (10°C) decrease in water temperature during decompression. In other words, being cold during decompression caused a larger increase in DCS risk than being warm during the bottom time or doubling the bottom time.

Table 2. Effect of temperature on DCS incidence for 120 fsw dives of varying bottom time (BT) with 91 minutes total decompression time (13).

Thermal Conditions	Depth/BT		Outcome	
BT/Deco	fsw/:Minutes	#DCS/ #dives	%DCS	(95% CI)
Cold/Warm	120/:30	0/80	0.0	(0.0, 4.5)
	120/:50	0/8	0.0	(0.0, 36.9)
	120/:70	2/158	1.3	(0.2, 4.5)
Warm/Cold	120/:30	7/32	21.8	(9.3, 40.0)
	120/:25	4/80	5.0	(1.4, 12.3)
Cold/Cold	120/:60	4/18	22.2	(6.4, 47.6)

That water temperature has a less potent effect on DCS risk during bottom time than during decompression is supported by the absence of a temperature effect on DCS incidence in experimental heliox no-stop dives (14). This series of heliox dives compared water temperatures of 45 °F to 55°F (7 - 12 °C) to 70°F (21 °C), and the complete absence of temperature effect may be due to exercise thermogenesis keeping the wetsuited heliox divers (14) warmer than divers wearing swimsuit and T-shirt (13). Additionally, manipulating diver thermal status during the bottom time of experimental air SURDO2 dives did not result in a significant difference in DCS incidence. However, since only one mild skin DCS occurred, the dives may have not been sufficiently stressful to manifest a difference in DCS incidence (Gerth, personal communication).

<u>Post-dive temperature</u>

Whereas there is now strong evidence of a thermal effect during the dive on DCS risk, the evidence concerning thermal exposure following diving remains weak. It is physiologically plausible that cold exposure post-dive could delay gas washout from peripheral tissues and prolong supersaturation, bubbles and risk of DCS. The VGE study described earlier found a slower decline in VGE after diving in divers passively re-warmed than actively rewarmed (12). A retrospective comparison of DCS incidents with meteorological records noted an association of incidents with cold air temperatures (15). Following a 30-fsw subsaturation dry chamber dive, VGE were detected in only one of four divers during 3 hours post-dive monitoring at 104°F (40°C) air temperature (16). Following an identical dive profile with 50°F (10°C) post-dive air temperature, VGE were detected in three of the same divers and all four developed pruritis and mild pain that did not require recompression (16). Perhaps coincidentally, the divers reported pruritis and pain following a hot shower, but this is consistent with unpublished anecdotes of hot showers precipitating skin bends following diving.

Exercise

Like temperature, strenuous exercise has long been considered a risk factor for DCS. Again turning to the same passage quoted above from U.S. Navy Diving Manual, "…if his (the diver's) workload was relatively strenuous, the next longer decompression schedule than the one he would normally follow should be selected (6)."

<u>Exercise during the dive</u>

Exercise causes increased cardiac output and redistribution of blood flow, primarily an increase blood flow to the exercising muscles (17). It is physiologically plausible that exercise during bottom time could increase gas uptake leading to increased decompression requirement or increased supersaturation, bubble formation and growth, and DCS risk for the same decompression. Conversely, exercise during decompression could increase gas washout and reduce decompression requirements or reduce DCS risk.

Exercise during bottom time has been shown to increase decompression requirements. Figure 3 shows some results of a study of closed-circuit scuba decompression in which an increased decompression requirement was associated with increasing level of swimming exercise from light to heavy (1, 2, and 3 L/min oxygen consumption) on the bottom (18). Figure 4 shows the results of air dives followed by surface decompression on air where less DCS occurred when divers rested on the bottom compared to identical dive profiles in which divers did weight-lifting exercises on the bottom (19).

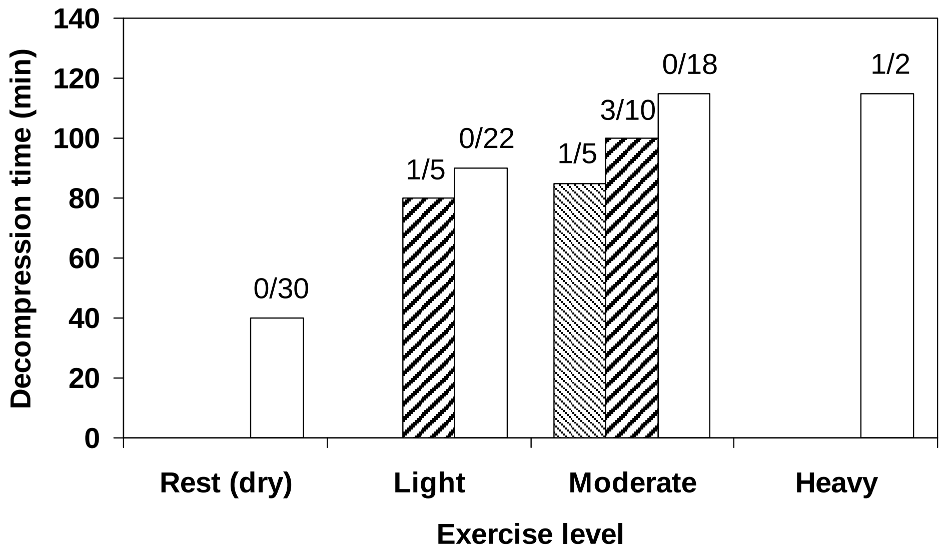

Figure 3. Effect of exercise during bottom time on decompression requirement for 100 fsw for 60-minute dives breathing constant 0.7 atm oxygen partial pressure in nitrogen. Numbers above bars are #DCS/#dives. Redrawn from data in (18).

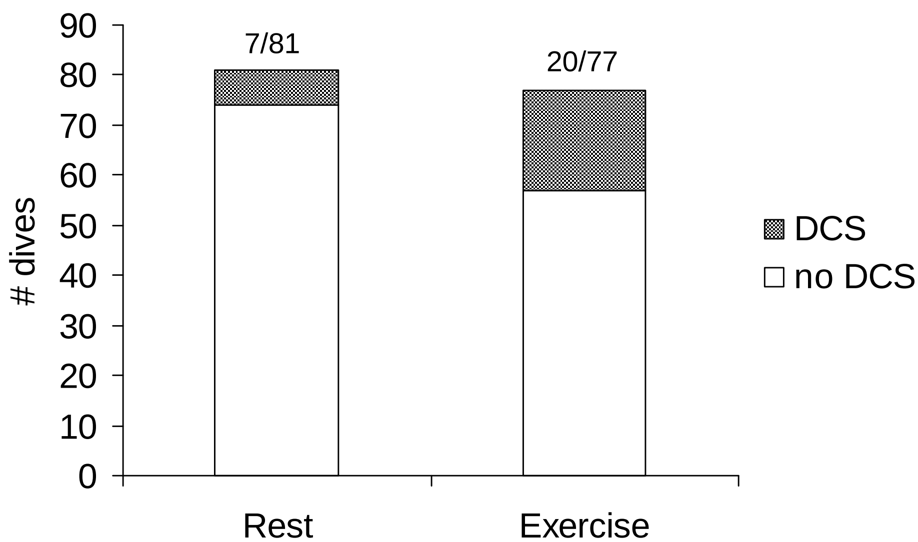

Figure 4. Effect of exercise during bottom time on DCS incidence. Combined results for air dives (fsw/min BT: 100/85, 130/55, 150/38 and 170/38) with surface decompression on air. Numbers above bars are #DCS/#dives. Drawn from data in (19).

Less evidence exists for the effect of exercise during decompression. In a separate arm of the closed-circuit decompression study mentioned above, divers performed light exercise throughout the dive or rested during decompression. A representative result is the 100 fsw for 60-minute bottom-time dives where an 80-minute resting decompression resulted in 1 DCS out of 5 divers but 60 minutes of exercising decompression resulted in no DCS in 26 dives (18). In a study using VGE as the primary end point, light arm or leg exercise during decompression resulted in lower VGE scores than resting decompression although there was no significant difference in DCS with 1 DCS/28 dives in the resting group and 2/16 in the exercising group (20). These results are consistent with light exercise during decompression potentially reducing DCS risk by accelerating inert gas elimination. This mechanism is well supported by studies of altitude DCS where exercise accelerates whole-body nitrogen elimination during oxygen pre-breathe before altitude exposure (21) and has been used to reduce the pre-breathe time (22, 23).

Post-dive exercise

On the basis of the preceding evidence and by analogy with temperature effects, it might be expected that post-dive exercise would reduce the risk of DCS. On the contrary, however, it has been demonstrated that post-dive exercise increases the risk of DCS. Following long, no-stop dry chamber air dives (100 fsw for up to 60-minute bottom time and 150 fsw for up to 36- minute bottom time), there was a higher incidence of DCS in divers performing weight-lifting exercises for 2 hours than those who rested (24). This must be an effect separate from increased blood flow and enhanced gas washout. Perhaps weight-bearing exercise stimulates bubble formation as has been inferred from the detection of more VGE during altitude exposures immediately following deep knee-bend exercise than following a one- or two-hour delay (25). Exercise following decompression to altitude is well established to increase the risk of DCS (see (26) for references dating back to the World War II era). For instance, exercise at 10% of maximum oxygen uptake caused DCS in 40% of exposures to subjects' previously determined symptom-free altitude (26).

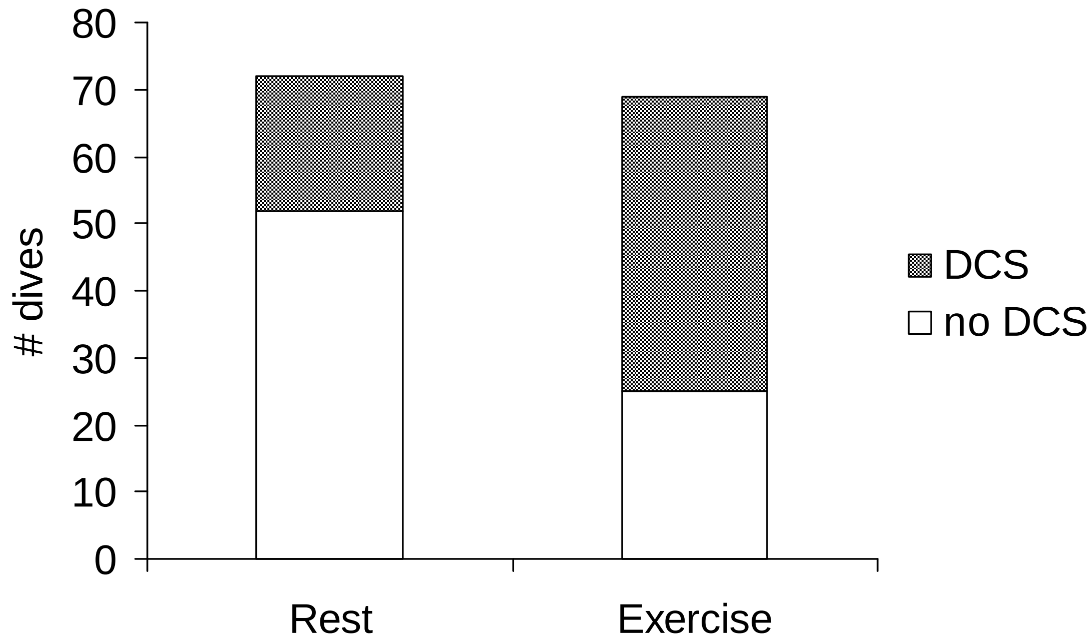

Figure 5. Effect of weight-lifting exercise following decompression from long, no-stop air dives to 100 and 150 fsw. Numbers above bars are #DCS/#dives. Drawn from data in (24).

<u>Pre-Dive Aerobic Exercise</u>

Several studies have indicated that endurance trained animals are less susceptible to severe DCS (27-29). In humans, lower VGE scores were found in those divers with higher levels of aerobic fitness (30). This association with aerobic fitness has been called in to question by the findings of the most recent of the animal studies (29) which found that a single bout of high intensity aerobic exercise about 20 hours before diving provided the same protection against DCS as two or six weeks of training. Thus, any apparent training effect may be due to the most recent single bout of exercise. A 230 fsw for 45-minute, dry, no-stop air dive followed by anesthesia (to facilitate VGE detection) resulted in high VGE grades and killed 80 to 100% of 310 g rats within 60 minutes (29,31). A single, 90-minute bout of treadmill running (2- and 8-minute intervals at 50-60% and 85-90% maximal oxygen uptake, respectively) conducted 20 hours, but not 48, 10, 5, or 0.5 hours, before diving allowed rats to survive 60 minutes post-dive with few VGE (29,31). In the lethal dives, rats likely died from cardiopulmonary DCS ("chokes") due to massive embolization of the lungs, the only manifestations of DCS unequivocally attributable to VGE. The relevance to much milder decompression stress typical of human dives is unclear. Two human studies have shown that a single, 40- to 45-minute bout of high intensity running 20-24 hours before a dry chamber dive resulted in lower VGE grades than if the dive was not preceded by exercise (32-33). A recent report, similar in all respects to the earlier of the preceding studies, conversely found that, compared to no exercise, exercise at either 2 hours or 24 hours before diving resulted in the similar maximum VGE grades and longer times before VGE disappeared from the circulation (34). Also, there was no difference in the incidence of DCS between no exercise and 30 minutes of intense exercise on each of 3 days preceding altitude exposure (35).

Exercise Immediately before Diving

Unlike exercise the day before diving, exercise immediately before diving may increase the risk of DCS. Anecdotal reports have linked DCS incidents with preceding exercise within 24 hrs of diving (2,36). Indeed, the concern was sufficient at DCIEM, that although subjects in dive trials were not restricted from exercise, they were not to introduce new forms of exercise on the morning of experimental dives (Nishi, personal communication). In rat VGE experiments similar to those described above, a bout of intense exercise 30 minutes prior to diving reversed the protective effect of exercise 24 hours previously (37). An exercise effect may be short lived since in the altitude study mentioned earlier, deep knee bend exercise enhanced VGE detection if performed immediately prior to altitude exposure, but the effect declined with a half-time of about one hour (25).

Acclimatization to Decompression

Acclimatization (or “work-up”) refers to the situation where a diver is at reduced risk of DCS as a result of dives conducted during the preceding days. The phenomenon was clearly demonstrated in an analysis of 40,000 decompressions of caisson workers showing the incidence of DCS drops from approximately 12% to 1% over the first 10 to 15 decompressions (5 days per week). Acclimatization was lost during 2 to 10 days break from compressed air work (38). In development of heliox decompression schedules, two to four work-up dives in the days immediately preceding test dives resulted in a lower incidence of DCS, and acclimatization was lost over four to 11 days without diving (14, 39). In a study designed with VGE as an end point, 14 divers conducted the same dry chamber air decompression dive schedule once a day for 12 consecutive days, and although there was no change in VGE, it was noted that pruritis diminished over consecutive days and, interestingly, a 15th subject was excluded from the trial because of spinal DCS on the first day (40). Similarly, in open water occupational air dives, no difference was observed in self-reported health scores over consecutive days of diving, but the only incidents of DCS occurred in divers returning to diving after a break (41). Rats exposed to daily 30-minute dry chamber air work-up dives for one or two weeks prior had a lower incidence of serious and lethal DCS following a 175 fsw/60 no-stop dive compared to rats that are not worked up (42).

The mechanism of acclimatization is unknown. It is unlikely that work-up dives result in changes in blood flow and inert gas uptake and washout. More plausible is a reduction in bubble formation or a change in response to bubbles. VGE have been investigated and as noted above, in one study, no change was found in VGE scores over 12 days of diving. Similarly, no change in VGE scores was noted during 6 days of repetitive no-stop diving (43). However, in open water recreation diving, VGE scored diminished with successive days diving (44).

Summary

There are a number of well-established factors that will increase the risk of DCS. For safer decompression, try to avoid being cold during and following decompression and heavy exercise at any time immediately before, during, or soon after diving. In addition DCS risk will be greatest on the first day of diving and after a break of about a week. Conversely, decompression safety might be increased by keeping cool on the bottom and using active warming during decompression, limiting exertion on the bottom, for instance, by using a scooter instead of swimming, and exercising gently during decompression. However, don't expect the substantial differences seen in the experimental trials were extreme levels of risk factors were used. Additionally, common sense dictates that these factors not be applied in such a fashion as to increase other diving risk such as hypothermia, hyperthermia, dehydration or oxygen toxicity.

References

1. Vann R, Denoble P, Doolette D. Assessing the risk of decompression sickness. In: Vann R, Mitchell S, Anthony G, Denoble P, eds. Technical Diving Conference; January 18-19, 2008; Durham, NC: Divers Alert Network; 2009: 158-177.

2. Vann RD. MK XV UBA decompression trials at Duke: A summary report. Final report on Office of Naval Research Contract N00014-77-C-0406; 1982.

3. Nishi RY. Doppler and ultrasonic bubble detection. In: Bennett PB, Elliott DH, eds. The physiology and medicine of diving. 4 ed. London: Saunders 1993:433-53.

4. Shannon J. The relationship of inert gas and venous gas emboli to decompression sickness. M.S. Thesis, Mechanical Engineering and Materials Sciences Dept.: Duke University; 2003.

5. Shannon J, Vann R, Peiper C, Thalmann E, Gerth W. Relationship between inert gas type, venous gas emboli (VGE), and decompression sickness (DCS). Undersea and Hyperbaric Med. 2004;31:336-7.

6. United States Naval Sea Systems Command. U.S. Navy Diving Manual (Air Diving). NAVSEA 0994-LP-001-9110, Revision 1 ed. Washington DC: Naval Sea Systems Command; 1993.

7. Toner CB, Ball R. The effect of temperature on decompression and decompression sickness risk: a critical review. Technical Report. Silver Spring (MD): Naval Medical Research Center; 2004. Report No.: 2004-003.

8. Van der Aue OE, Kellar RJ, Brinton ES, Barron G, Gilliam HD, Jones RJ. Calculation and testing of decompression tables for air dives employing the procedure of surface decompression and the use of oxygen. Research Report. Washington DC: Navy Experimental Diving Unit; 1951. Report No.: 13-51. 56 p.

9. Shields TG, Lee WB. (Centre for Offshore Health, Robert Gordon's Institute of Technology). The incidence of decompression sickness arising from commercial offshore air-diving operations in the UK sector of the North Sea during 1982/83. Offshore Technology Report. Sheffield (UK): Health and Safety Executive; 1997. Report No.: OTO 97 812. Contract No.: TA 93/22/147 and OT/F/1008. Sponsored by UK Department of Energy.

10. Leffler CT, White JC. Recompression treatments during the recovery of TWA Flight 800. Undersea Hyperb Med 1997;24:301-8.

11. Balldin UI, Lundgren CE. Effects of immersion with the head above water on tissue nitrogen elimination in man. Aerosp Med 1972;43:1101-8.

12. Dunford R, Hayward J. Venous gas bubble production following cold stress during a no-decompression dive. Undersea Biomed Res 1981;8:41-9.

13. Gerth WA, Ruterbusch VL, Long ET. The influence of thermal exposure on diver susceptibility to decompression sickness. Technical Report. Panama City (FL): Navy Experimental Diving Unit; 2007. Report No.: 06-07.

14. Thalmann ED. Development of a decompression algorithm for constant 0.7 ATA oxygen partial pressure in helium diving. Technical Report. Panama City (FL): Navy Experimental Diving Unt; 1985. Report No.: 1-85. 182 p.

15. Broome JR. Climatic and environmental factors in the aetiology of DCI in divers [abstract]. Undersea Biomed Res 2008;19 Suppl:15.

16. Mekjavic IB, Kakitsuba N. Effect of peripheral temperature on the formation of venous gas bubbles. Undersea Biomed Res 1989;16:391-401.

17. Astrand P-O, Rodahl K, Dahl HA, Strømme SB. Textbook of work physiology. 4 ed. Champaign (IL, USA): Human kinetics; 2003.

18. Vann RD, Gerth WA, Leatherman NE. Exercise and decompression sickness. In: Vann RD, editor. The physiological basis of decompression. Proceedings of the 38th Undersea and Hyperbaric Medical Society Workshop; Durham (NC). Bethesda (MD): Undersea and Hyperbaric Medical Society; 1989. p. 119-37.

19. Van der Aue OE, Brinton ES, Kellar RJ. Surface decompression: derivation and testing of decompression tables with safety limits for certain depths and exposures. Technical Report. Washington DC: Navy Experimental Diving Unit; 1945. Report No.: 5-45.

20. Jankowski LW, Nishi RY, Eaton DJ, Griffin AP. Exercise during decompression reduces the amount of venous gas emboli. Undersea Hyperb Med 1997;24:59-65.

21. Gerth WA, Vann RD, Leatherman NE. Whole-body nitrogen elimination during oxygen prebreathing and altitude decompression sickness risk. In: Vann RD, editor. The physiological basis of decompression. Proceedings of the 38th Undersea and Hyperbaric Medical Society Workshop; Durham (NC). Bethesda (MD): Undersea and Hyperbaric Medical Society; 1989. p. 147-51.

22. Vann RD, Gerth WA, Leatherman NE. Influence of O2 prebreathe duration and exercise on the risk of decompression sickness at 4.3 psia. Procedures of the 60th Annual Scientific Meeting of the Aerospace Medical Association. 1989; 13:71.

23. Webb JT, Pilmanis AA, Balldin UI. Altitude decompression sickness at 7620 m following prebreathe enhanced with exercise periods. Aviat Space Environ Med 2004;75:859-64.

24. Van der Aue OE, Kellar RJ, Brinton ES. The effect of exercise during decompression from increased barometric pressures on the incidence of decompression sickness in man. Technical Report. Washington DC: Navy Experimental Diving Unit; 1949. Report No.: 8-49. 44 p.

25. Dervay JP, Powell MR, Butler BD, Fife CE. The effect of exercise and rest duration on the generation of venous gas bubbles at altitude. Aviat Space Environ Med 2001; 73:22-7.

26. Pilmanis AA, Olson RM, Fischer MD, Wiegman JF, Webb JT. Exercise-induced altitude decompression sickness. Aviat Space Environ Med 1999;70:22-9.

27. Rattner BA, Gruenau SP, Altland PD. Cross-adaptive effects of cold, hypoxia, or physical training on decompression sickness in mice. J Appl Physiol 1979;47:412-7.

28. Broome JR, Dutka AJ, McNamee GA. Exercise conditioning reduces the risk of neurologic decompression illness in swine. Undersea Hyperb Med 1995;22:73-85.

29. Wisløff U, Brubakk AO. Aerobic endurance training reduce bubble formation and increase survival in rats exposed to hyperbaric pressure. J Physiol (Lond) 2001;537:607-11.

30. Carturan D, Boussuges A, Vanuxem P, Bar-Hen A, Burnet H, Gardette B. Ascent rate, age, maximal oxygen uptake, adiposity, and circulating venous bubbles after diving. J Appl Physiol 2002;93:1349-56.

31. Wisløff U, Richardson RS, Brubakk AO. Exercise and nitric oxide prevent bubble formation: a novel approach to the prevention of decompression sickness? J Physiol 2004;555:825-9.

32. Dujic Z, Duplancic D, Marinovic-Terzic I, Bakovic D, Ivancev V, Valic Z et al. Aerobic exercise before diving reduces venous gas bubble formation in humans. J Physiol 2004;555:637-42.

33. Blatteau JE, Gempp E, Galland FM, Pontier JM, Sainty JM, Robinet C. Aerobic exercise 2 hours before a dive to 30 msw decreases bubble formation after decompression. Aviat Space Environ Med 2005;76:666-9.

34. Gennser M, Blogg SL, Jurd KM, Thacker JC, Loveman GM, Stansfield M et al. The effect of exercise at 24 and 2 hours prior to diving on the evolution of venous gas emboli [abstract]. Undersea Hyperb Med 2008;35 4:242-3.

35. Kumar KV, Waligora JM, Gilbert JH, III. The influence of prior exercise at anaerobic threshold on decompression sickness. Aviat Space Environ Med 1992;63:899-904.

36. Nishi RY, Eatock BC, Buckingham IP, Ridgewell BA. Assessment of decompression profiles by ultrasonic monitoring, phase III: no-decompression dives. Downsview (ON, CAN): Defence and Civil Institute of Environmental Medicine; 1982. Report No.: 82-R-38. 26 p.

37. Loset A, Jr., Mollerlokken A, Berge V, Wisloff U, Brubakk AO. Post-dive bubble formation in rats: effects of exercise 24 h ahead repeated 30 min before the dive. Aviat Space Environ Med 2006;77:905-8.

38. Walder DN. Adaptation to decompression sickness in caisson work. In: Tromp SW, Weihe WH, editors. Biometeorology. Proceedings of the Third International Biometeorological Congress; 1963 Sep 1-7; Pau, France. Oxford: Pergamon Press; 1967. p. 350-9.

39. Elliott DH. Some factors in the evaluation of oxy-helium decompression schedules. Aerosp Med 1969;40:129-32.

40. Eckenhoff RG, Hughes JS. Acclimatization to decompression stress. In: Bachrach AJ, Matzen MM, editors. Underwater Physiology VIII. Proceedings of the 8th Symposium on Underwater Physiology. Bethesda (MD): Undersea Medical Society; 1984. p. 93-100.

41. Doolette DJ. Health outcome following multi-day occupational air diving. Undersea Hyperb Med 2003;30:127-34.

42. Montcalm-Smith EA, Auker CJ, Lillo RS, Porter WR, Brown DJ, McCarron RM. Acclimation to decompression [abstract]. Undersea Hyperb Med 2004;31 3:337.

43. Hamilton RW, Rogers RE, Powell MR, Vann RD. Development and validation of no-stop decompression procedures for recreational diving: the DSAT recreational dive planner. Santa Ana (CA, USA): Diving Science and Technology Inc. and Hamilton Research Ltd.; 1994. 118 p.

44. Dunford RG, Vann RD, Gerth WA, Pieper CF, Huggins K, Wachholz CJ et al. The incidence of venous gas emboli in recreational diving. Undersea Hyperb Med 2002;29:247-59.

Discussion

SIMON MITCHELL: The data you presented on acclimatization is very interesting, especially because every diver who learns to dive on a standard recreational course gets taught that multiday diving is a significant risk factor for decompression sickness. So how do you accommodate those two vastly different viewpoints?

DAVID DOOLETTE: Well, the second one is wrong.

SIMON MITCHELL: I happen to agree with you.

DAVID DOOLETTE: I think you can multiday dive as long as you're sensible and acclimatize rather than increase your risk, but there is probably evidence that repetitive diving is a risk factor if it's not done correctly.

RICHARD MOON: I have a question concerning acclimatization to DCS, David. One explanation is that DCS susceptibility decreases with repeated exposures. Another explanation is culling or selection, that is, people who have had DCS decide to do something else, and you're left with a different population. Any comments on the data that you presented in that context?

DAVID DOOLETTE: I don't know how carefully the study looked at that as far as the numbers. I know because they had different lines they looked at groups they knew they could follow for short and longer periods of time. Dick suggested they looked at it fairly carefully.

DICK VANN: This was the Medical Research Council study of compressed air workers in the Tyne Tunnel Project (1). A man who was bent one day was treated and back to work the next day unless severity prevented full recovery. The authors followed the same groups of men for as long as they worked continuously including 120 men for 10 compressions, 90 men for 50 compressions, 80 for 100, and 20 for 300.

PETER BENNETT: In the DAN courses we did all over the world, we found there would be two or three cases of DCS at the end of the week. It was a very nice practicum for the students, but I figured we had to stop it. So on Wednesday, we did a night dive and took the next day off. We never had any cases after that.

DAVID DOOLETTE: That's similar to what occurred at the SPUMS meetings. DCS tended to be later in the week. The attendees suggested alcohol and lack of sleep were the causes. Perhaps it was the difference between a series of 10 repetitive dives over 10 days as opposed to a single day. As you suggested, a night dive with a break the next day breaks the repetitive cycle.

KARL HUGGINS: What are your recommendations about hot-tubbing after diving especially after the long, cold exposures?

DAVID DOOLETTE: It will almost certainly help gas washout, and it's been proposed as a first-aid measure if you've got nothing else available to you, but there are anecdotes that hot showers after diving have precipitated skin bends and that sort of thing. You certainly wouldn't want it too hot (see (2)). {Mekjavic, 1989 #905}). I'm hedging around the question. I don't have a recommendation.

DICK VANN: Perhaps another important factor is timing. If you get into a hot tub right after the dive before many bubbles have formed, it might be helpful based on the Balldin and Dunford studies (3, 4). If you wait several hours as they did in the Mekjavic study (2), however, they had an increase in VGE and DCS, perhaps because there was time for bubbles to grow. But the data are slim.

PAUL GERNHARDT: Is there much research being done on increased helium tissue tensions after gas switches?

DAVID DOOLETTE: I did a lot of animal work looking at switches in nitrogen and helium and the gas tensions in the brain and heart muscle. In those tissues, helium and nitrogen seem to wash out at about the same rates. I don't think there's much research being done as far as specifically measuring increased tissue tension during diving. There are a couple organs that have unusual anatomy, the inner ear and the skin where it appears there may be increased tension (5). I don't think there's any ongoing research at the moment, and there's very little laboratory decompression studies looking at gas switches.

STEVE MORTELL: Dr. Moon, is there any information with respect to decompression sickness and smoking?

RICHARD MOON: We looked at decompression injuries in DAN recreational dive database (6). Divers who are heavy smokers seem to have more severe bends than others. Does that mean that smoking makes you more susceptible to severe bends or does it protect you from mild bends? It's an unanswerable question, but there does seem to be a difference in the distribution of severity among smokers and nonsmokers.

JEFF BOZANIC: There are a number of dive computer models that can be modified to make decompression profiles more or less conservative. Your studies apply to very specific dive profiles. Do you think that some of the civilian dive computer models are risk factors themselves? How would you evaluate these models, software and algorithms?

DAVID DOOLETTE: I'm not quite sure how to answer that question.

Discussion References

1. Paton WDM, Walder DN. Compressed air illness. An investigation during the construction of the Tyne tunnel 1948-50. London: Medical Research Council; 1954. Report No.: Special Report No. 281.

2. Mekjavic IB, Kakitsuba N. Effect of peripheral temperature on the formation of venous gas bubbles. Undersea Biomed Res. 1989 Sep;16(5):391-401.

3. Balldin UI, Lundgren CEG. Effects of immersion with the head above water on tissue nitrogen elimination in man. Aerosp Med. 1972;43(10):1101-8.

4. Dunford R, Vann R, Gerth W, Pieper C, Huggins K, Wachholz C, et al. The incidence of venous gas emboli in recreational divers. Undersea Hyperbaric Med. 2003;29(4):247-59.

5. Doolette DJ, Mitchell SJ. Biophysical basis for inner ear decompression sickness. J Appl Physiol. 2003 Jun;94(6):2145-50.

6. Buch D, Dovenbarger J, Uguccioni D, El-Moalem H, Moon R. Effect of cigarette smoking on the severity of Decompression Illness (DCI) symptoms. Undersea and Hyperbaric Medicine 2000;27(Suppl):29.

DEEP STOPS AND THEIR EFFICACY IN DECOMPRESSION

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Introduction

Ascent to surface from a dive may require interruption with one or more decompression stops to avoid or mitigate the occurrence of decompression sickness (DCS) (1). During each decompression stop, a period of time is spent at a constant depth to allow "safe" washout of inert gas from body tissues before resumption of the ascent. A "deep stop" is a decompression stop at a depth deeper than that of the first stop prescribed for the ascent by a decompression algorithm. This definition of a deep stop is inherently relative because the distinction of a deep stop from any other depends on the algorithm used to compute the decompression schedule. For ascent from a given dive, a deep stop in a schedule prescribed by one algorithm may be a normal stop in another schedule computed with a different algorithm.

In what follows we will distinguish between two classes of what are colloquially called deep stops. Deep stops of the first class are those that are inserted into a schedule to ostensibly make the ascent safer, shorter, or both, compared to the schedule originally prescribed by a given algorithm. We will identify two types of deep stop within this class. Deep stops of the second class are one or more initial stops that are deeper in a schedule prescribed by one algorithm than the first stop in a schedule prescribed for the same ascent by a different algorithm.

The differences between the different deep stop classes and types, and their potential benefits, can be illustrated in relatively general, model-independent terms that only require the context of the well-accepted modern paradigm for the etiology of DCS and a few practically universally accepted assumptions to give quantitative meaning to the terms.

Assumptions

The modern paradigm for the etiology of DCS is schematized in Fig. 1. A central feature of this paradigm is that DCS arises from adverse effects of *in vivo* bubble formation and growth, for which gas-supersaturation is a thermodynamically necessary condition. It follows that dissolved gas, whether in subsaturation, saturation or supersaturation amounts, is tolerated without adverse effects.

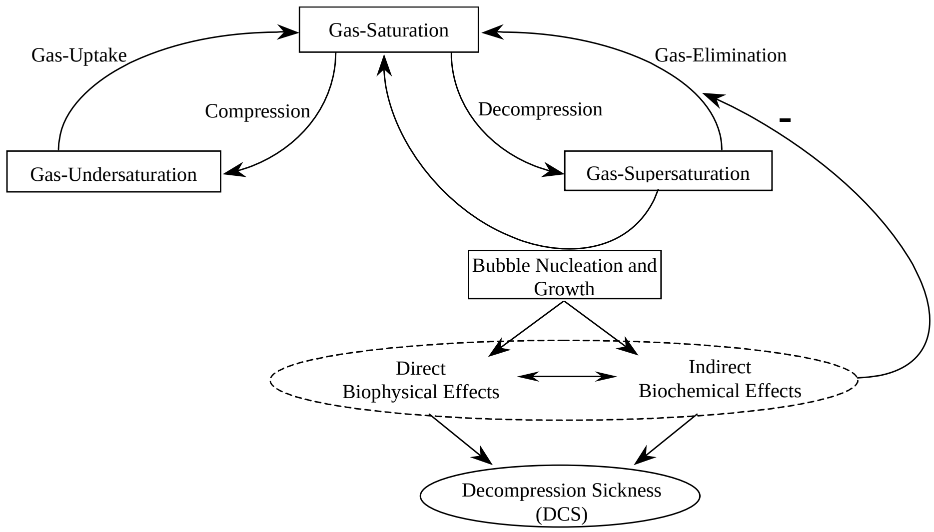

Figure 1. Modern paradigm for the etiology of DCS. Modified from (1).

Safe decompressions are consequently scheduled by either limiting the gas-supersaturations attained or the profusions and volumes of gas bubbles formed during ascent. Safe ascent criteria are formulated to quantify these limits for specific decompression schedule calculations, which are almost universally undertaken with the following additional assumptions:

- Seek shortest total decompression time possible for a given ascent while remaining within the safe ascent criteria.
- The body is considered to consist of a collection of gas exchange compartments with different characteristic rates of gas uptake or elimination for a given change in inspired gas pressure or composition. (The exact form of the gas exchange function is not important for the following discussion. The only requirement is that it be monotonic for a given blood-tissue gas tension gradient.)
- The rates of gas uptake or elimination in the compartments are assumed to span a finite range from “fast” to “slow.”
- Safe ascent criteria of the same type are applicable to each of the individual compartments under consideration.

For purposes of illustration in this presentation, compartments are assumed to be parallel perfused and each well-stirred with perfusion-limited gas exchange between compartmental tissue and blood (Fig. 2). Under these assumptions, the rate of gas uptake or elimination from each compartment is proportional to the dissolved gas tension gradient between tissue and arterial blood. The proportionality constant is a function of compartmental volume, perfusion rate, and gas solubility.

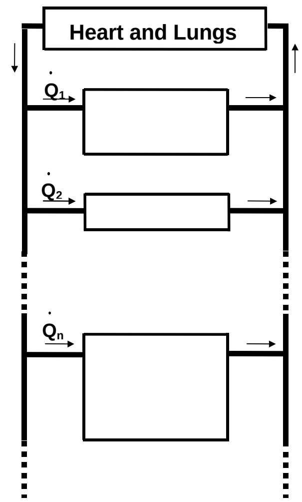

Figure 2. Schematic of n parallel perfused compartment model of whole body. Association of compartments with specific anatomical sites is usually disclaimed except to assert that the modeled compartments represent tissues or tissue components that are involved in the occurrence of DCS.

Additionally, the safe ascent criterion will be defined at zero gas-supersaturation. A decompression will be considered safe provided that the total tissue gas tension remains less than or equal to the prevailing ambient hydrostatic pressure. A decompression of greatest safe extent will consequently be one effected within this constraint and that ends with the total tissue gas tension *equal* to the prevailing ambient hydrostatic pressure.

Essential Concepts

<u>Thermodynamic and Atmospheric Saturation Depths</u>

Times spent at different depths during a dive impact subsequent decompression obligations differently in different compartments depending on the prevailing compartmental dissolved gas contents and inspired gas composition and pressure. In a given compartment, the prevailing total dissolved gas content, including oxygen, carbon dioxide, and water vapor, corresponds to an atmospheric saturation depth that is the pressure equivalent depth of the prevailing inspired gas that would produce the same total dissolved gas tension at equilibrium. The compartmental dissolved gas contents remain constant only when the compartmental atmospheric saturation depth equals the prevailing inspired gas pressure. At depths deeper than the prevailing compartmental atmospheric saturation depth the compartmental dissolved gas contents increase with a net influx of gas from the arterial inflow. At depths shallower than the compartmental atmospheric saturation depth the compartmental dissolved gas contents decrease with a net efflux of gas into the venous outflow. By virtue of the metabolic conversion of O_2 to the much more soluble CO_2 in the tissue, the depth corresponding to the total compartmental dissolved gas tension (i.e., the compartmental thermodynamic saturation depth) under steady-state conditions is always less than the compartmental atmospheric saturation depth. The relationship between the dissolved gas content and the atmospheric saturation depth of a compartment at equilibrium with inspired air at 170 fsw is shown in Fig. 3.

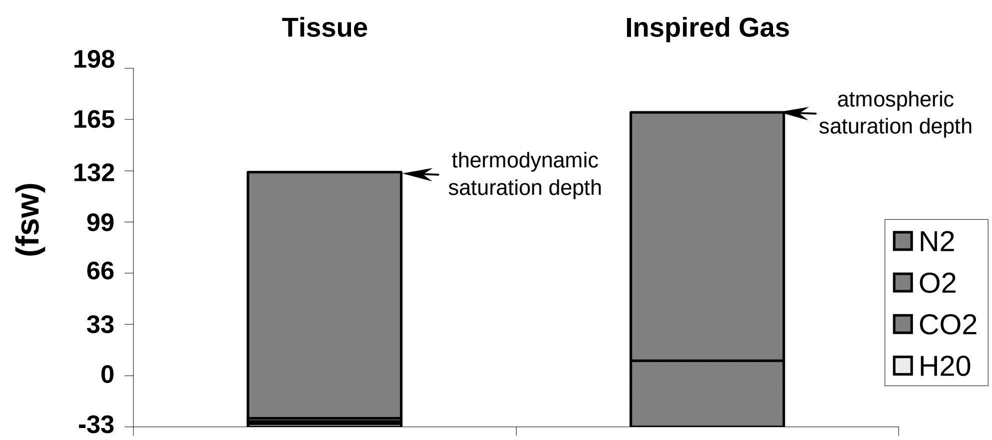

Figure 3. Thermodynamic and atmospheric saturation depths in a tissue compartment at equilibrium with inspired air at 170 fsw.

When starting decompression from a depth equal to the atmospheric saturation depth of a compartment, the difference between the compartmental thermodynamic saturation depth and the prevailing ambient hydrostatic pressure provides an "oxygen window" (1) within which ascent can be affected without producing gas-supersaturation. This window is overtaken to gas-supersaturate the compartment if the rate and extent of decompression exceeds the attendant rates of inert gas elimination and compartmental O_2 metabolism.

<u>Instantaneous and Safe Ascent Depths</u>

The concepts of instantaneous ascent depth (IAD) and safe ascent depth (SAD) are closely associated with the safe ascent criteria. The IAD at any point in time during a dive is the shallowest depth to which ascent can be effected at an infinite rate without violating the safe ascent criteria, whatever those criteria may be. In general, each compartment has its own IAD at any instant, and the IAD for the whole body is the deepest of the compartmental IADs. The compartment in which this deepest IAD prevails is called the "controlling tissue." With the safe ascent criterion adopted here, a given compartmental IAD is the compartmental thermodynamic saturation depth.

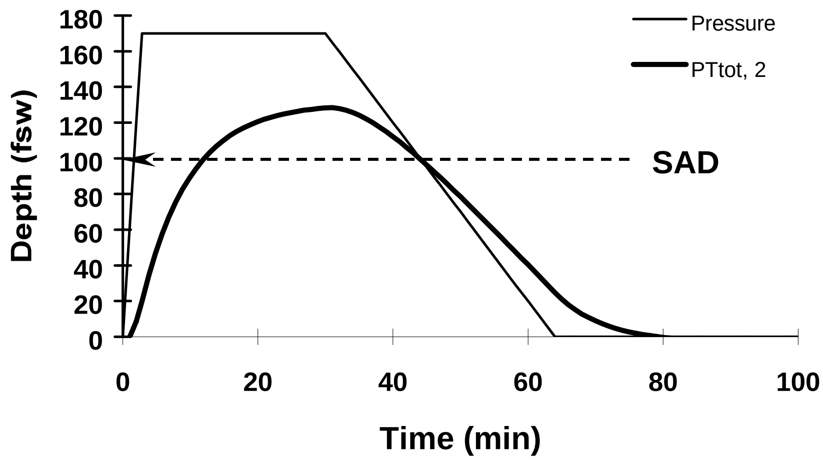

Figure 4. Variation of instantaneous ascent depth (IAD) in a 5-min half-time compartment during a 170 fsw/30 min air dive with a 5 fsw/min ascent rate. The IAD equals the ambient pressure at the safe ascent depth (SAD).

During the course of a continuing ascent, the decreasing depth and IAD converge and become equal at the SAD (Fig. 4). The depth of convergence and SAD depend on how the compartmental dissolved gas content changes during the ascent, and hence on the times spent deeper and shallower than the compartmental atmospheric saturation depth. The SAD at any point in time during a dive is consequently a projection of the IAD and depth that depends on the ascent rate.

The compartmental SAD increases (gets deeper) with decreasing rate of ascent between the prevailing depth and compartmental atmospheric saturation depth. The example in Fig. 5 shows the variation of IAD and SAD in a compartment initially deeper than its atmospheric saturation depth at start of ascents from a 170 fsw/30 min air dive at two different rates. During decompression, the compartment initially continues to accumulate gas until the corresponding atmospheric saturation depth equals the prevailing depth. In this depth range, the shallowest SAD occurs with an infinitely fast or instantaneous ascent. For the shortest decompression, we consequently want to leave bottom with ascent to the deepest compartmental atmospheric saturation depth as rapidly as possible, subject of course to ascent rate limits required to avoid barotrauma and recruitment of a faster compartment as the controlling compartment.

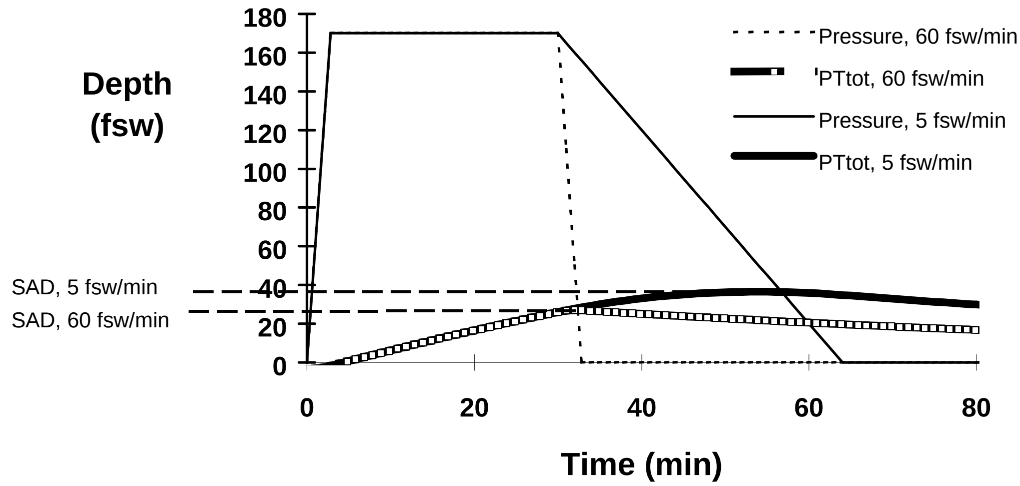

Figure 5. Variation of compartmental IAD and SAD during decompressions at two different rates from an initial depth deeper than the compartmental atmospheric saturation depth. The shallowest SAD occurs with instantaneous ascent. The SAD deepens with slower ascent and increases required decompression time. (170 fsw/30 min air; T½ = 80 min, IAD @ zero gas-supersaturation).

Continued ascent occurs with the controlling compartment at depths shallower than its atmospheric saturation depth, where it eliminates gas to the atmosphere. The compartmental SAD consequently decreases (gets more shallow) with decreasing ascent rate in this depth range. These conditions are illustrated in Fig. 6, where the variation of IAD and SAD during ascents from a 170 fsw/30 min air dive at two different rates are shown as before, but for a faster compartment in which the atmospheric saturation depth has reached the prevailing depth before the leave-bottom time.

The SAD eventually reaches surface as the rate is slowed, and with further slowing, becomes negative in correspondence to pressures at altitude. The remaining ascent to surface can consequently be safely completed at any rate equal to or slower than that for which the SAD is at surface. However, the *shortest* remaining ascent to surface is obtained with fast-as-possible ascents[1] to intermediate decompression stops at regular depth intervals and with times at those stops computed to assure that the safe ascent criteria are not violated with ascent to any next stop.

[1] Subject to limits required to avoid barotrauma and recruitment of a faster compartment as the controlling compartment.

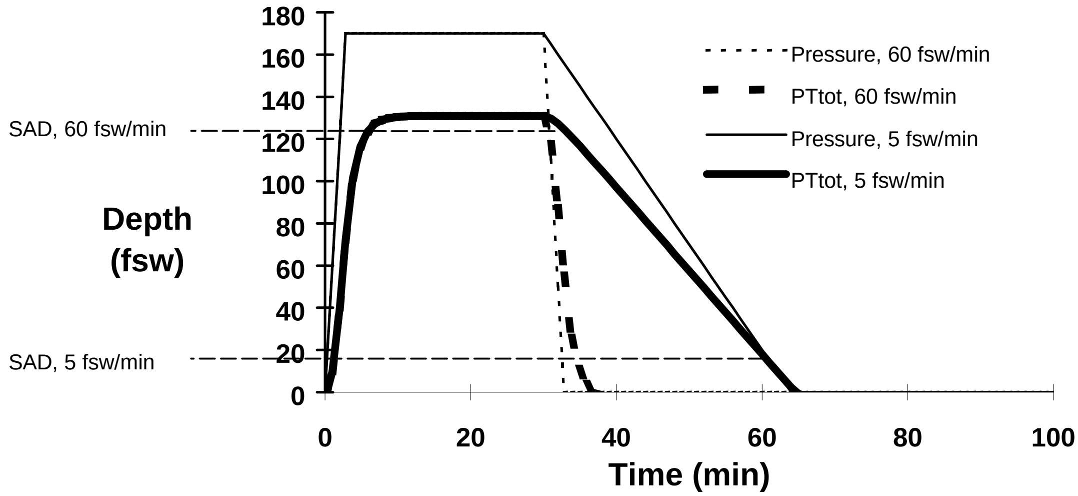

Figure 6. Variation of compartmental IAD and SAD during decompressions at two different rates from an initial depth shallower than the compartmental atmospheric saturation depth. The deepest SAD occurs with instantaneous ascent. The SAD gets shallower with slower ascent. (170 fsw/30 min air; T½ = 5 min, IAD @ zero gas-supersaturation.)

Class I, Type 1 Deep Stop

We can now consider our first class of "deep stop;" one or more stops added deeper than the initial algorithmically prescribed SAD for a given ascent rate but shallower than the atmospheric saturation depth of the controlling compartment at start of the ascent.

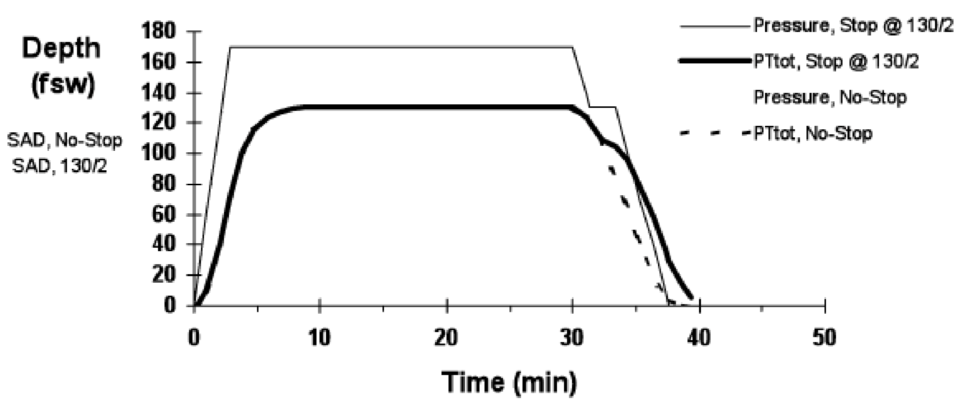

Figure 7. Variation of IAD and SAD in a "fast" compartment (T½ = 5 min) during decompressions without and with an inserted 2-min stop at 130 fsw. The inserted stop decreases the SAD in this compartment and makes subsequent ascent to the initial SAD (and 1st algorithmically prescribed stop) more conservative.

Such stops increase gas washout from the controlling compartment – and all faster compartments – before arrival at the original SAD and make the original SAD more conservative (Fig. 7). The same effect can also be obtained with appropriate reduction of the ascent rate to the original SAD. Such stops or slowed ascent may consequently compensate for algorithmic insufficiencies that make the original SAD in fact unsafe. However, any benefit of the added stops or slowed ascent is limited to the controlling compartment on arrival at the original SAD and any faster compartments. The added stops or slowed ascent increase time at depths deeper than the atmospheric saturation depths of compartments slower than the controlling compartment, where such compartments continue to on-gas (Fig. 8). As a result, subsequent decompression must be lengthened.

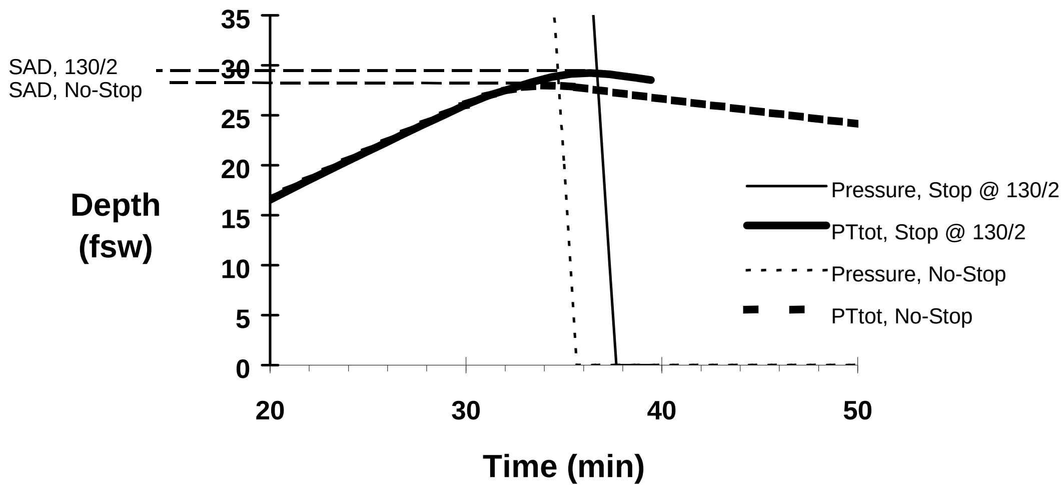

Figure 8. Variation of IAD and SAD in a "slow" compartment (T½ = 80 min) during a portion of the decompressions illustrated in Fig. 7. The inserted 2-min stop at 130 fsw increases the SAD in this compartment and hence increases the required decompression time for subsequent ascent.

Excessive depth of the added stop, time at the added stop or slowing of the ascent can even cause one of these slower compartments to become the controlling tissue and deepen the SAD. In no case will insertion of this type of deep stop or slowing of ascent allow shortening of the subsequent decompression under the original safe ascent criteria – unless a switch to a breathing gas with increased oxygen partial pressure (PO_2) is made at the stop. The overall effects of inserted deep stops in a hypothetical air-only decompression from a 170 fsw/30 min air dive are shown in Fig. 9.

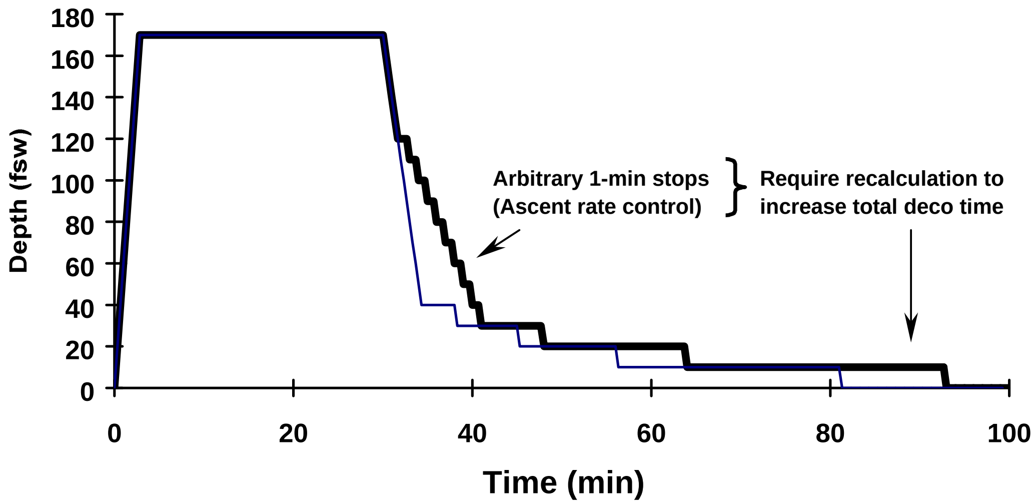

Figure 9. Overall effect of inserted Class I, Type 1 deep stops in a hypothetical decompression.

Class I, Type 2 Deep Stop

This brings us to a second type of deep stop within this class; a deep stop added to a schedule to switch to a breathing gas with increased PO_2. Such a stop will usually have favorable effect, allowing shortening of the subsequent decompression or reduction of the overall DCS risk. This is NOT because of the "deepness" of the stop, but because the increased gradient for inert gas elimination caused by the gas switch hastens gas elimination after the switch - and hence the rate at which the SAD approaches surface - in *all* compartments.

The ultimate "deep stop" of this kind entails O_2 pre-breathing at depth, the efficacy of which was man-tested at the Navy Experimental Diving Unit (NEDU) in application to decompressions from nitrox saturation (2). The decompression schedules in two profiles from this work are illustrated in Fig. 10. The total decompression times in the two schedules are nearly equal if the O_2 breathing period before decompression in the pre-breathe profile is considered to be an O_2-breathing deep stop. Although the difference between the observed DCS incidences on these two profiles is significant only at P = 0.16 (Fisher exact, two-tail), the trend for a lower incidence on the pre-breathe schedule illustrates the efficacy of the Class I, Type 2 deep stop in this context.

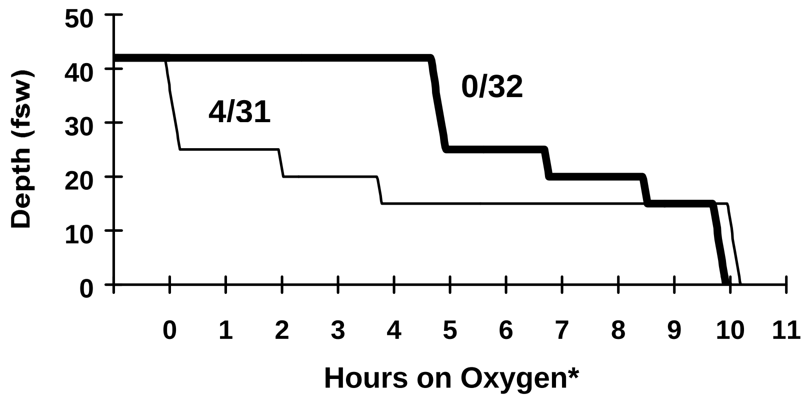

Figure 10. O_2-accelerated decompression from nitrox saturation. Each decompression was preceded by 72 hr on 0.3 atm PO_2-in-N_2 at the 42 fsw dive depth (50 fsw equivalent air depth). The fraction associated with each curve is the observed DCS incidence (DCS cases/# trials) in man-trials of the respective schedules. (*Hours on oxygen include a 15-min air-breathing break after each hour of O_2 breathing.)

Avoidance of pulmonary and CNS O_2 toxicity usually precludes 100% O_2 breathing at depth. More practical applications of the method entail switches to decompression gas mixes with high O_2 fractions at inserted deep stops, as illustrated in Fig. 11.

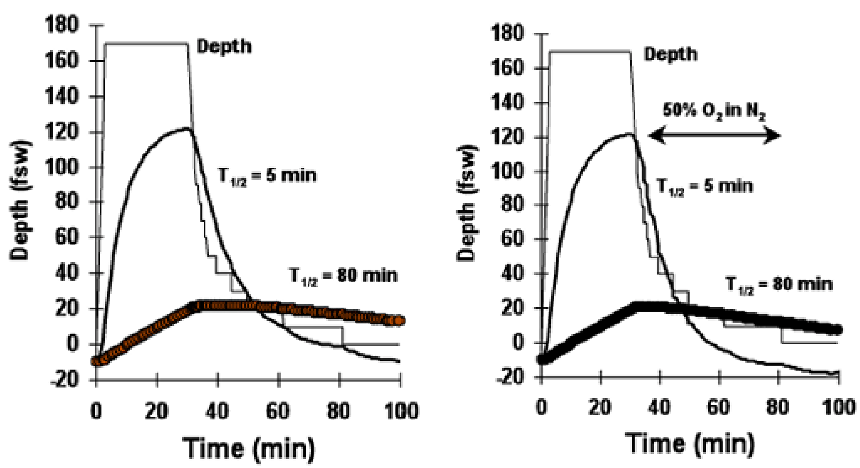

Figure 11. Depth and compartmental total dissolved gas tension profiles for a 170 fsw/30 min air dive with 1-min inserted deep stops at 10 fsw intervals starting at 90 fsw (left panel), and for the same dive with a breathing gas switch to higher FO_2 at the first of the inserted stops (right panel). The gas switch causes more rapid gas elimination in *all* compartments.

Class II Deep Stop

Our third type of deep stop is of a different class in which first stops in ascents computed for a given ascent with one algorithm occur at depths deeper than first stops in ascents computed with a different algorithm. Arguably, the most interesting stops of this class occur in schedules computed with algorithms designed to limit the volumes and profusions of gas bubbles in the body. Such schedules tend to exhibit a skew of total decompression time for a given ascent to stops at longer and deeper depths than stops in schedules computed with algorithms designed to limit compartmental dissolved gas contents. The deeper stops prevent or delay bubble formation during the decompression to provide two potential benefits.

The first is avoidance of the adverse effects of bubble formation on gas elimination kinetics. In the absence of bubbles, or formation of only relatively few bubbles in a large compartmental volume, modeled blood-tissue gas exchange follows the familiar semi-exponential function of time evident in the solid line curve of Fig. 12.

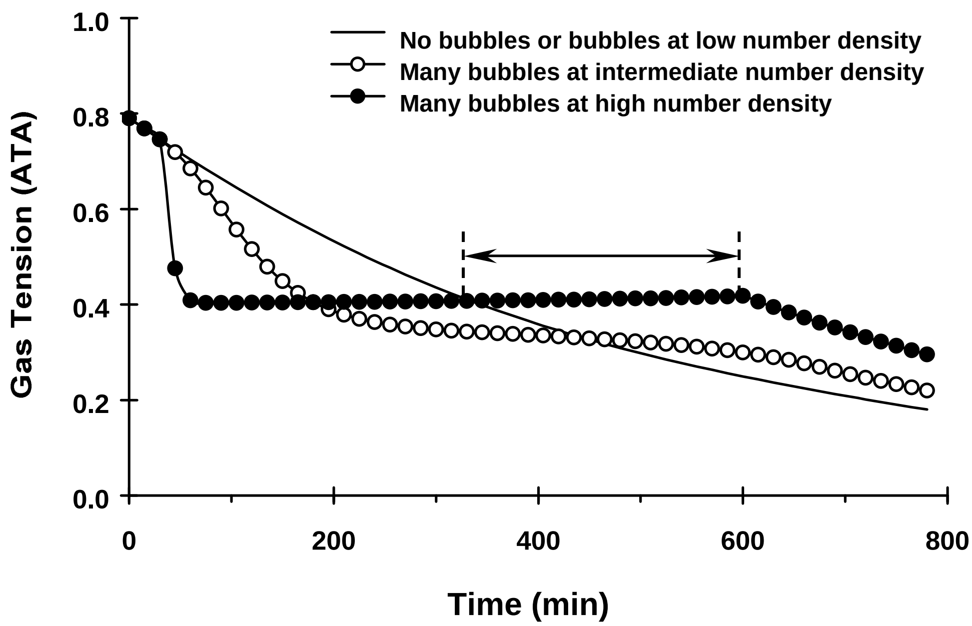

Figure 12. Impact of bubble formation and bubble-tissue mass balance on compartmental gas tension and gas elimination kinetics. (Adapted from (3).)

The formation and growth of bubbles in increasing numbers, however, consumes increasing amounts of the compartmental dissolved gas, which reduces the compartmental dissolved gas tension and relieves the compartmental gas-supersaturation. In the limit as this relief is complete (curve with filled circles in Fig. 12), the total compartmental gas tension is clamped to the total pressure of gases in the bubble, which for practical purposes is a function of ambient hydrostatic pressure only. In an isobaric stage, the tissue tension consequently remains constant and gas elimination from the tissue follows slower time-linear kinetics until the bubbles are completely resolved. Once the bubbles have dissolved, the rate of gas elimination resumes as a semi-exponential function of time along a curve practically parallel to that prevailing for no bubble formation, but displaced in time by the indicated delay. This slowing of gas elimination from the tissue with increasing bubble number density is a central feature of the Exponential-Linear (EL) model described by Thalmann (4).

The second potential benefit of delaying or minimizing bubble formation during decompression arises from the attendant delay or minimization of DCS risk accumulation directly attributable to the bubbles per se. For example, schedule A1 in the top panel of Fig. 13 is the schedule prescribed by the VVal-18 Thalmann Algorithm (5) for a 170 fsw/30 min air dive. Except for use of exponential-linear kinetics, the Thalmann Algorithm is a traditional deterministic gas content model in which decompressions are prescribed to limit compartmental dissolved gas contents in accord with a table of depth-dependent M-values or “maximum permissible tissue tensions.” The accompanying compartmental bubble volume profiles are as estimated for the schedule with the BVM(3) probabilistic model of DCS incidence and time of occurrence (6,7) in which DCS risk is modeled as a time integral function of compartmental bubble volumes. BVM(3) has only three gas exchange compartments with respective half-times of 1.0, 21.4, and 317.3 min.

Schedule A2 in the bottom panel of Fig. 13 is the schedule for decompression from the same 170 fsw/ 30-min dive that incurs minimum-attainable DCS risk under the BVM(3) model with the 174 min total stop time in schedule A1. Schedule A2 was obtained with an iterative “internal search” algorithm based on the algorithm described by Weathersby, et al. (8). The deep skew of decompression stop time in the A2 schedule compared to the A1 schedule affords a reduced extent of bubble formation and growth that, under the BVM(3) model, reduces the estimated DCS risk from 6.2% to 3.7%.

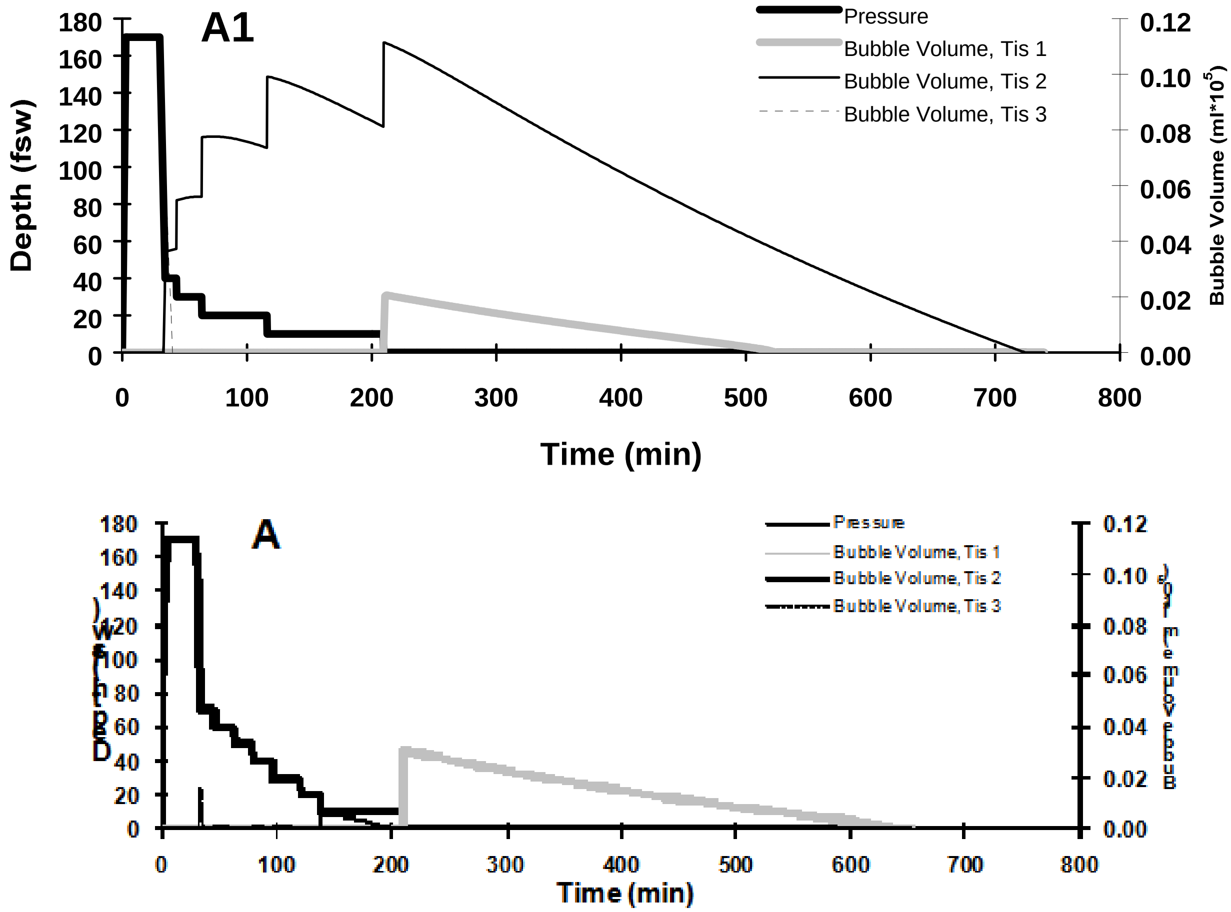

Figure 13. Hypothetical bubble-dependent DCS risk in two 170 fsw (52 msw)/ 30-min air dives identical except for the depth/time distributions of a 174-min total decompression stop time. Under the BVM(3) model, bubble formation in the A1 schedule causes the profile to incur an estimated DCS risk of 6.2%. Under the same model, the reduced extent of bubble formation afforded by the deep skew of decompression stop time in the A2 schedule causes the profile to incur an estimated DCS risk of 3.7%.

Compared to a schedule for a given dive computed to limit compartmental gas-supersaturations, a schedule with stops deep enough to prevent or limit compartmental bubble formation can theoretically require less total decompression time for a given DCS risk or incur decreased DCS risk for a given total decompression time.

A man-dive trial was recently conducted at the NEDU under a NEDU Institutional Review Board-approved protocol (9) to test the efficacy of deep stops in air decompression diving (10). The methodological approach entailed comparison of DCS incidence following the two air decompression dives shown in Fig. 13. The two dive profiles are overlaid for comparison in Fig. 14.

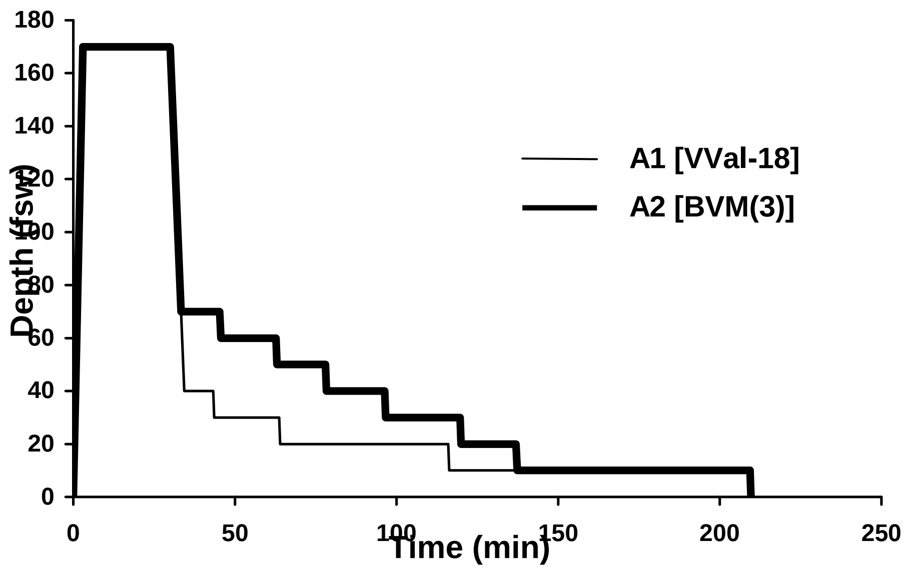

Figure 14. Overlay of the two 170 fsw/30 min air dive profiles man-tested at NEDU.

The profiles were man-dived under the following conditions:

Descent rate = 60 fsw/min (18 msw/min)
Ascent rate = 30 fsw/min (9 msw/min),

Divers wore swimsuits and T-shirts, breathed surface-supplied air via full face masks (U.S. Navy MK 20 MOD 0 underwater breathing apparatus), and were immersed in 86°F (30°C) water in the NEDU Ocean Simulation Facility (OSF) wet pot throughout each dive.

Conditions were equivalent to 60-65°C cold conditions for wet-suited divers (11), but obviated introduction of any depth-dependent influence of suit compression on diver thermal exposure and DCS susceptibility (12).
Divers performed 115 watt cycle ergometer work at 170 fsw until 1 minute before leaving bottom, then rested during subsequent decompression.
Divers were monitored for venous gas emboli (VGE) with trans-thoracic cardiac 2-D echo imaging (Siemens Medical Solutions® Acuson Cypress Portable Colorflow Ultrasound System) at 30 minutes and 2 hours postdive.

Three hundred seventy five (375) man-dives on each schedule were planned with stopping rules to prevent unnecessary or excessively hazardous exposures. The trial was terminated after midpoint interim analysis when 81 divers had completed 390 man-dives and DCS incidence in Schedule A2 (deep stops, 11 DCS/198 dives) had emerged as significantly higher than in Schedule A1 (3/192, p=0.030, one-sided Fisher Exact). Figures 15 and 16 illustrate the trial outcome.

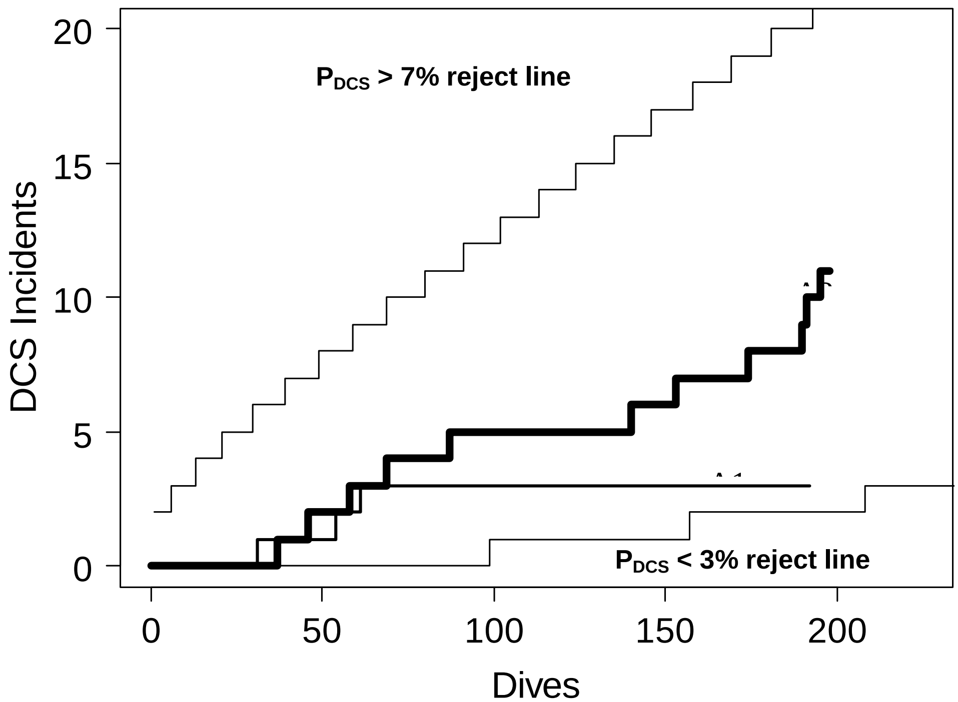

Figure 15. Cumulative DCS incidents on the A1 Traditional (light line) and A2 Deep Stops (heavy line) schedules. Outer lines show the sequential trial envelope designed to reject high with DCS risk > 7% and reject low with DCS risk < 3%, either at 95% confidence.

On review, one Schedule A2 DCS was excluded, but the result remained significant (p=0.047). Most DCS was mild, late onset (mean 9, SD 8 hours, n=11), Type I, but one case on each schedule involved progressing CNS manifestations.

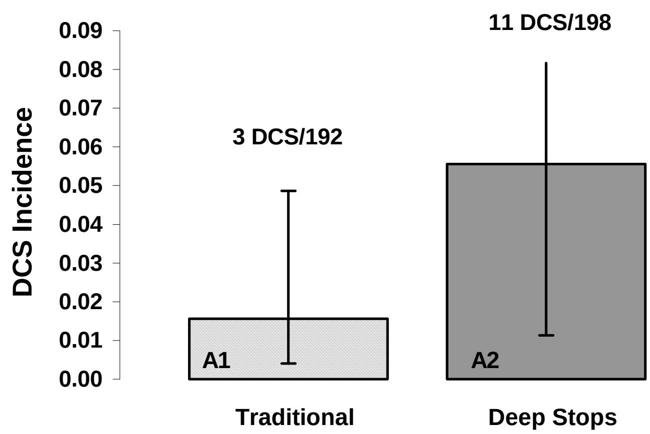

Figure 16. Observed DCS incidences (mean, 95% CI) for the two test dive profiles. (All 14 DCS cases are included.)

The association between DCS occurrence and maximum observed intravascular bubble grade is illustrated in the receiver-operator characteristic (ROC) curve (13,14) shown in Fig. 17. High VGE grades were relatively insensitive and nonspecific indicators of DCS, with area under the ROC curve (AUC) only slightly greater than the no-discrimination value of 0.5.

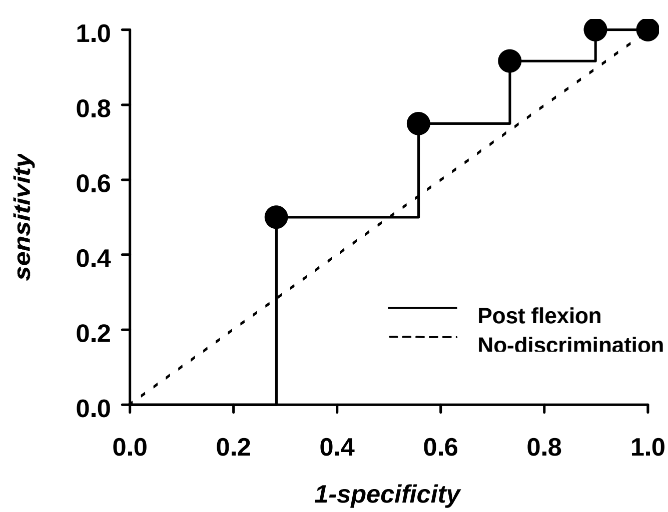

Figure 17. ROC curve for association of DCS occurrence with maximum observed VGE grades. Points graduate with increasing false positive rate (1-specificity) in order: VGE grades IV, III-IV, II-IV, I-IV, and 0-IV. AUC=0.68.

Despite the poor overall association between DCS and VGE, median VGE scores (maximum at rest and after limb flexion, Fig. 17) were significantly higher after Schedule A2 than after Schedule A1 (Wilcoxon rank sum test, W=12967, $p<0.0001$). VGE scores at the 2-hour exam were increased over those at the 30-minute exam after Schedule A2 (Wilcoxon rank sum test, W=4418, p=0.0006) but not after Schedule A1 (Wilcoxon rank sum test, W=2578, p=0.734)

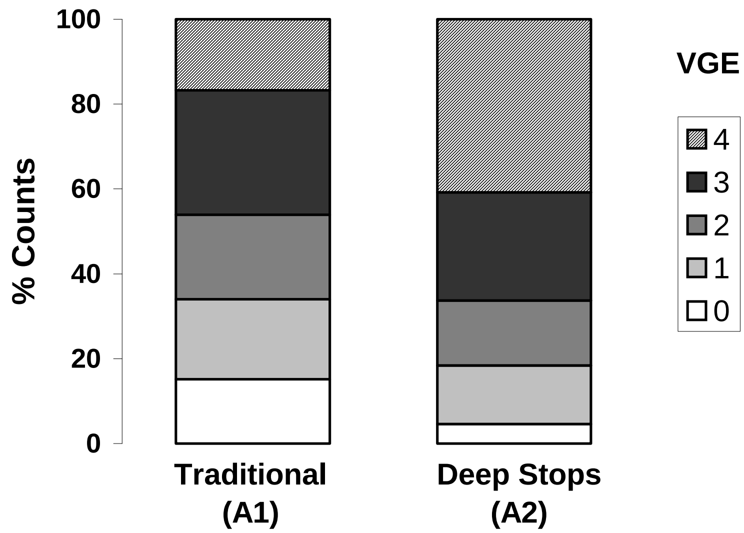

Figure 17. Maximum VGE Grade in all exams.

Conclusions

Two classes of deep stop can be identified. Deep stops of the first class are stops added deeper than the first prescribed by a given decompression algorithm. These may be beneficial under certain circumstances but serve to correct a deficient algorithm. They cannot allow shortening of the originally prescribed schedule unless switch to a breathing gas with higher PO_2 is associated with the added stop or stops. Deep stops of the second class arise in comparison of schedules for a given ascent computed with different algorithms and types of safe ascent criteria. One serious attempt to empirically confirm the theoretical benefits of a deep stop air decompression schedule computed to control bubble formation compared with a traditional schedule computed to limit compartmental dissolved gas content was unsuccessful. Both DCS and VGE were higher after the deep stops schedule than after the traditional schedule. Slower gas elimination or continued gas uptake offset benefits of reduced bubble growth at deep stops in the tested deep stop schedule.

References

Tikuisis P, Gerth WA. Decompression Theory. In: Brubakk AO and Neuman TS, eds. Bennett and Elliott's Physiology and Medicine of Diving. 5th Edition. W.B. Saunders Co., London. 2003.

Latson G, Flynn E, Gerth W, Thalmann E, Maurer J, Lowe M. Accelerated Decompression Using Oxygen for Submarine Rescue – Summary Report and Operational Guidance. NEDU TR 11-00, Navy Experimental Diving Unit, Panama City, FL., December 2000.

Srinivasan RS, Gerth WA, Powell MR. Mathematical models of diffusion-limited gas bubble dynamics in tissue. J Appl Physiol 1999;86(2): 732-741.

Thalmann ED. Computer Algorithms Used in Computing the MK 15/16 Constant 0.7 ATA Oxygen Partial Pressure Decompression Tables, NEDU TR 1-83, Navy Experimental Diving Unit, Panama City, FL, Jan 1983.

Gerth WA, Doolette DJ. VVal-18 and VVal-18M Thalmann Algorithm Air Decompression Tables and Procedures. NEDU TR 07-09, Navy Experimental Diving Unit, Panama City, FL, May 2007.

Gerth WA, Vann RD. Development of Iso-DCS Risk Air and Nitrox Decompression Tables Using Statistical Bubble Dynamics Models, Final Report, National Oceanic and Atmospheric Administration, Office of Undersea Research, Bethesda, MD, 1996.

Gerth WA, Vann RD. Probabilistic Gas and Bubble Dynamics Models of DCS Occurrence in Air and N_2O_2 Diving. Undersea Hyperb Med 1997;24(4):275–292.

Weathersby PK, Hays JR, Survanshi SS, Homer LD Hart BL, Flynn ET and Bradley ME. Statistically based decompression tables II: Equal risk air diving decompression schedules. Bethesda, MD. NMRI Technical Report 85-17, 1985.

Gerth WA, Gault KA, Ruterbusch VL, Melton JL, Doolette DJ. Empirical evaluation of the efficacy of deep stops in air decompression diving. NEDU Protocol Number 05-23/32174, Navy Experimental Diving Unit, Panama City, FL, November 2005.

Gerth WA, Gault KA, Doolette DJ. Empirical Evaluation of the Efficacy of Deep Stops in Air Decompression Dives. Undersea Hyperb Med 2007;34(4):231–2.

Doolette DJ, Gault KA, Gerth WA. Water Temperatures for Matched Cold Exposures in Divers With or Without Wetsuits During Air Decompression Dives. Undersea Hyperb Med 2007;34(4):251–2.

Gerth WA, Ruterbusch VL, Long, ET. The Influence of Thermal Exposure on Diver Susceptibility to Decompression Sickness. NEDU TR 06-07, Navy Experimental Diving Unit, Panama City, FL., November 2007.

Robertson EA, Zweig MH, Steirteghem AC. Evaluating the clinical efficacy of laboratory tests. Am J Clin Pathol 1983;79:78–86.

Zweig MH, Campbell G. Receiver-operator characteristic (ROC) plots: A fundamental evaluation tool in clinical medicine. Clin Chem 1993;39(4):561–577. (Erratum published in Clin Chem 1993;39:1589.)

Discussion

JOHN MURRAY: You analyzed the 170 fsw, 30-min dive with 174 minutes of decompression using the VVal-18 and bubble models, and there was quite a large spike in one of the bubble model compartments. Had you shortened the decompression for the bubble model, would the bubbles have been smaller? My concern is that perhaps 174 minutes of decompression was optimal for VVal-18 but not for the bubble model. With less decompression for the bubble model, would the DCS risk have been lower and the outcome different?

WAYNE GERTH: I think you are referring to the fast compartment of the bubble model. The question can only be answered within the context of a given model. The comparison of the two outcomes depends on the observed data. In the end, it didn't matter what algorithm was used to calculate the decompression profiles. One had a deeper stops and the other didn't. That was the only difference between the two schedules.

JOHN MURRAY: I hate to have a man abandon his religion. When deciding which profiles to test, had you used the bubble model to calculate the risk and assign the decompression, would it have assigned less than 174 minutes and would have had a lower risk?

WAYNE GERTH: That's correct. We would have had the same risk for a shorter decompression. There were two ways to do the experimental design. One was to test the two algorithms with different schedules and different decompression times but the same DCS risk. The other, which we selected, was to keep the decompression times the same but have different DCS risks. Either approach was conceptually equivalent, but we decided that with the same dive time, we would need fewer man-dives to prove there was no difference in risk or to discern a small difference. You also asked about a spike in one bubble model tissue. There's an essential difference in the class II type of deep stop when one of the models involved in the comparison is probabilistic. With a probabilistic model, every compartment is involved in the calculation of risk throughout the entire profile. In a deterministic model, however, there is a sequence of controlling tissues graduating from fast to slow throughout the whole profile. Once bubbles start forming, the probabilistic model becomes harder to explain and would have taken me longer to describe.

JOHN MURRAY: I was concerned that by having an arbitrarily long decompression with the bubble model, that you were absorbing nitrogen.

WAYNE GERTH: That was the optimum allocation of that stop time under the bubble model. The model distributed the stops it believed were correct and didn’t believe it was over-decompressing.

JOHN MURRAY: At that risk?

WAYNE GERTH: No, at that decompression time.

JOHN MURRAY: That wasn't the lowest risk for the bubble model for that dive?

WAYNE GERTH: No. But then we would have been comparing schedules with different decompression times and different risks.

DAVID DOOLETTE: The optimal decompression time for the bubble model was 174 minutes. If a shorter decompression had been used, the optimal distribution of stops would have been different with a higher DCS risk than the 174-minute schedule. That’s no different from any other decompression model.

ASSESSING THE RISK OF DECOMPRESSION SICKNESS

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What we really want to know is how to reliably prevent decompression sickness (DCS) when diving with helium. We cannot do that yet. The best we can do is to discuss the meaning of safety, suggest hypotheses concerning DCS mechanisms for testing, and give examples of methods that for answering the reliability question.

Uncertainty and Probability

One hundred years ago, the incidence of decompression sickness was disproportionately high, and deaths were not unusual. Death was not necessarily immediate, however, because a diver who was paralyzed often developed infections that, without antibiotics, could be fatal (Fig. 1).

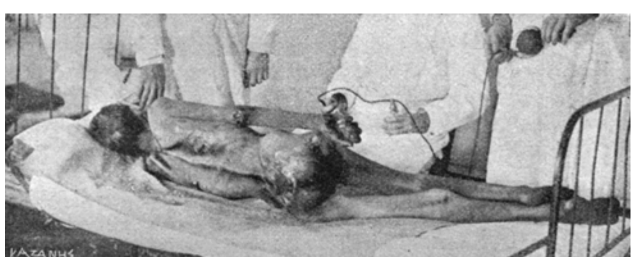


Figure 1. Secondary deterioration after paralytic decompression sickness (29).

Introduction of the Haldane decompression algorithm virtually eliminated DCS fatalities unless from accidental ascent (4), and the improvement was obvious. Since that time, there have been many modifications to the Haldane algorithm, but differences between algorithms are no longer so obvious. How do we decide when an algorithm is safe and which algorithms are safe enough?

Figure 2 illustrates this problem with seven decompression schedules for a 20 min dive to 200 fsw with decompression times ranging from 40 to 82 min (24). The 1968 British Navy schedule is the longest. Is it safe enough? Are the shorter schedules safe?

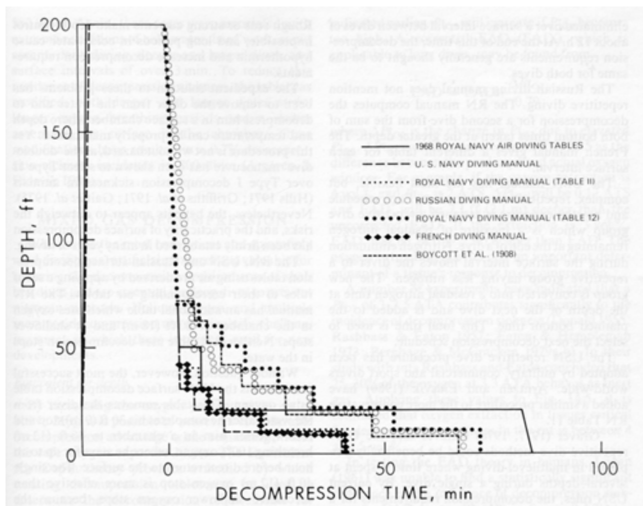
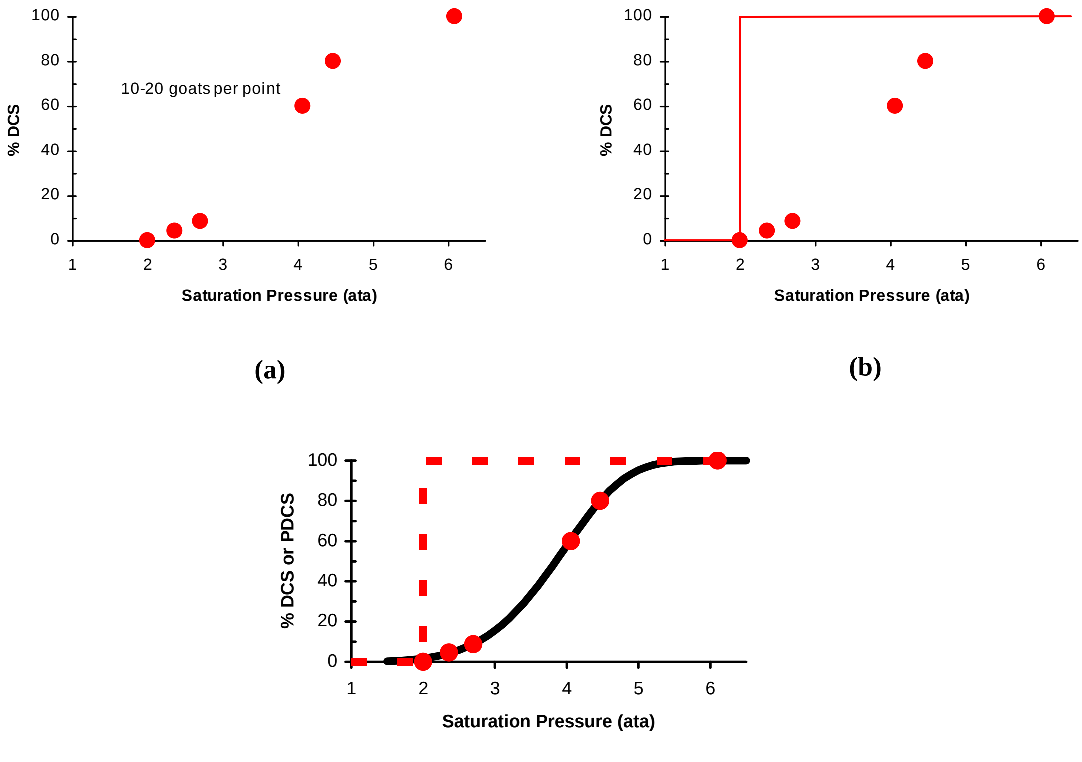


Figure 2. Seven published decompression schedules for a 200 fsw, 20 min dive (24).

“What works, works” is a diving adage that has been applied to both DCS and oxygen toxicity, but how often must a decompression schedule "work" before you can be confident it is reliable. Does a schedule "work" if 10 divers use it and no-one gets DCS? How likely is the 11th diver to use the schedule to get DCS? The answer is embodied in the 95% binomial confidence interval (CI).

With 10 DCS free dives, we can be 95% confident that the true DCS risk for that schedule is between zero and 25%. In other words, the best we can say is that the risk of DCS is less than 25%, but this is only true if all divers followed exactly the same profile under exactly the same conditions. If you made one DCS-free dive last weekend, you can be 95% confident that the true DCS risk of that schedule is between zero and 95%. In the 1980s, Navy schedules were often tested with 20 man-dives. If the result was zero DCS, the 95% CI was 0-14%. The 95% CI becomes narrower as more safe dives are made.

Let's consider the nature of DCS probability using Haldane's goats as an example. Suppose in Fig. 3a, each point represents 10-20 goats that were saturated at an initial pressure before decompression to the surface. The x-axis is the initial saturation pressure, and the y-axis is the percent DCS that was observed after surfacing. As the saturation pressure increased, the percentage of goats with DCS also increased.



(c)

Figure 3. Hypothetical experiment that saturates 10-20 goats to various pressures before decompression to sea level: (a) raw results; (b) "safe" threshold exposure; and (c) statistical model of probability fit to raw results.

The results indicate that all goats developed DCS at 6 ata, but none at 2 ata. To be as safe possible according to these data, we should avoid any saturation greater than 2 ata (Fig. 3b). This is a deterministic model. It is simple, easy to use, and was very powerful in Haldane's time. On the other hand, its simplicity limits the ability to simulate reality – that DCS risk is a probabilistic rather than a threshold (yes/no) phenomenon.

To treat the goat data as probabilistic, we fit a curve to the data points as in Fig. 3c, so we don't just classify a dive as "safe" or "unsafe" but can assign a probability of DCS to any dive. Intuitively this makes sense, but fitting complex models to complex dive profiles is not a trivial exercise. A probabilistic decompression model has three parts. (a) A biophysical component used to compute a measure of exposure stress for any dive profile. This could be a Haldane model, a bubble model, or another configuration. The model usually has parameters with unspecified values. (b) Parameter calibration data that include depth-time profiles and DCS outcome information. (c) A statistical model that links the exposure stress and calibration data. The parameter values must be found to determine the best agreement between predicted DCS probability and observed DCS incidence.

The Navy has had the greatest success with probabilistic modeling (19, 26, 27). DAN's efforts have focused on gathering data from ordinary recreational dives and, more recently, from technical dives, that might be used to calibrate future probabilistic decompression models. In the work discussed below, we used two Navy models to estimate decompression stresses for recreational and technical dives collected by DAN or dive trials conducted by the Navy or at Duke.

Dive Conditions and DCS Incidence

To investigate the effects of dive conditions for air and nitrox dives, we used the BVM3 bubble model (11) to predict a DCS probability for each dive and used the predicted probabilities as measures of decompression stress. For dives during which helium was breathed, we used the LEM multi-gas model (10) for which there was less data and experience and greater uncertainty compared to BVM3.

With generous support from many dive computer manufacturers*, DAN has collected depth-time profiles and medical outcomes from air and nitrox dives for over 100,000 dives in several diving environments (21, 25). Figure 4 summarizes dives collected from 1995-2005. About one quarter of the dives were nitrox and three-quarters air, each group having a DCS incidence of about 0.03%.

* Cochran, Delta P Technology, DiveRite, HHS Software, Liquivision, Oceanic, ReefNet, Shearwater, SUUNTO, Uwatec, and Vision Electronics.

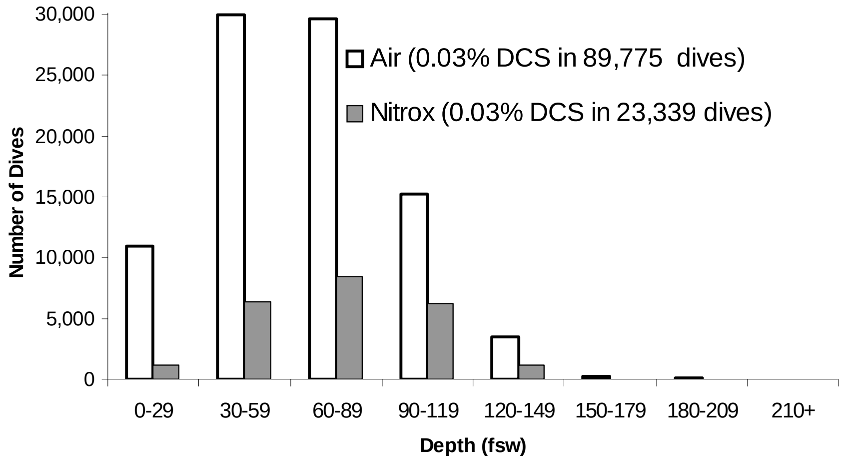


Figure 4. Air and nitrox dive profiles collected by DAN from 1995 to 2005.

A subset of these data was analyzed to examine the influence of diving environment on probability of DCS. This subset included: (a) 51,497 Caribbean liveaboard and dayboat dives with 8 DCS cases for 0.02% DCS; (b) 6,527 cold water wreck dives in Scapa Flow, Scotland with 18 DCS cases for 0.3% DCS; and (c) 2,252 military dive trials (Canadian, British, and U.S. Navy) with 70 DCS cases for 3.1% DCS (21). Each dive was assigned an indicator of the diving environment (Caribbean, Scapa Flow, military trials) and the outcome (DCS, no-DCS). To control for differences among depth-time-gas profiles, the dives were also assigned decompression stresses calculated by BVM3. The DCS probabilities for the dives were determined by fitting a logistic regression model to the outcome data (DCS, no-DCS) while controlling for decompression stress and dive environment.

To illustrate approximate effects of the three diving environments, we estimated DCS probabilities for no-stop air dives to 60 fsw as a function of bottom time. These are shown in Fig. 5 where the x-axis is the bottom time at 60 fsw, and the y-axis is the estimated DCS probability. Green represents the Caribbean dives, blue the Scapa Flow dives and red for the military trials. The DCS probabilities for the military trials were double those for Scapa Flow and 30 times greater than for the Caribbean dives. The vertical black arrows in Fig. 5 indicate the no-decompression limits of 45 min for the DCIEM dive tables (2) and 60 min for the Navy tables (1). Between 45 and 60 min, the DCS probability increased from 0.03 to 0.05% for Caribbean dives, from 0.42 to 0.73% for Scapa Flow dives and from 0.88 to 1.64% for the military trials.

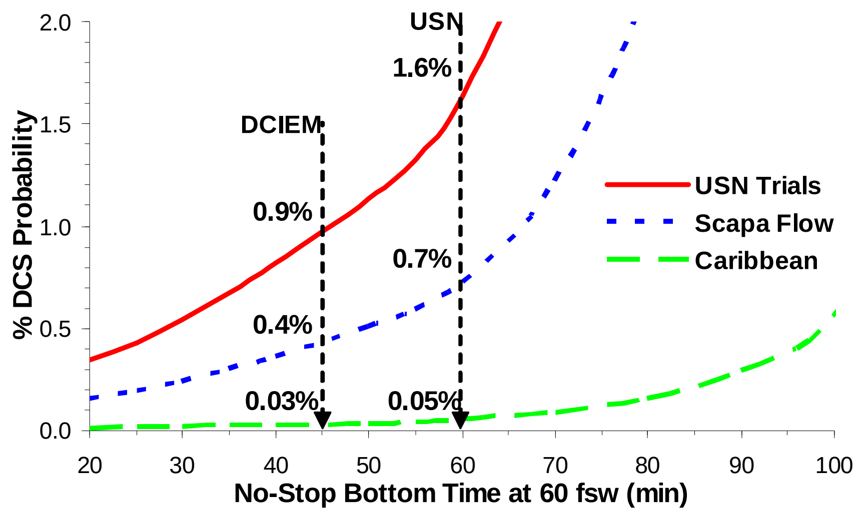


Figure 5. DCS probability for no-stop air dives to 60 fsw estimated for Caribbean and Scapa Flow dives and for military dive trials.

What might explain the differences in DCS probability among the dive groups? About three-quarters of the military trials were long decompression dives where the divers wore wetsuits, exercised at depth, rested during decompression, and were cold when they surfaced. About one quarter of the Scapa Flow dives were decompression, and virtually all divers wore drysuits for protection against the ~50°F (10°C) water. The Caribbean dives were all no-D in 70-80°F (21-27°C) water. Most Caribbean recreational diving involved little exercise at depth, and the divers were assisted into an out of the water so there was little exercise before or after diving

As discussed in DCS Risk Factors in these proceedings (8), differences in DCS probability among the three dive locations are probably explained by the effects of exercise and thermal state. The point to remember is that differences in dive conditions appear to influence DCS probability more that the depth-time profiles themselves for some dives. Thus, depth and time are not the only factors to be considered when planning decompression: (a) avoid exercise (use a scooter if possible) and be cool rather than warm while at depth; (b) perform mild exercise and stay as warm as practical during decompression; and (c) avoid exercise after decompression. New methods for active and passive thermal protection are under development and should help to control thermal conditions such that DCS probability can be reduced (see Thermal Concerns in Cold Water Diving in these proceedings (14)).

Decompression Safety

Decompression safety is acceptable risk (as it is for CNS oxygen toxicity (23)) where risk is determined by the probability and severity of injury. Fortunately, there are more data for decompression than for oxygen toxicity, fewer factors that influence probability, and DCS is usually less hazardous than CNS oxygen toxicity. Acceptable DCS probability is obviously greater for mild injury, such as knee pain, than for serious injury, such as paralysis, but the choice of acceptable probability is arbitrary and at the discretion of the diver or diving organization. The U.S. Navy, for example, has indicated preferences for mild DCS to be <2% and serious DCS to be <0.1% (20).

What would be the consequences of applying the Navy limits for mild and serious DCS to the no-stop bottom times at 60 fsw? Suppose we define Type I DCS as mild and Type II DCS as serious. In Fig. 6, the green curve represents mild DCS and the red curve serious DCS (28). Applying the 2% Navy limit for mild DCS to the mild curve, the longest allowable no-stop dive is 58 min. Applying the 0.1% limit for serious DCS to the serious curve, reduces the allowable dive time to 37 min.

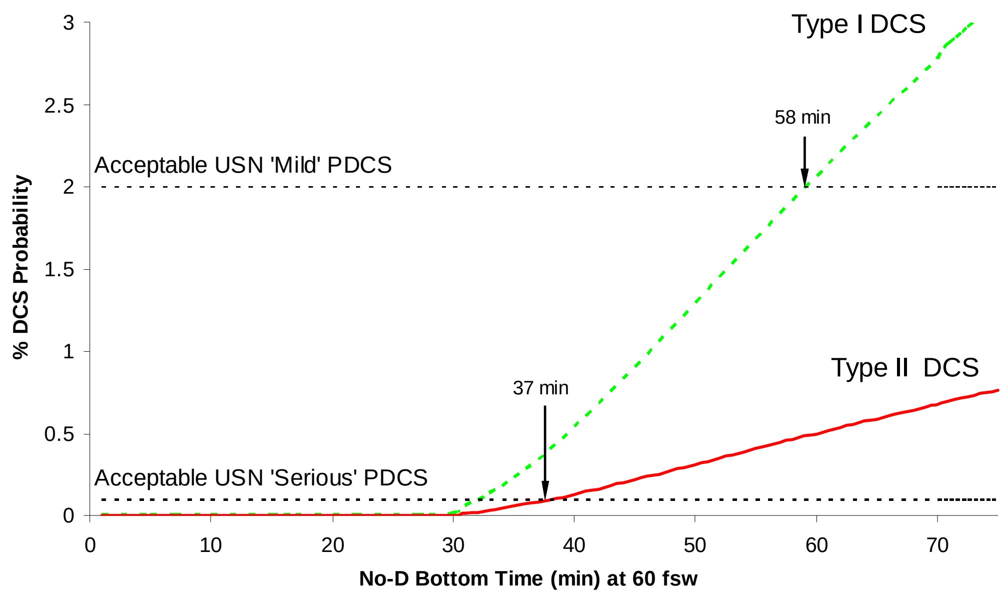


Figure 6. DCS probability estimated for no-stop dives to 60 fsw for “Mild” (Type I) DCS and “Serious” (Type II) DCS (28).

Two comments apply to this example. First, not all Type II DCS are truly serious. The categories Type I and Type II are no longer considered satisfactory, and the definitions of mild and serious DCS require objective study (22). Second, after a satisfactory definition of serious DCS has been established, application of this definition could potentially limit dive time as indicated in Fig. 6.

DCS Outcomes in Navy Helium Diving

Helium dives are less common than nitrogen dives, but trials the Navy conducted at NEDU in 1984-5 with the closed-circuit Mk 16 UBA were useful for comparing the decompression outcomes of nitrogen and helium (17, 18). The oxygen setpoint was a constant 0.7 atm throughout the dives with no changes in breathing gas. There were 873 nitrogen dives to depths of 50-190 fsw and 1,508 helium dives to depths of 60-300 fsw.

An analysis of these data found that the overall DCS incidence (Figure 7) was significantly higher for nitrogen (5.4%) than for helium (3.6%), but the incidence of Type II DCS was significantly greater for helium (1.4%) than for nitrogen (0.8%) (15, 16).

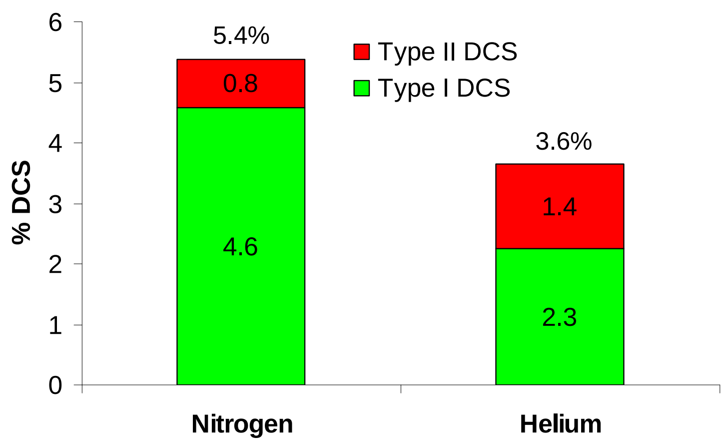


Figure 7. Helium, nitrogen, and DCS outcomes.

In 2002, the Navy conducted a series of helium trials with the Mk 16 UBA with an O_2 setpoint of 1.3 atm (12). There were nine DCS incidents in 527 trials for an overall incidence of 1.8%. Manifestations included: (a) pain and numbness; (b) abdominal rash; (c) excessive fatigue (two cases); (d) excessive fatigue and paresthesia; (e) excessive fatigue and decreased alertness; (f) fuzzy thinking, pain, paresthesia; (g) elbow pain and positive Romberg (falling to one side); and (h) decreased consciousness. As in the earlier 0.7 atm setpoint trials, Type II DCS was common.

Why might Type II DCS be more common with helium than with nitrogen? The divers in the earlier 0.7 atm trials were monitored by Doppler ultrasound for venous gas emboli (VGE) (17, 18), and significantly more divers had Doppler scores of 3 or 4 after helium dives (43%) than after nitrogen dives (25%). This suggests a hypothesis that might be tested in an animal study: helium VGE may be more likely to reach the arterial circulation through the pulmonary capillaries than nitrogen VGE.

Technical Diving DCS

Figure 8 is the computer-recorded depth-time profile for a DCS incident after a trimix dive at Edwards Springs. The black line is depth and the green line is the oxygen partial pressure. The diver breathed 21% oxygen until switching to 100% oxygen at 20 fsw. Upon reaching the surface, he was cold, confused, and very fatigued – symptoms that were similar to the 1.3 atm Mk 16 DCS cases the Navy reported (12). He was treated on a Table 6 about eight hours after surfacing which relieved the extreme fatigue. The DCS probability estimated by LEM was 2.9%.

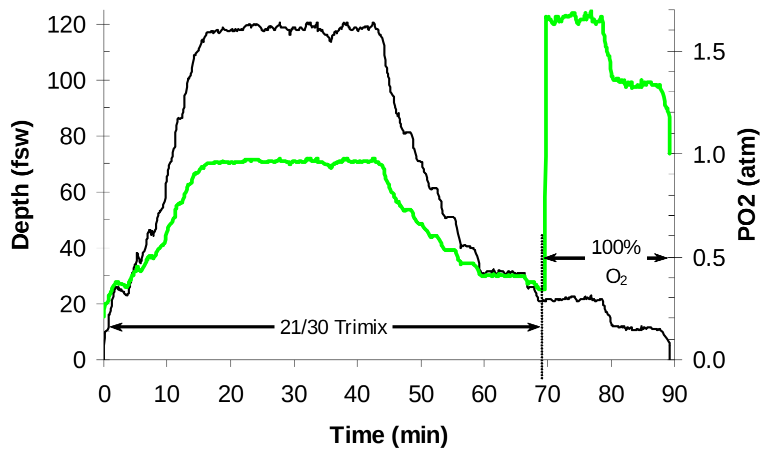


Figure 8. DCS at Edwards Springs after a trimix dive.

Figure 9 shows a case treated by Karl Huggins at the Catalina Island chamber (13). As the diver did not carry a recording dive computer, the depth-time profile in Fig. 9 was estimated using the decompression software. The depth was 250 fsw with trimix 16% O_2/50% N_2 at depth, 50% nitrox at 70 fsw, and 100% oxygen at 20 fsw. The diver developed severe shoulder pain five hours after the dive and was treated 14 hrs later on a Catalina Table 6-12 (8.5 hr treatment time with six O_2 cycles at 60 fsw and 12 O_2 cycles at 30 fsw) with complete relief. He had moved tanks after the dive which may have increased his DCS probability (8). The DCS probability estimated by LEM was 3.4%.

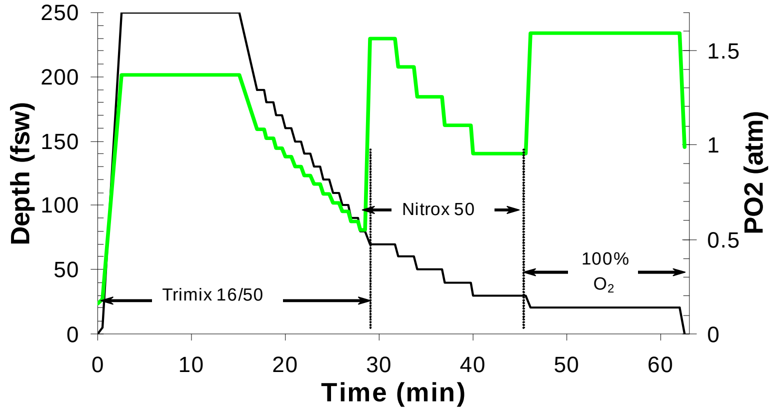


Figure 9. Dive profile for DCS Case 1 treated at Catalina Island (13).

A second Catalina case involved a dive to more than 200 fsw with the same gases as the previous case. The dive profile was recorded (Fig. 10) but not all the depth-time nodes are shown. During decompression, the diver had flexed his left arm in order to hold shut a leaking valve on his buoyancy compensator. Thirty minutes after the dive, he developed 6 out of 10 left-hand pain and motor weakness. When checked by Doppler for VGE, he had Grade 3+ bubbles in the left arm but only Grade 1 in the right arm. Treatment at four hours post dive on a Catalina Table 8-18 left him with slight residual pain which resolved by morning. The DCS probability estimated by the LEM model was 5.1%.

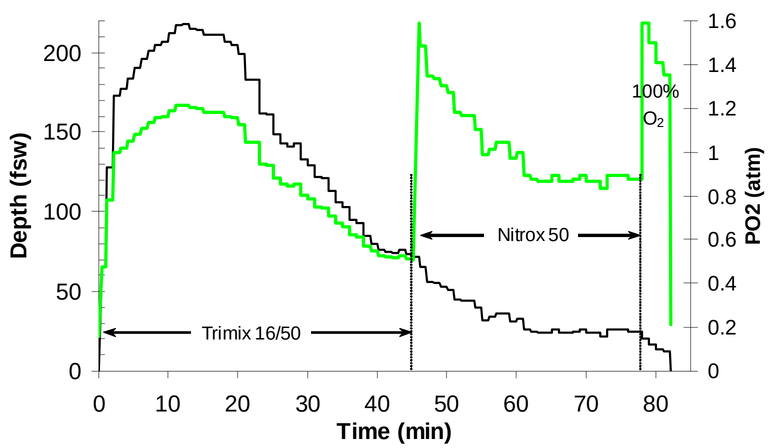


Figure 10. Dive profile for DCS Case 2 treated at Catalina Island (13).

A third Catalina case is shown in Fig. 11. There were two dives to 180 feet with the same gases as in the previous cases. Two minutes after surfacing from the second dive, the diver developed nausea and pain and motor weakness in the arm. He was treated on a long Catalina table five hours and 40 minutes post-dive after which he had minor residual pain and weakness which resolved on an extended Table 6 the next day. The DCS probability estimated by the LEM model was 4.6%.

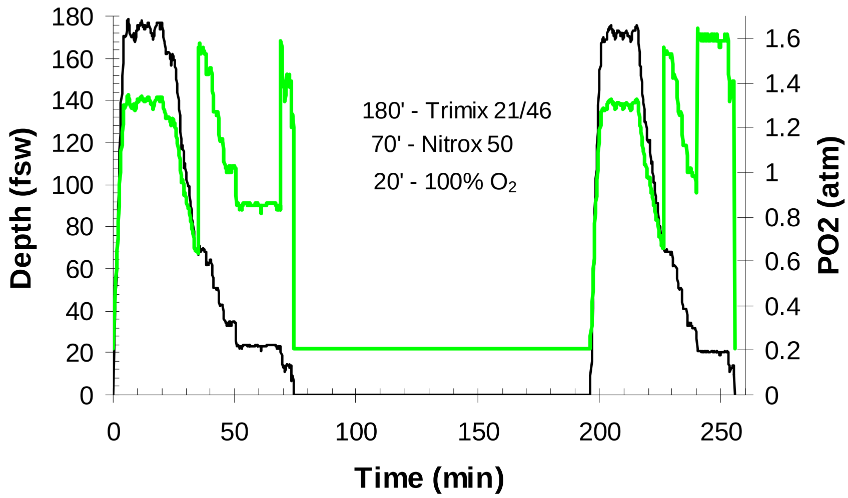


Figure 11. Dive profile for DCS Case 3 treated at Catalina Island (13).

DCS in an Experimental Dive Series

Commercial diving for offshore oil became an important national issue during the oil embargo of the 1970s, and diving companies competed to develop the fastest possible decompression schedules for short, deep dives. A number of laboratories participated in the competition, and Figure 12 shows schedules that were tested for a 30 min dive to 500 fsw [24]. The Hyperbaric Center at Duke University conducted 168 dives man-dives (3). There were 23 cases of decompression sickness for an overall DCS incidence of 13.7%, in agreement with the 15% DCS probability estimated by the LEM model [10].

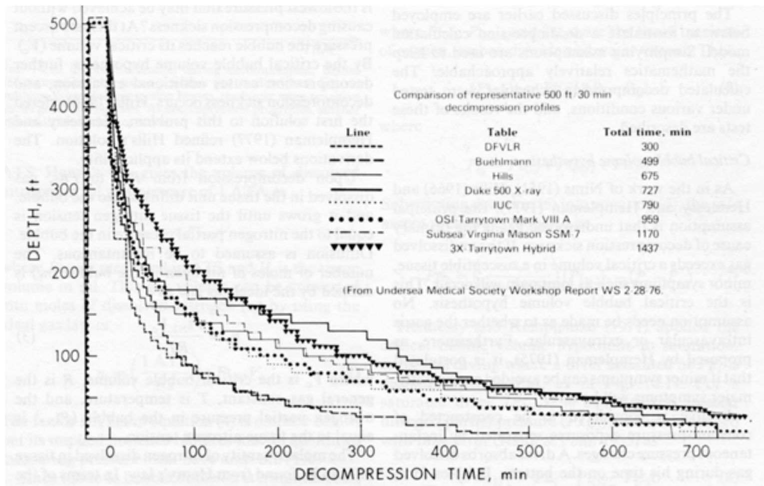


Figure 12. Eight decompression schedules for a 30 min dive to 500 fsw (24).

Several of the 500 fsw tests are relevant case studies. Figure 13 shows the dive profile for 500 Juliet. The black line is depth, and the green line is the oxygen partial pressure. Upon reaching 130 fsw, the divers switched from helium-oxygen to air, and inner ear DCS occurred almost immediately. Deep, rapid changes from helium to nitrogen mixes are now recognized as a risk factor for inner ear DCS (9). The physiological mechanism is not altogether clear, but supersaturation in the labyrinthine space due to counterdiffusion of helium and nitrogen between endolymph and perilymph has been proposed (9).

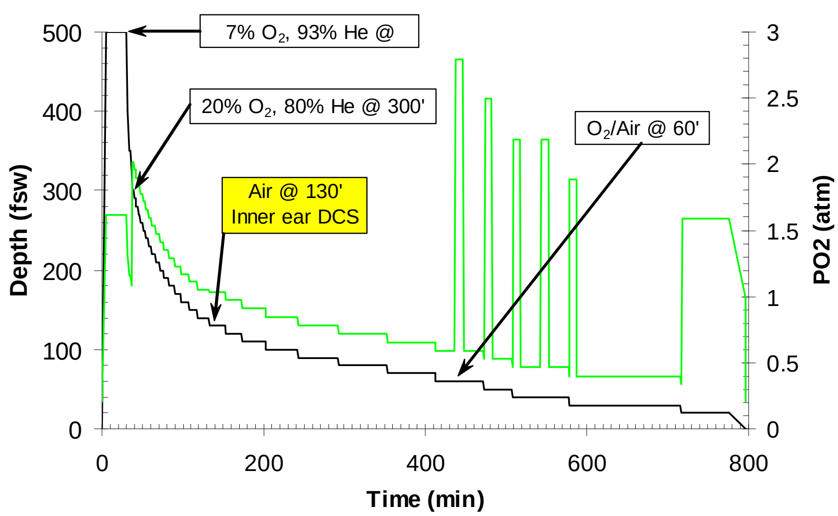


Figure 13. 500 Juliet dive profile that resulted in inner ear DCS (3).

To avoid the inner ear problem that occurred on 500 Juliet in Fig. 13, the switch from helium-oxygen to air was changed from 130 fsw to 100 fsw for schedule 500 Lima (Fig. 14). This was followed by cycles of 100% oxygen and air breathing beginning at 60 fsw as was common practice in the mid 1970s. On dive 500 Lima (Fig. 14), however, there was an oxygen convulsion at 60 fsw.

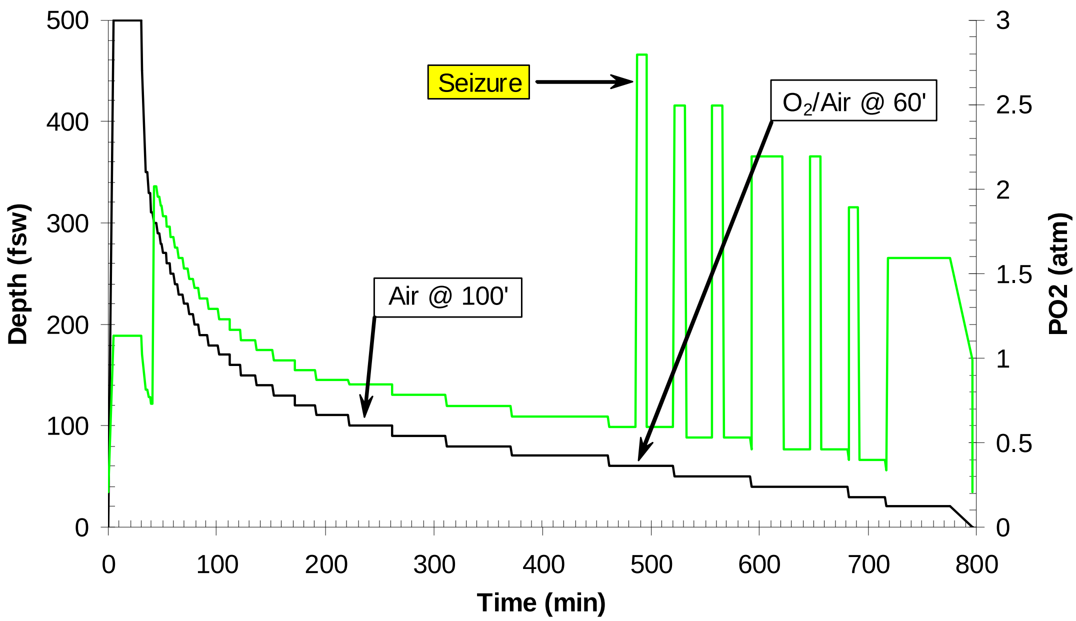


Figure 14. 500 Lima dive profile that resulted in an oxygen convulsion (3).

Schedule 500 Lima offered the opportunity to compare DCS risks estimated with the LEM model (10) for: (a) the intermittent high inspired oxygen partial pressures (1.1 atm time-weighted average) that resulted in an oxygen convulsion; and (b) a constant 1.3 atm oxygen setpoint that as used in a modern rebreather. These are shown in Fig. 15. The estimated DCS probability was 15% for the intermittent mixes and 8% with the constant 1.3 atm mix. Thus, the constant 1.3 atm oxygen partial pressure may not only reduce oxygen toxicity risk but also DCS risk by maintaining a higher average oxygen partial pressure.

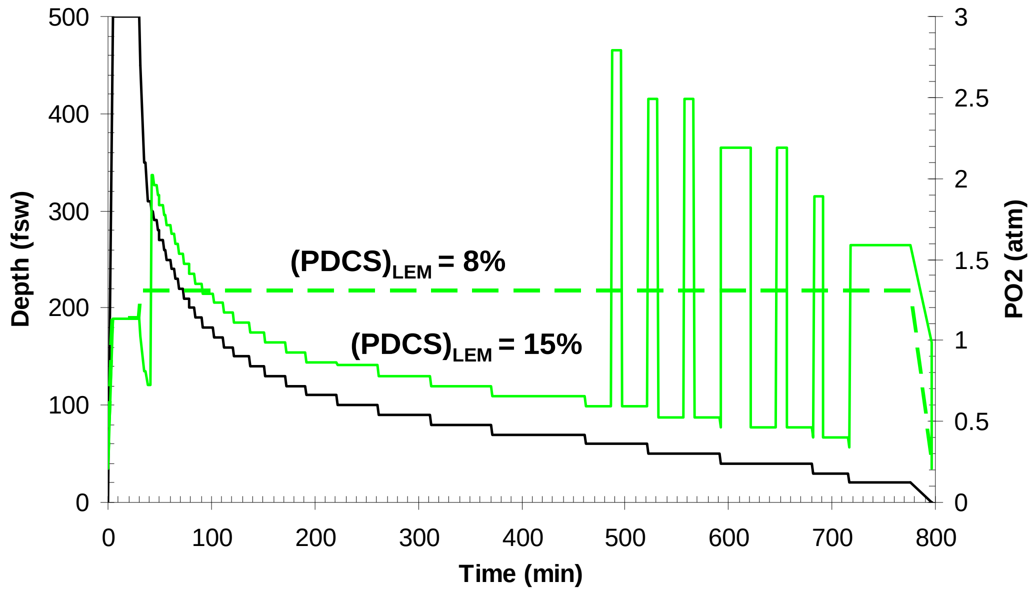


Figure 15. Comparison of 500 Lima dive profiles with fixed oxygen fractions as dived or a constant 1.3 atm oxygen partial pressure (3).

DCS on a Technical Diving Expedition

In 2006, Dr. Petar Denoble accompanied John Chatterton and Richie Kohler on a diving expedition to the *Britannic* for the History Channel (5-7). Dr. Denoble's task was to collect dive profiles and monitor the divers with Doppler for precordial VGE. Figure 19 shows a typical dive profile. The O_2 partial pressure (green line) represented the mean of the three O_2 sensors in the rebreather. The red line is the O_2 setpoint which was 1.3 atm until about 5 msw where it was reduced to 0.7 atm. The mean O_2 sensor reading varied around the 1.3 atm setpoint as the depth changed and oxygen was consumed or added. When the setpoint was reduced to 0.7 atm, the diver added oxygen manually to achieve a higher partial pressure. The LEM model estimated a DCS probability well above 20%.

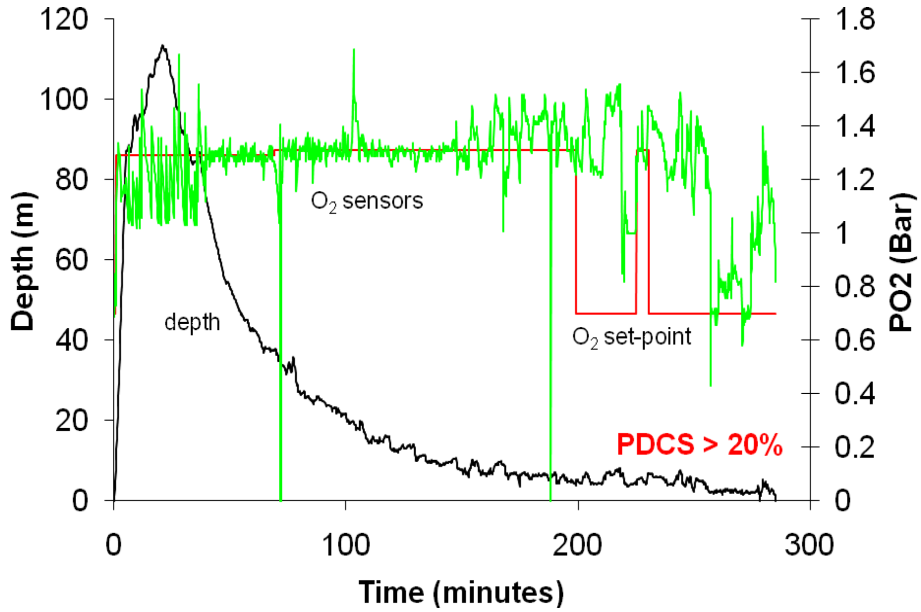


Figure 18. 2007 *Britannic* expedition dive profile (5-7).

Dr. Denoble returned with depth-time recordings from 20 dives having a mean depth of 343 fsw (range of 296-380 fsw) and mean dive time of 4:40 (range 2:20-7:17). The mean estimated DCS probability was 28%. If these estimates were correct, six DCS incidents would have been expected. None were reported.

The difference between observed and predicted DCS was statistically significant. There are three possible explanations for this discrepancy: (a) the divers did not recognize or report their symptoms; (b) the *Britannic* divers were less susceptible to DCS than most military or commercial divers; and (c) the LEM model predictions were too high.

Regarding explanation (a), LEM model predictions are for DCS of any severity, and the divers may not have reported some very mild symptoms. Regarding explanation (b), perhaps these experienced expedition divers were self-selected, and divers more susceptible to DCS had withdrawn. Regarding explanation (c), probabilistic models are only as good as the calibration data, and the LEM calibration data has a 5.4% incidence of DCS [12]. Thus, the mean estimated risk of 28% for the *Britannic* dives may have been unreliable. In addition, the LEM model was calibrated against cold, working dives and will overestimate the risk of dives conducted in warm water with little exercise (8). At present, it is not possible to distinguish between these alternatives.

Finally, the *Britannic* dive profiles were recorded at 10 s intervals and the LEM model is quite sensitive rapid changes in depth such that the risk estimates of these dives may not be realistic. This is illustrated in Fig. 19 for one *Britannic* dive. The green line is the dive profile for which depth was recorded with an estimated DCS probability of 41%. The red line represents an error in depth-time recording during the rapid ascent phase with an estimated probability was 52%. Dive profiles recollected from diver memory are untrustworthy, and depth-time profiles must be recorded electronically. The minimum sample interval should be less than 10 sec for an accurate record of the rapid ascent phase. The rapid ascent phase is where the argument about deep stops is found.

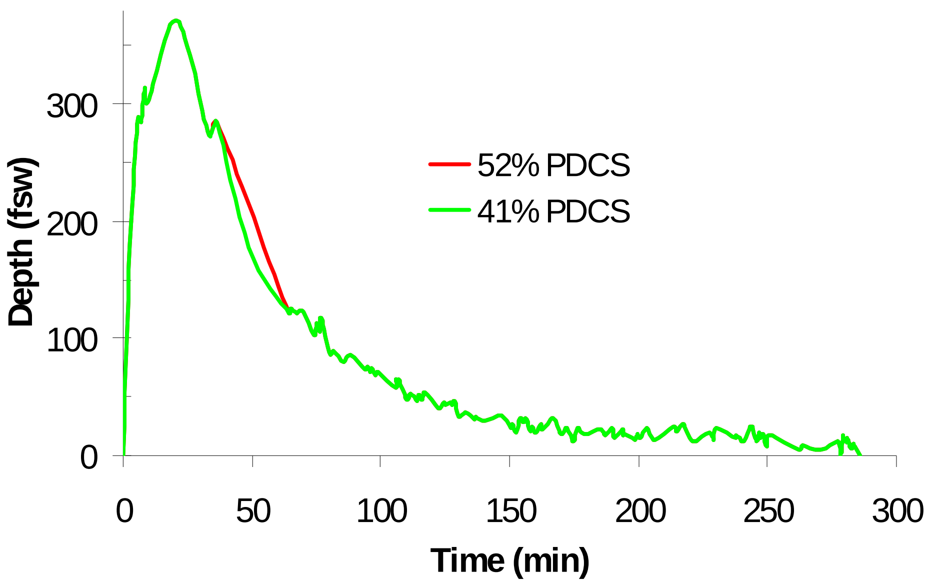


Figure 19. Effect of an error in depth-time recording on estimated DCS probability (5-7).

Conclusions

There are no crisp, clean risk-free limits for either decompression sickness or oxygen toxicity. Safety depends on the severity and probability of injury which makes safety an arbitrary choice. If a satisfactory probabilistic decompression model were available, a diver could select an acceptable DCS probability and dive the corresponding procedures. For accurate probability estimates, the model would need to be calibrated with the same environmental conditions anticipated for the dive.

Probabilistic decompression models require depth-time profile and medical outcome data, but such information is unlikely to be developed in laboratory trials for technical diving.

Rebreathers with black-box recorders are excellent data collection tools. There are few changes in breathing gas with rebreathers, and oxygen sensor values are recorded. Technical divers are encouraged to submit their dive profiles and outcomes to DAN.

References

1. United States Navy Diving Manual. Vol 2, Rev 3. Washington, DC: United States Department of the Navy 1991.

2. DCIEM Diving Manual. Parts 1 and 2. North York, ON, Canada: Defence and Civil Institute of Environmental Medicine, Department of National Defence 1992.

3. Bennett P, Vann R. Theory and development of subsaturation decompression procedures for depths in excess of 400 feet. In: Hamilton RJ, editor. Development of decompression procedures for depths in excess of 400 feet; 1976; Wash, DC: Undersea Medical Society; 1976. p. 119-39.

4. Boycott AE, Damant GCC, Haldane JS. The prevention of compressed air illness. J Hyg, Camb. 1908;8:342-443.

5. Denoble P. The expedition to the Britannic: Part 1. Alert Diver. 2007;Jan/Feb:36-9.

6. Denoble P. The expedition to the Britannic: Part 2. Alert Diver. 2007;March/April:43-7.

7. Denoble P. The expedition to the Britannic: Part 3. Alert Diver. 2007;March/April:40-5.

8. Doolette D, Vann R. DCS risk factors. In: Vann R, Mitchell S, Anthony G, Denoble P, eds. Technical Diving Conference; January 18-19, 2008; Durham, NC: Divers Alert Network; 2009: 119-137.

9. Doolette DJ, Mitchell SJ. Biophysical basis for inner ear decompression sickness. J Appl Physiol. 2003 Jun;94(6):2145-50.

10.Gerth W, Johnson T. Development and validation of 1.3 ata PO2-in-helium decompression tables for the Mk 16 Mod 1 UBA. Panama City: Navy Experimental Diving Unit; 2002 August 2002.

11. Gerth WA, Vann RD. Probabilistic gas and bubble dynamics models of decompression sickness occurrence in air and nitrogen-oxygen diving. Undersea and Hyperbaric Medicine. 1997;24(4):275-92.

12. Gerth WA, Johnson TM. Development and validation of 1.3 ata PO2-N2-He decompression tables for the Mk 15 Mod 1 UBA. Panama City, FL: Navy Experimental Diving Unit; 2002. Report No.: NEDU TR 02-10.

13. Huggins K. Treatment of decompression sickness in recreational trimix (technical) divers: report of three cases. 2008.

14. Nuckols M. Thermal concerns in cold water diving. In: Vann R, Mitchell S, Anthony G, Denoble P, eds. Technical Diving Conference; January 18-19, 2008; Durham, NC: Divers Alert Network; 2009: 99-108.

15. Shannon J. The relationship of inert gas and venous gas emboli to decompression sickness. M.S. Thesis, Mechanical Engineering and Materials Sciences Dept.: Duke University; 2003.

16. Shannon J, Vann R, Peiper C, Thalmann E, Gerth W. Relationship between inert gas type, venous gas emboli (VGE), and decompression sickness (DCS). Undersea and Hyperbaric Med. 2004;31:336-7.

17. Thalmann ED. Air-N202 decompression computer algorithm development; 1985. Report No.: NEDU Report 8-85.

18. Thalmann ED. Development of a decompression algorithm for constant 0.7 ATA oxygen partial pressure in helium diving; 1986. Report No.: NEDU Report 1-85.

19. Thalmann ED, Parker E, Survanshi SS, Weathersby PK. Improved probabilistic decompression model risk predictions using linear-exponential kinetics. Undersea Hyper Med. 1997;24(4):255-74.

20. Van Liew H, Flynn E. Decompression tables and dive-outcome data: graphical analysis. Undersea Hyperb Med. 2005;32 (4):187-98.

21. Vann R, Denoble P, Uguccioni D, Pollock N, Freiberger J, Pieper C, et al. The risk of decompression sickness (DCS) is influenced by dive conditions. Diving for Science; 2005: AAUS; 2005.

22. Vann R, Moon R, Freiberger J, Denoble P, Dear G, Stolp B, et al. DCI diagnosis and decompression study design. Aviat Space Environ Med. 2008;79:1-3.

23. Vann R, Hamilton R. CNS oxygen toxicity. In: Vann R, Mitchell S, Anthony G, Denoble P, eds. Technical Diving Conference; January 18-19, 2008; Durham, NC: Divers Alert Network; 2009: 38-66.

24. Vann RD. Decompression theory and application. In: Bennett PB, Elliott DH, eds. *The physiology of diving and compressed air work*. 3 ed. London: Bailliere Tindall 1982: 352-82.

25. Vann RD, Freiberger JJ, Caruso J, Denoble PJ, Pollock NW, Uguccioni DM, et al. DAN Annual Diving Report: 2006 Edition (Based on 2004 Data). Durham, NC: Divers Alert Network; 2006.

26. Weathersby PK, Homer LD, Flynn ET. On the likelihood of decompression sickness. J Appl Physiol. 1984 Sep;57(3):815-25.

27. Weathersby PK, Survanshi SS, Homer LD, Parker E, Thalmann ED. Predicting the time of occurrence of decompression sickness. J Appl Physiol. 1992 Apr;72(4):1541-8.

28. Weber P, Howle L, Denoble P, Vann R, CF P. Probability models of mild and serious decompression sickness (DCS). Undersea and Hyperbaric Med. 2007;34(4):229.

29. Zografidi S. Revue de Médecine. 1907 27:159.

Discussion

GREG STANTON: Could you put into perspective the application of surface interval oxygen and the management of DCS risk.

DICK VANN: I think surface interval oxygen is useful for either reducing the DCS risk or for reducing the surface intervals between repetitive dives. You ran the tests, Greg. I never will forget that, and I thank you very much. That data will be incorporated into a probabilistic decompression model.

RICH PYLE: You mentioned the need for information about factors besides high-resolution depth-time profiles such as exertion level and water temperature. Those might be as or more important than the dive profiles. I also want to comment on self-selection. I know a lot of technical divers and several who have stopped doing technical dives because they've had close calls. I know many more who have had close calls but continue to dive. I don't think self-selection is common in the sense of removing themselves from the pool, but when divers get badly bent, they do it differently on the next dive. I think the non-dive profile issues are the devil in the details and really important in determining DCS risk. That would be an important part of the black-box information.

KARL HUGGINS: You estimated the DCS probability for three groups of divers and showed three different curves attributed to environmental factors. Could those results also be attributed to how the model fit the very different types of dives they did – no-D diving versus decompression diving beyond the limits of the Navy dive tables?

DICK VANN: We can't rule that out. We controlled for differences between dives using BVM3 to estimate a decompression stress for each dive (11). While there was a pretty good fit between observed and estimated DCS after controlling for decompression stress, there's no guarantee it was perfect. We will re-do the analysis with a larger dataset.

DAVID DOOLETTE: I believe some of the *Britannic* divers were put on surface oxygen after the dives. If this was not included in the risk analysis, the overall risk would have been lower and might explain the big discrepancy between the estimated risk and lack of admitted DCS.

PETAR DENOBLE: Only one diver breathed 2-3 cycles of surface oxygen post-dive. I suggested he do this because he had grade 5 bubbles. We included the oxygen breathing in the risk analysis. Without oxygen, his estimated DCS risk was 21%. With oxygen, it was 19%.

THERAPY FOR DECOMPRESSION ILLNESS

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Introduction

As was discussed by Dr Moon in his earlier paper, decompression illness (DCI) arises when bubbles form in (or are introduced into) blood or body tissues during or after ascent from a compressed gas dive. This occurs most commonly when bubbles evolve from "inert" gas that has been absorbed during the dive. As all participants in this workshop will understand, divers utilize dive planning algorithms that attempt to predict this uptake of gas to guide the process of decompression so that symptomatic bubble formation will not occur.

Equally well understood will be the fact that DCI may still occur even when these algorithms are followed and, conversely, DCI may not occur when these algorithms are violated. Although there are no definitive data on the matter, diving physicians agree that the predictive accuracy of decompression algorithms is lower for deep technical diving than for normal recreational diving. In addition, because technical divers frequently incur large decompression obligations, there is an increased risk of severe DCI if problems occur underwater and decompression is not completed. It is therefore inevitable that some technical divers will find themselves in the position of having to manage a case of DCI in the field, not uncommonly in a remote location, and it is quite likely that the victim will be seriously affected. Technical divers should therefore "expect" challenging DCI events under difficult circumstances, and plan for them.

This paper will facilitate that process by discussing therapy for DCI. It is beyond our scope to provide a "from the ground up" account of the process of treating a sick diver. Instead, we will focus on some topical aspects, culminating in consideration of the controversial issue of in-water recompression. <u>We remind the reader that this paper is targeted at the workshop's technical diving audience, rather than those with expert knowledge of diving medicine</u>.

<u>1. What are the therapies for DCI?</u>

Ask this question of any virtually any diver and they will say "recompression." This is an appropriate answer, but is it not a complete one. In fact, there are a number of potential therapeutic interventions for DCI and, and as will be discussed, there are instances where recompression may not always be the first priority or perhaps not even necessary at all.

There is no universally accepted classification of therapy for decompression illness, but the "preeminence" of recompression as the primary treatment has led to a classification based around "recompression" and "other modalities", where "other modalities" may be used as first aid, and / or adjuncts to recompression.

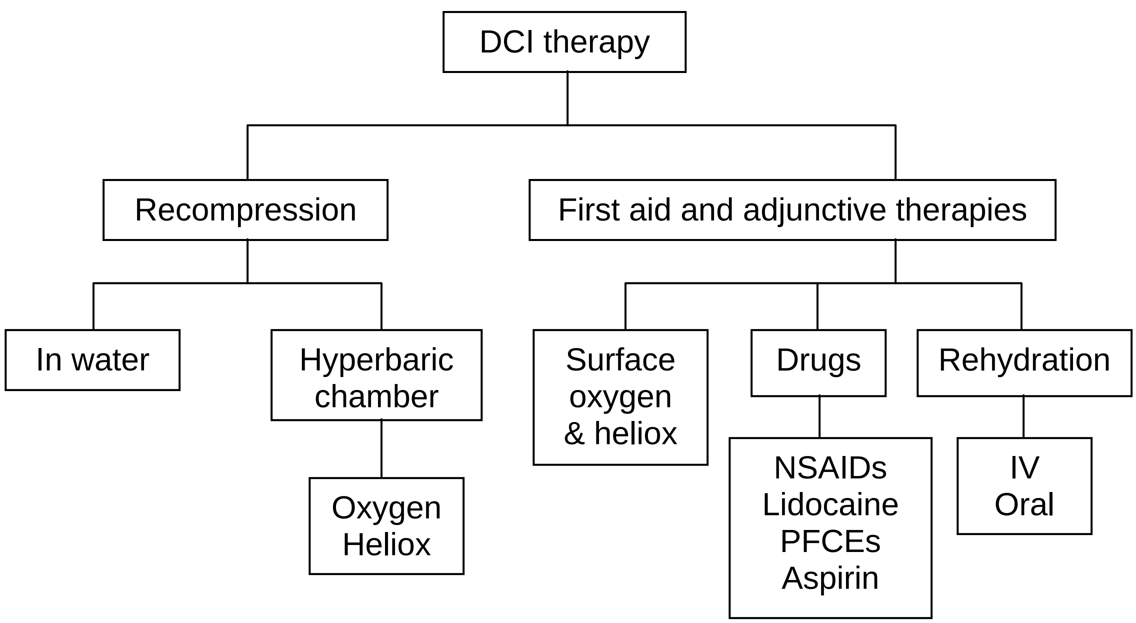


Figure 1. Summary of therapies for DCI. "?" denotes uncertainty or controversy in respect of a treatment modality. IV = intravenous. NSAIDs = non-steroidal anti-inflammatory drugs. PFCEs = perfluorocarbon emulsions.

We will now move on and consider some relevant questions in relation to these therapies.

2. What is optimal first aid for DCI?

Arguably the most controversial issue in therapy for DCI is whether in-water recompression is an appropriate first aid strategy. We will consider this matter later in the paper. For now, we will consider the "traditional" first aid strategies which are drawn from the list in Fig. 1.

a. Oxygen.

The administration of oxygen (preferably in an inspired fraction of 100%) has long been advocated as the most important first-aid treatment for DCI. The putative benefits include an increase in the "partial pressure vacancy" in tissues (or "opening of the oxygen window") which accelerates diffusion of inert gas out of bubbles and tissues, and correction of hypoxia in compromised tissue. Not surprisingly, accelerated resolution of tissue bubbles has been demonstrated during oxygen breathing in animals (1). However there had been little firm evidence of clinical benefit from first-aid oxygen until the recent demonstration by Longphre et al. (2) that divers receiving first-aid oxygen responded more rapidly to recompression treatment and were less likely to require multiple recompressions than those who received no oxygen. Interestingly, there was no difference in final outcome after completion of all recompression therapy between those receiving or not receiving first aid oxygen. Nevertheless, there seems a strong argument for continuing to aggressively promote the use of first-aid oxygen for treatment of DCI. The Longphre study did not address the benefit of higher versus lower fractions of inspired supplemental oxygen because of problems with data capture, but there is sound logic to the recommendation that 100% oxygen is the optimal concentration.

Typical errors in oxygen first aid include not having a device capable of administering 100% oxygen, not having enough oxygen to complete an evacuation of realistic length, and not starting oxygen administration quickly enough (the median delay between symptom onset and first aid oxygen administration in the Longphre study (2) was 4 hours!). Technical divers are less likely to commit these first two errors. An oxygen-clean demand valve is an ideal device for 100% oxygen administration to a conscious diver, and large oxygen supplies are usually carried on technical diving trips. Closed-circuit rebreathers also make ideal oxygen administration devices, and will make a small supply last considerably longer. Air breaks are not usually necessary unless the evacuation is likely to be very long, and guidance should be sought from the receiving physician.

The potential use of heliox as a first aid gas in technical diving is mentioned later.

b. Rehydration

Dehydration is widely cited as a predisposing factor for DCI, and logically, treatment protocols frequently refer to rehydration as an important first-aid strategy. There is more uncertainty about this than is usually reflected in the "popular literature." While it makes sense that dehydration might predispose to the adverse effects of bubble formation, there are only sparse data supporting the idea. In fact, two different animal studies drew opposite conclusions (3, 4). With respect to treating DCI, critical cases exhibiting hypovolemic shock (severely low blood volume) plainly require aggressive intravascular fluid therapy as a life saving measure, but it is much less clear that rehydration makes any difference in DCI of mild or moderate severity.

Despite these caveats, diving physicians usually take the view that attempts to "rehydrate" a diver suffering DCI are far more likely to result in benefit than harm, especially if the fluid can be given intravenously. In the hospital setting, IV fluids would be titrated against pulse, blood pressure and other hemodynamic parameters, the hematocrit, and urine output. In the field, virtually any diver with DCI would safely tolerate 1000ml of a balanced electrolyte solution such as 0.9% saline given rapidly. Glucose-containing solutions should probably be avoided and are less effective as volume replacements. The need for further therapy would be judged according to the patient's condition or administered on the advice of the receiving physician.

Oral fluids should be avoided in a diver with impaired consciousness or who is rapidly deteriorating toward that point. A "full" stomach can be very dangerous in the diver whose consciousness is impaired because it may result in regurgitation and aspiration. There would also be little point in giving oral fluid to a diver who is nauseated or vomiting. Very sick, distressed divers are unlikely to be absorbing much from their gastrointestinal tract, and most likely the fluid will just sit in the stomach. This, and the fact that there are no relevant supportive data, is why oral fluid is designated "controversial" in Figure 1. Despite this, divers who are not distressed, nauseated, deteriorating rapidly, or exhibiting impaired consciousness may receive oral fluids, preferably in small amounts given often. "Gatorade" is close to an ideal oral rehydration fluid (5).

c. Drugs

In the only randomized double-blind trial of any therapy in DCI, Bennett et al. (6) showed that divers given the non-steroidal anti-inflammatory agent tenoxicam required fewer recompressions than divers who received a placebo. The final outcomes in the two groups were the same when the divers were assessed at discharge from hospital and again 30 days later. Many of the divers in this trial had mild DCI in which pain was the prominent symptom, and some critics suggested that the tenoxicam was merely acting as a “pain killer” and thereby “masking” the DCI symptoms. This hardly seems to matter. The tenoxicam-treated divers required fewer treatments (an advantage), but their outcomes were neither better nor worse when assessed at discharge and 30 days later. This result puts some perspective on previous concerns that divers with pain should not be given pain relief for fear that it might mask their symptoms which, in turn, might result in the withholding of the recompression treatment that they need. In our opinion, there is no reason why a diver with pain cannot be given a non-steroidal anti-inflammatory drug for pain relief.

Many other drugs have been recommended over the years as potentially useful in treatment of DCI, but none can be recommended (especially for use as first aid) at this time.

The issue of taking aspirin as both a preventative and a therapeutic agent is frequently raised on Internet forums. Aspirin has theoretic advantages and disadvantages. On the one hand, it inhibits platelets which might react to the presence of bubbles in the blood by initiating or promoting clot formation; on the other hand, this inhibition of platelets might worsen small hemorrhages that appear to be caused by bubbles in the spinal cord. There are no relevant human data that guide decision making.

Lidocaine is used as a local anesthetic agent and to treat certain heart rhythm problems. It protects the brain in animal models of arterial gas embolism, and this benefit has been demonstrated in humans undergoing heart surgery (7, 8). It is occasionally used as an adjunct to recompression of divers suspected of suffering arterial gas embolism (9) but is not recommended as a first aid strategy in the field.

Perfluorocarbon emulsions are low viscosity synthetic blood substitutes in which inert gases are extraordinarily soluble. They may significantly enhance the elimination of inert gases after decompression, and animal studies suggest a significant advantage in DCI (10, 11). These agents are the most exciting prospective therapy on the horizon and are likely to be suitable for intravenous administration as first aid in the field. Unfortunately, progress is slow because there are no preparations currently manufactured and licensed for human use.

d. Positioning

For completeness, the issue of positioning in DCI first aid should be mentioned. The current recommendation is that a DCI victim should rest and be positioned horizontally. The rationale for these recommendations is first, that post-dive exercise may be associated with precipitation or worsening of DCI symptoms (12) and second, that the horizontal position may result in reduced distribution of any arterial bubbles to the cerebral circulation in comparison to an upright or sitting position. In addition, when compared to sitting, a horizontal position has been associated with accelerated washout of nitrogen; probably because of improved tissue blood flow (13).

If consciousness is impaired then the recovery position (on the side) is important, but otherwise, the patient can choose. In situations where an arterial gas embolism is suspected (rapid onset of unconsciousness or other neurological symptoms within a minute or two of surfacing), it is recommended that the victim remains horizontal, irrespective of any spontaneous recovery, until seen at a hyperbaric unit. This is based on anecdotal reports of dramatic and sudden relapses induced by changes in posture, where it is presumed that a bubble lodged somewhere (such as one of the heart chambers) has become free when the victim shifts from horizontal to upright, and has "re-embolised" the brain circulation. In practice, such events seem rare.

3. What is optimal recompression therapy for DCI?

Recompression reduces the volume of bubbles in accordance with Boyle's law. In addition, increasing the pressure of gas in a bubble by compressing it will, depending on the pressure of dissolved gas in the surrounding tissues, reduce or reverse the gradient for further diffusion of gas into the bubble. The breathing of high fractions of oxygen (usually 100% during typical recompressions) enhances diffusion gradients for the transfer of inert gas from the bubble, to tissue, to blood, and to the lungs. In addition, oxygen breathing at elevated pressures will, in theory, help oxygenate sensitive tissues whose blood supply may have been compromised by the presence of bubbles.

There are several recompression therapy parameters that might be varied to optimize efficacy, such as pressure, duration, and inspired gas composition. However, despite much debate over several decades, the question of what constitutes optimal recompression therapy remains unresolved. Not surprisingly, practice is varied across the globe, but it is fair to claim that the protocol most widely used for initial recompression therapy in recreational divers (including technical divers) is the U.S. Navy Treatment Table 6 (see Fig. 2) (14). This treatment involves compression to 2.8 ATA for three oxygen breathing periods of 20 minutes each, followed by decompression to 1.9 ATA for a further two oxygen breathing periods of 60 minutes each, then decompression to 1 ATA. The oxygen breathing periods are interspersed with "air breaks" to reduce the risk of cerebral oxygen toxicity as shown in Fig. 2. Another two oxygen breathing periods or "extensions" can be added at each pressure depending on patient progress. This table was introduced in the 1960s and has remained largely unchanged ever since.

The question most frequently raised in relation to this treatment is whether or not treatment pressures greater than 2.8 ata would provide extra benefit. In fact, for many years it was assumed that under certain circumstances they would. It was believed that a relatively short "deep spike" to 6 ata (patient breathing air) was indicated at the start of these treatments in cases where there was a strong suspicion of arterial gas embolism. Accordingly, the U.S. Navy introduced the Table 6A, which was essentially the same as the Table 6 above but for an initial 30 minute period of air breathing at 6 ata. The putative benefit of this intervention was enhanced reduction in bubble size which would favor the early redistribution of any bubbles blocking blood vessels. This reduction is not as great as might be suggested at first glance on the basis of Boyle's law. For example, whereas compression to 3 ata will reduce bubble <u>volume</u> to 33%, the bubble <u>diameter</u> is still 69% of baseline. The corresponding figures for 7 ata are 14% and 52% respectively (15). Thus, a reduction in bubble size is accrued from exposure to the greater pressure but the gain is not dramatic.

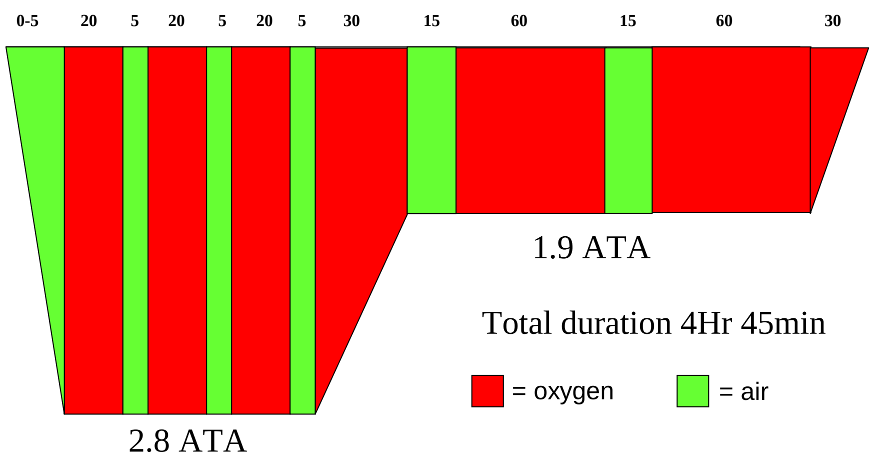


Figure 2. U.S. Navy Table 6.

Over time, the use of initial deep spikes has waned, mainly because the added logistic complications do not appear to be justified by clear evidence of benefit. Indeed, there are data from experimental studies in animals (13) and observational studies in humans (16) which suggest that no benefit accrues from "deeper" treatments. Equally, there are recent observational data from a single Hawaiian centre that suggest good outcomes for deep treatments, but the study does not readily allow for comparisons with outcomes following "conventional" treatments like the U.S. Navy Table 6 (17).

The issue can only be described as "controversial" and "unresolved" particularly in respect of deep technical divers among whom there is a prevalent belief that DCI following a deep bounce dive "automatically" requires recompression to greater pressures than 2.8 ATA. While this is almost certainly not true, most diving physicians will acknowledge the theoretic possibility of benefit from deeper compression in a technical diver who, for example, presents early in a critically ill state after omission of a significant decompression obligation. Perhaps the ideal situation for such a diver is to be treated at a comprehensive facility by an experienced, open-minded diving physician who has the option of trying a deeper compression if the clinical situation justifies it. The latter is an important point because many hyperbaric chambers are not configured to run treatments at greater pressures than 2.8 ata.

Another common question in regard to "optimal recompression" relates to the breathing gas utilized for treatments at greater pressure than 2.8 ata. Beyond this pressure the risk of cerebral oxygen toxicity rises sharply if 100% oxygen is breathed, so an "inert gas" must be substituted. There has been much interest in the use of heliox for treatment of DCI in "air divers", even if the treatment pressure does not exceed 2.8 ata. A review of the related evidence is beyond the scope of this paper, but there are compelling data from animal studies suggesting that breathing heliox may be more efficacious than oxygen in resolving nitrogen bubbles, both in the first-aid setting (1) and during recompression (18). A small non-randomized comparative study in air divers has suggested greater improvement after the first recompression in divers treated with heliox (compared to oxygen) (19). Despite these positive indications, the use of heliox cannot be considered "established," and it is certainly not a standard of care. Indeed, heliox breathing systems add complexity and cost to hyperbaric chambers, and many are therefore not equipped for it. Moreover, recompression with oxygen and / or nitrox has a long history and a high rate of success (20).

The theoretical attraction of both an increase in pressure beyond 2.8 ATA and the use of heliox has led to the relatively frequent use of the so-called Comex 30 table (or local equivalents) for treatment of air divers who present early with serious neurological DCI (see Figure 3 reproduced from Moon and Gorman (21)). Anecdotally, this table has also been a popular alternative to the U.S. Navy Table 6 for treatment of technical divers with serious DCI. It may be a better choice than other "deep" treatment tables involving air breathing. A recent animal study monitored helium bubbles in fatty tissue in rats decompressed from a heliox dive and showed that oxygen or heliox breathing resulted in shrinkage of the bubbles whereas air breathing caused their steady growth (22). It is important not to over-interpret such studies, but this may suggest that recompression of helium divers beyond 2.8 ATA should be performed with heliox rather than air and that helium divers with DCI at the surface should be breathing either oxygen as a first choice, or heliox as a second choice, whilst avoiding air. There are still no human data supporting any particular gas choice or recompression strategy over another for deep technical divers.

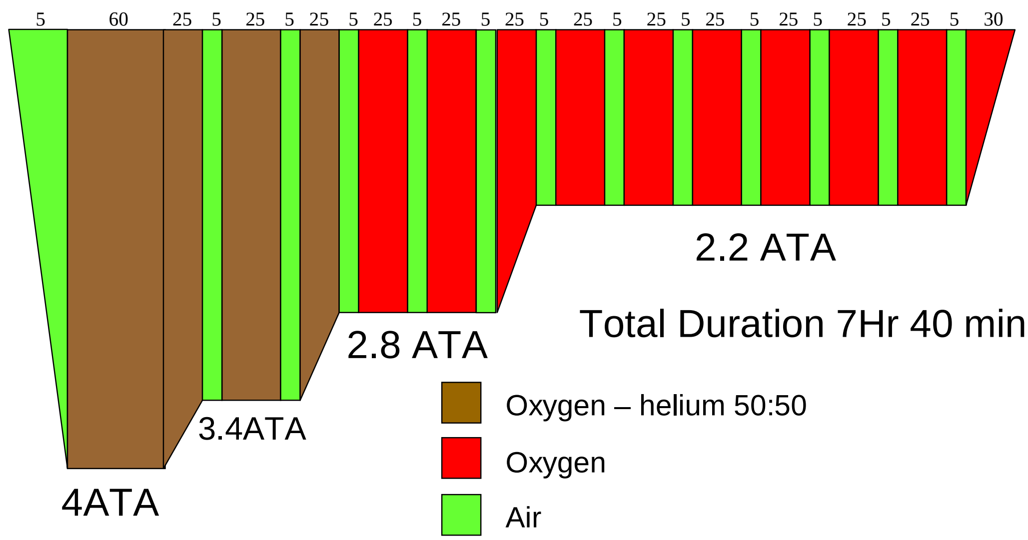


Figure 3. "Comex 30" table.

4. Is recompression always necessary?

The question of whether recompression should be considered an absolute necessity in all cases of DCI has recently been examined, prompted by the modern trend of dive travel and diving in isolated locations. The cost of evacuation of divers from such locations in 1 ata pressurized air ambulances is enormous and the relevance of this issue to technical diving expeditions in remote locations is obvious.

A workshop was convened by the UHMS and DAN in 2004 to review this issue (23). It became clear early in the discussions that there would be ethical problems with prescribing one standard of care for patients who happened to be close to a recompression chamber and another standard for those in isolated places. Consequently, the central question evolved from "which divers in remote locations with symptoms suggestive of DCI might not require recompression?” to “which divers might not require recompression no matter what their location?”

The discussions took place around a series of presentations on relevant issues, such as what is known about the natural history of DCI in the absence of recompression, and what alternative therapies to recompression are available. A full account can be found in the workshop proceedings, but one of the resulting consensus statements is relevant here. It reads:

“The workshop acknowledges that some patients with mild symptoms and signs after diving can be treated adequately without recompression. For those with DCI, recovery may be slower in the absence of recompression.”

This is the first time that a group of experts has concluded that it is reasonable not to recompress some divers suspected of having DCI. It must be pointed out that “mild DCI” is precisely defined in the conference proceedings and that the designation cannot be made unless the patient has been examined by a medical practitioner to exclude subtle but important signs. In addition, while the statement deems it reasonable not to recompress a diver meeting the criteria for mild DCI, it cannot be interpreted as suggesting that these cases <u>should</u> not be recompressed; hence the caveat that symptoms will probably resolve more slowly if the diver is not recompressed. As a practical example, the statement would support a decision to manage a diver with isolated elbow pain after diving with first aid measures only, provided the diver had been medically examined and no other abnormalities found. There are undoubtedly some expedition situations where scenarios like this might arise. Indeed, anecdote would suggest that there are some technical divers who are already making such decisions.

<u>5. Is recompression always the first priority?</u>
Recompression is always a high priority in serious DCI, but it is not always the first priority. We sound this cautionary note because there have been cases in which critically ill divers have been rushed into the nearest chamber irrespective of its staffing and capabilities and have died during the recompression treatment. In very severe DCI, some of the most serious and life-threatening problems that develop are not resolved by recompression *per se*. Such divers may require advanced resuscitation and intensive care prior to and during recompression, to survive. A telling example was recently reported by Trytko and Mitchell (24). The message here is that some thought needs to be given to where critically ill divers should be treated. A very sick diver should not necessarily be taken to the closest recompression facility unless it is staffed and equipped to cope with cases requiring intensive care. The key to avoiding dangerous mismatches between diver status and facility capability is appropriate evaluation by the authority advising the diving

party on treatment and evacuation. Early and accurate communication between those on the scene and an expert authority is therefore essential, and technical divers should always be aware of how to access expert advice (e.g., DAN) from any location where they are operating. Unfortunately, it is likely that as technical diving activity increases, serious DCI cases in which these considerations are important may become more common.

6. In DCI, what is the effect on outcome of a delay to recompression?

This vexing question has troubled diving physicians for decades, and the answer is still uncertain. One point is clear however; it depends a lot on the severity of the disease. Indeed, the findings of the remote DCI workshop discussed above suggest that there are some very mild presentations where a long delay to recompression or even not being recompressed at all is not expected to adversely affect the final outcome.

For severe DCI the situation is almost certainly different, but it has been more difficult than might be expected to demonstrate better outcomes from earlier recompression. There are several reasons for this.

First, the severity of the DCI influences the delay to getting treatment. Simply put, divers with more severe DCI get to hyperbaric units more quickly because they can't ignore or deny the symptoms. The potential bias that this introduces is obvious. Any attempt to examine the effect of delay to recompression without stratifying the cases according to severity could misleadingly suggest that presenting early is associated with a worse outcome, just because all the severe cases present early! In fact, when DAN researchers analyzed outcome data for patients coarsely stratified by severity of disease, they did find a weak benefit for getting recompressed early (25). A potential reason for this benefit not being as significant as might be expected arises from the next point.

Second, virtually all the delays to presentation in recreational diving DCI cases are measured in hours, often many hours. It is entirely possible that we are missing an important effect of delay to recompression because everybody is presenting too late. Put another way, the maximum delay to recompression for being "certain" of a good outcome may be measured in minutes from symptom onset, rather than hours. Thus, there may not be much difference in outcome between recompression after 2 hours or 6 hours, but if it were possible to compare <30 minutes with a 2 hour delay, then there might be a much larger difference. There is some anecdotal evidence to support this contention from military and occupational diving where rapid recompression in on-site recompression chambers means significant progression of early DCI symptoms is unusual.

Perhaps the most dramatic example of this principle comes from the practice of surface decompression on oxygen (SurDO_2) that is employed by many occupational divers. To avoid long decompressions in the water, the divers intentionally omit the majority of their decompression obligation and return to the surface. They are rapidly “undressed,” put in a recompression chamber, and recompressed while breathing oxygen to complete their “decompression” in the chamber. If the diver simply remained on deck after omitting so much decompression they would likely suffer serious DCI. The fact that they don’t in the SurDO_2 procedure is testimony to the efficacy of rapid recompression on oxygen at controlling bubble formation and symptom progression. The analogy to treatment of DCI is perhaps flawed in that these divers don’t (usually) have symptoms at the point of recompression; so it is essentially an “omitted decompression” procedure. Nevertheless, it can be argued that omitted decompression procedures for asymptomatic divers and early recompression at the first sign of DCI symptoms are much the same thing separated slightly on a time continuum.

The high probability of successful treatment if recompression is instituted early forms one of the strongest arguments in favor of in-water recompression as a first aid measure. The rest of this paper will focus on the logistics and arguments for and against this controversial technique.

In-Water Recompression (IWR)

For the purposes of this article, we shall define in-water recompression (IWR) as an attempt to treat symptoms of DCI by returning an affected diver to the water (26, 27). The practice originated among multiple independent groups of commercial sea harvest divers around the world, particularly in Australia and in Hawaii. It has been discussed in several review articles, both in general terms (26, 28-34), and with specific reference to the Technical Diving community (27, 25-38).

The practice of IWR has been generally discouraged, if not outright condemned by the mainstream hyperbaric medical community for many years, and for good reason. The potential complications of returning a DCS-stricken diver to the water are many. These include the risks of absorbing more nitrogen (if using air), acute oxygen toxicity (if using oxygen), an uncontrolled environment, drowning, hypothermia, hampered communication, and hazardous marine life, among others. The only real theoretical advantage of IWR, as alluded to above, is the immediacy with which afflicted divers can be recompressed. This theoretical imbalance notwithstanding, the actual track record of IWR attempts seems to have painted a somewhat different picture.

Data from an observational study by Frank Farm and collaborators suggest a high rate of success for IWR attempts by diving fishermen (32). Other observational data from both from within and outside the technical diving community, suggest a similar trend (27, 38). In response to this apparent success, the technical diving community has been more willing to embrace IWR as a planned immediate response to the onset of decompression sickness symptoms.

Four formal methods of IWR have been published. The oldest is the "Australian Method," which involves a descent to 10 m breathing 100% oxygen, with 30 to 90 minutes spent at that pressure depending on severity of symptoms. This is followed by a slow ascent back to the surface and subsequent periods of surface oxygen (26, 28). The second is known as the "Hawaiian Method." It is similar to the Australian Method, except it includes the addition of a deep "spike" while breathing air, to a depth not to exceed 50 m (32, 35). The third method appears in the U.S. Navy Dive Manual, and is similar to the Australian method except that discrete decompression stops at 3 m and 6 m are used instead of a slow continuous ascent to the surface (31). The fourth method, sometimes referred to as the "Pyle Method." was modified from the Australian and Hawaiian methods for use specifically by technical divers (27), and is reproduced here in an appendix. All of these methods advocate oxygen as the breathing gas for IWR at depths of 10 m or less, and most require or at least strongly recommend use of a full-face mask, a harness or other means to control the diver's depth, and a tender diver to monitor and assist the diver performing IWR. Most or all methods also prescribe follow-up assessment and/or treatment by a qualified physician at an appropriate hyperbaric facility.

There are good reasons why technical diving lends itself to IWR protocols. First, as noted earlier, there is an increased potential need for the practice as dive profiles tend to be relatively extreme and are often performed in very remote locations far from hyperbaric treatment facilities. Second, technical divers are perhaps better prepared to implement IWR procedures, given their routine use of oxygen as a decompression breathing mixture, the usual availability of nitrox for use during a deep spike, and various other factors relating to general technical diving equipment and techniques.

Perhaps the most complicated aspect of IWR concerns the process for deciding whether it should be contemplated and whether the specific circumstances warrant it (Fig. 4). Factors include the availability of gas, availability of equipment, availability of qualified tender(s), the type and severity of symptoms, overall condition of the diver, the likely time to evacuation to the nearest chamber, the weather and sea conditions, the time of day, marine life, the potential for hypothermia, and many others. Faced with such an array of factors, coupled with the inescapable risk of doing harm rather than good, it's not surprising that many people would advocate simply avoiding it altogether.

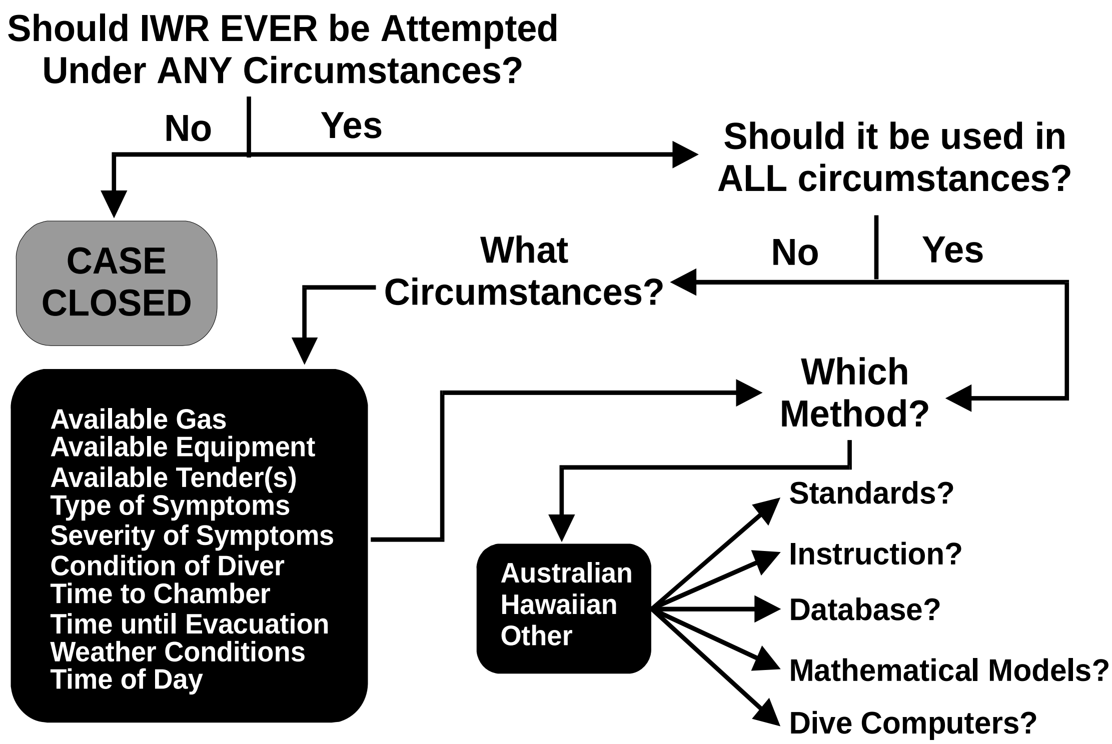


Figure 4. A schema for structured thinking and decision making around the issue of in water recompression.

One again, however, the technical diving milieu lends itself to coping with these issues more readily than typical recreational diving. Technical divers are used to making complex decisions based on multiple factors. They are probably better suited to assess conditions and predict or foresee potential problems, and are more practiced at assimilating complex information and reducing it to a straightforward outcome. Nevertheless, the implications remain non-trivial – in both directions.

Conspicuously missing, and of greatest need, is more robust data concerning attempted IWR and its outcomes. The "data" cited above are based largely on interviews long after the incidents occurred, or cases involving poorly documented circumstances. Though compelling, these cannot be considered much more meaningful than "robust anecdote." Perhaps the most important outcome of this workshop in respect of IWR would be the establishment of a data repository for capturing information about actual IWR cases. This would require participation both from an organization experienced with data gathering, archiving, and analysis, such as DAN, and willingness on the part of technical divers to record specific details concerning their attempts at IWR and share that information no matter what the outcome, and even when subsequent treatment in a chamber is not sought. To this end, all parties can only benefit from the reduction or elimination of the stigma typically associated with the practice of IWR.

Immersion without Recompression?

Many issues involving the practice of in-water recompression remain unresolved. However, one additional point warrants consideration. The effects of immersion on blood distribution may have effects on decompression symptoms and their onset. If so, then there may be room for a new approach to situations that would otherwise suggest IWR: immersion without recompression.

One of the most surprising aspects about many IWR successes is that many cases involve air as the only breathing mixture, and do not follow any set protocol. Indeed, the general success of air-only IWR (39) is difficult to explain in the context of recompression only. Perhaps it was not the recompression in these cases that afforded the benefit; but rather, the benefit may have come simply from immersion, and the consequent effect on redistribution of blood volume. This notion has some support in the experimental literature (40). Compelled by this idea, an emergency DCI plan was developed during a deep-diving cruise aboard the NOAA ship, *Townsend Cromwell* in 2000, involving the use of an onboard live well (41, 42). A 3-meter deep live well was filled with water to serve as an immersion tank in the event of DCI. This system would enable full-body immersion in a controlled environment, while the ship heads towards a shore-based hyperbaric facility. Although a need to invoke this system never occurred, the approach might represent a useful compromise between in-water recompression, and surface oxygen; perhaps yielding the best of both approaches.

References

Hyldergaard O, Moller M, Madsen J. Effect of He-O2, O2, and N2O-O2 breathing on injected bubbles in spinal white matter. Undersea Biomed Res 1991 18:361–71.

Longphre JM, Denoble PJ, Moon RE, Vann RD, Freiberger JJ. First aid normobaric oxygen for the treatment of recreational diving injuries. Undersea Hyperb Med 2007;34:43–9.

Broome JR, Kittel CL, Dick EJ. Failure of pre-dive hydration status to influence neurological DCI rate in pigs. Undersea Hyperb Med 1995;22(supp):35.

Fahlman A, Dromsky DM. Dehydration effects on the risk of severe decompression sickness in a swine model. Aviat Space Environ Med 2006;77:102–6.

Moon RE. Fluid resuscitation, plasma glucose and body temperature control. In: Moon RE (ed). Adjunctive therapies for decompression illness: the proceedings of the fifty third workshop of the Undersea and Hyperbaric Medicine Society. Kensington MD, USA: UHMS; 2003.

Bennett MH, Mitchell SJ, Dominguez A. Adjunctive treatment of decompression illness with a non-steroidal anti-inflammatory drug reduces compression requirement. Undersea Hyperbaric Med. 2003; 30: 195–205.

Mitchell SJ, Pellett O, Gorman DF. Cerebral protection by lidocaine during cardiac operations. Ann Thorac Surg. 1999; 67: 1117–24.

Wang D, Wu X, Li J, Xiao F, Liu X, Meng M. The effect of lidocaine on early postoperative cognitive dysfunction after coronary bypass surgery. Anesth Analg. 2002; 95: 1134–41.

Mitchell SJ, Benson M. Vadlamudi L, Miller P. Arterial gas embolism by helium: an unusual case successfully treated with hyperbaric oxygen and lidocaine. Ann Emerg Med 2000;35:300–3.

Dromsky DM, Spiess BD, Fahlman A. Treatment of decompression sickness in swine with intravenous perfluorocarbon emulsion. Aviat Space Environ Med. 2004; 75: 301–5.

Dainer H, Nelson J, Brass K, Montcalm-Smit E, Mahon R. Short oxygen prebreathing and intravenous perfluorocarbon emulsion reduces morbidity and mortality in a swine saturation model of decompression sickness. J Appl Physiol. 2007; 102: 1099–104.

Francis TJR, Mitchell SJ. Pathophysiology of decompression sickness. In: Brubakk AO, Neuman TS (eds). Bennett and Elliott’s Physiology and Medicine of Diving. Edinburgh 2003, Saunders Publishers: 530-556

Balldin UI. Effects of ambient temperature and body position on nitrogen elimination in man. Aerospace Med 1973;44:365-70

Navy Department. US Navy Diving Manual Revision 4, Volume 5. Washington DC 1999. Naval Sea Systems Command.

Leitch JR, Hallenbeck JM. Pressure in the treatment of spinal cord decompression sickness. Undersea Biomed Res 1985;12:291–305.

Leitch JR, Green RD. Additional pressurization for treating non-responding cases of air decompression sickness. Aviat Space Environ Med 1985;56:1139–43.

Smerz RW, Overlock RK, Nakayama H. Hawaiian deep treatments: efficacy and outcomes 1983-2003. Undersea Hyperb Med. 2005; 32: 363–73.

Hyldegaard O, Kerem D, Melamed Y. Effect of combined recompression and air, oxygen or heliox breathing on air bubbles in rat tissues. J Appl Physiol 2001;90:1639–47.

Shupak A, Melamed Y, Ramon Y, Bentur Y, Abramovich A, Kol S. Helium and oxygen treatment of severe air-diving-induced neurologic decompression sickness. Arch Neurol. 1997; 54: 305–11.

Thalmann ED: Principles of US Navy recompression treatments for decompression sickness. In: Moon RE, Sheffield PJ (eds): Treatment of Decompression Illness. Kensington, MD, Undersea and Hyperbaric Medical Society, 1996, pp 75–95.

Moon RE, Gorman DF. Treatment of the decompression disorders. In: Brubakk AO, Neuman TS (eds). Bennett and Elliott's Physiology and Medicine of Diving. London 2003. Saunders Publishers: 600–650.

Hyldegaard O, Jensen T. Effect of heliox, oxygen and air breathing on helium bubbles after heliox diving. Undersea Hyperb Med 2007;34:107–22.

Mitchell SJ, Doolette DJ, Wachholz C, Vann RD (eds). Management of mild or marginal decompression illness in remote locations – workshop proceedings. Washington DC, USA 2005: Undersea and Hyperbaric Medical Society: 240pp.

Trytko B, Mitchell SJ. Extreme survival: a deep technical diving accident. SPUMS J. 2005; 35: 23–7.

Freiberger JJ, Denoble PJ. Is there evidence for harm from delays to recompression treatment in mild cases of DCI? In: Mitchell SJ, Doolette DJ, Wachholz C, Vann RD (eds). Management of mild or marginal decompression illness in remote locations – workshop proceedings. Washington DC, USA 2005: DAN / Undersea and Hyperbaric Medical Society: 70–89.

Pyle RL, Youngblood D. In-water recompression as an emergency field treatment of decompression illness (Revised). SPUMS J 1997; 27: 154–169.

Pyle RL. Keeping up with the times: application of technical diving practices for in-water recompresssion. In: Kay E, Spencer MP, eds. In-Water Recompression: The 48th Workshop of the Undersea and Hyperbaric Medical Society. Undersea and Hyperbaric Medical Society and Diver's Alert Network 1999; 74–88.

Edmonds C, Lowry C, Pennefather J. Diving and Subaquatic Medicine. 3rd Edition. Butterworth Heinemann, Stoneham, MA 1991; 565 pp.

Knight J. In-water oxygen recompression therapy for decompression sickness. SPUMS J 1984; 14: 32–34.

Sullivan P, Vrana A. Trial of in-water oxygen recompression therapy in Antarctica. SPUMS J 1992; 22: 46–51.

U.S. Navy Diving Manual, Volume 1, revision 1, NAVSEA 0994-LP-001-9010 June 1985.

Farm FP Jr., Hayashi EM, Beckman EL. Diving and decompression sickness treatment practices among Hawaii's diving fishermen. Sea Grant Technical Paper UNIHI-SEAGRANT-TP-86-01. University of Hawaii Sea Grant College Program, Honolulu, HI. 1986.

Knight J. Diver rescue, decompression sickness and its treatment underwater using oxygen. SPUMS J 1987; 17:147–154.

Kay E, Spencer MP, eds. In-Water Recompression: The Forty Eighth Workshop of the Undersea and Hyperbaric Medical Society. Undersea and Hyperbaric Medical Society and Diver's Alert Network 1999; 1–108.

Pyle RL. In-Water Recompression: The Hawaiian Experience. AquaCorps 1993; 5:50.

Edmonds, C. In-Water Oxygen Recompression: A potential field treatment option for technical divers. AquaCorps 1993; 5: 46–49.

Starck, W. In Water Recompression, problem or solution. Golden Dolphin 2001; 1(1):unpaginated electronic media.

Pyle, RL. Insights on Deep Bounce Dive Safety From the Technical Diving Community. Proceedings of the16th Meeting of the United States-Japan Cooperative Programs on Natural Resources (UJNR), 1-3 November 2001, East-West Center, Honolulu, Hawaii. 2002; pp. 47–53.

Pyle RL. In-water recompression (Letter to the Editor). SPUMS J 1997; 27: 143.

Balldin UI, Lundgren CEG. Effects of immersion with the head above water on tissue nitrogen elimination in man. Aerospace Med 1972;43:1101-1108.

Parrish F, Pyle RL. Surface Logistics and Consumables for Open-Circuit and Closed-Circuit Deep Mixed-Gas Diving Operations Proceedings of the MTS/IEEE Oceans 2001 Conference 2001; 3: 1735–1737.

Parrish, FA, Pyle,RL. Field Comparison of Open-Circuit Scuba to Closed-Circuit Rebreathers for Deep Mixed-Gas Diving Operations. Mar. Tech. Soc. J. 2002; 36: 13–22.

Appendix – Pyle IWR Method.

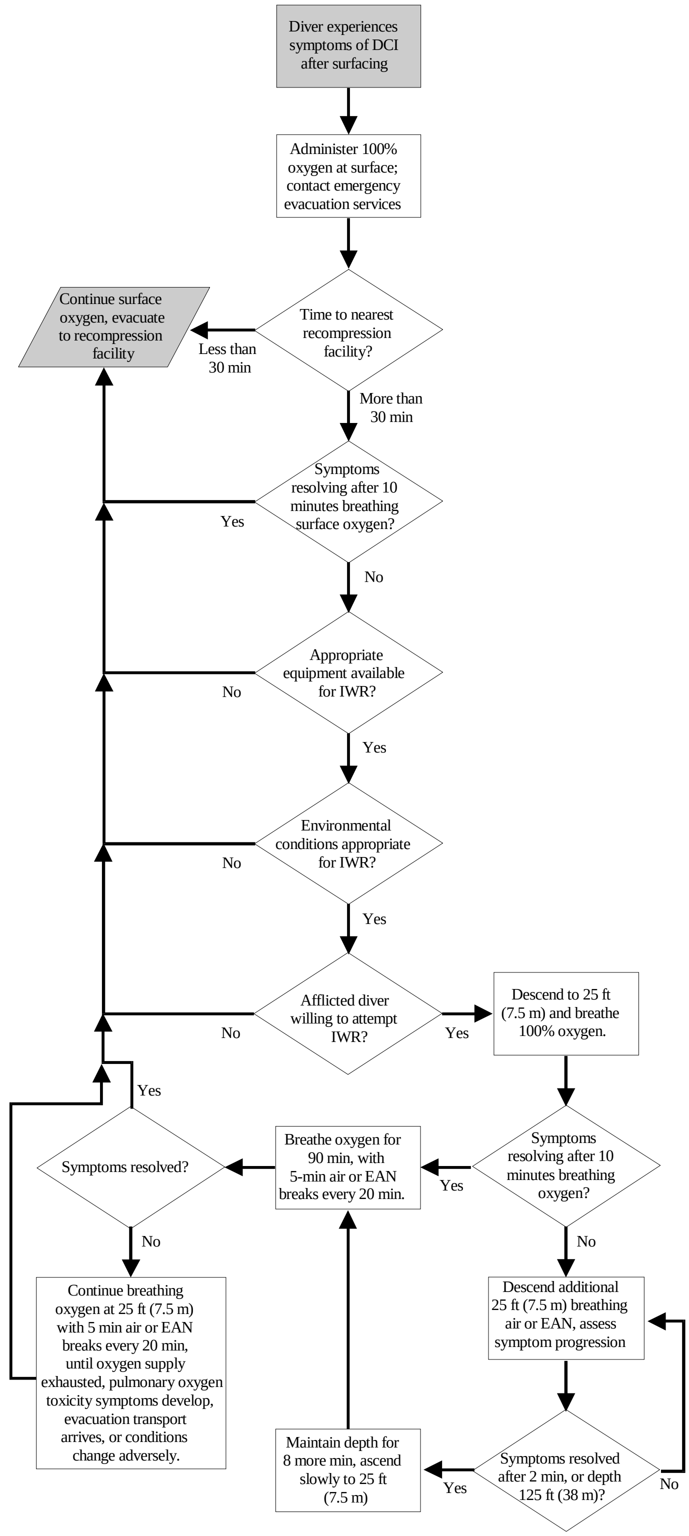
Required Equipment

1. An adequate supply of oxygen that can be delivered to a diver underwater, either in the form of an appropriately serviced scuba cylinder, surface-supplied apparatus, or rebreather device (the latter for appropriately trained divers *only*!)

2. An adequate supply of air, EAN, or other diluted oxygen mixture that can be delivered to a diver underwater, either in the form of an appropriately serviced scuba cylinder, surface-supplied apparatus, or rebreather device (the latter for appropriately trained divers *only*!)

3. Weighted descent or decompression line marked at 10-ft (3-m) intervals, extending to a depth of 130 ft (40 m) or the maximum available depth, whichever is shallower.

4. Some means of communicating basic information between the diver and the surface support.



Recommended Equipment

1. A full facemask or diving helmet to be worn by the afflicted diver.

2. Means to physically attach afflicted diver to decompression line.

Method

Immediately upon recognizing potential symptoms of DCI:

1. Administer 100% oxygen to diver while at surface for 10 minutes, assess the progression of symptoms, and evaluate conditions (time to nearest recompression facility, diver disposition, oxygen supply, availability of tender diver, weather conditions, time of day, etc.), contact emergency evacuation services, and decide whether IWR is warranted.

2. If IWR is warranted and symptoms are not resolving within 10 minutes of commencement of surface oxygen, place afflicted diver at a depth of 25 ft (7.5 m) on weighted decompression line, breathing 100% oxygen for 10 minutes, under close observation of a tender diver who can maintain communication with surface support.

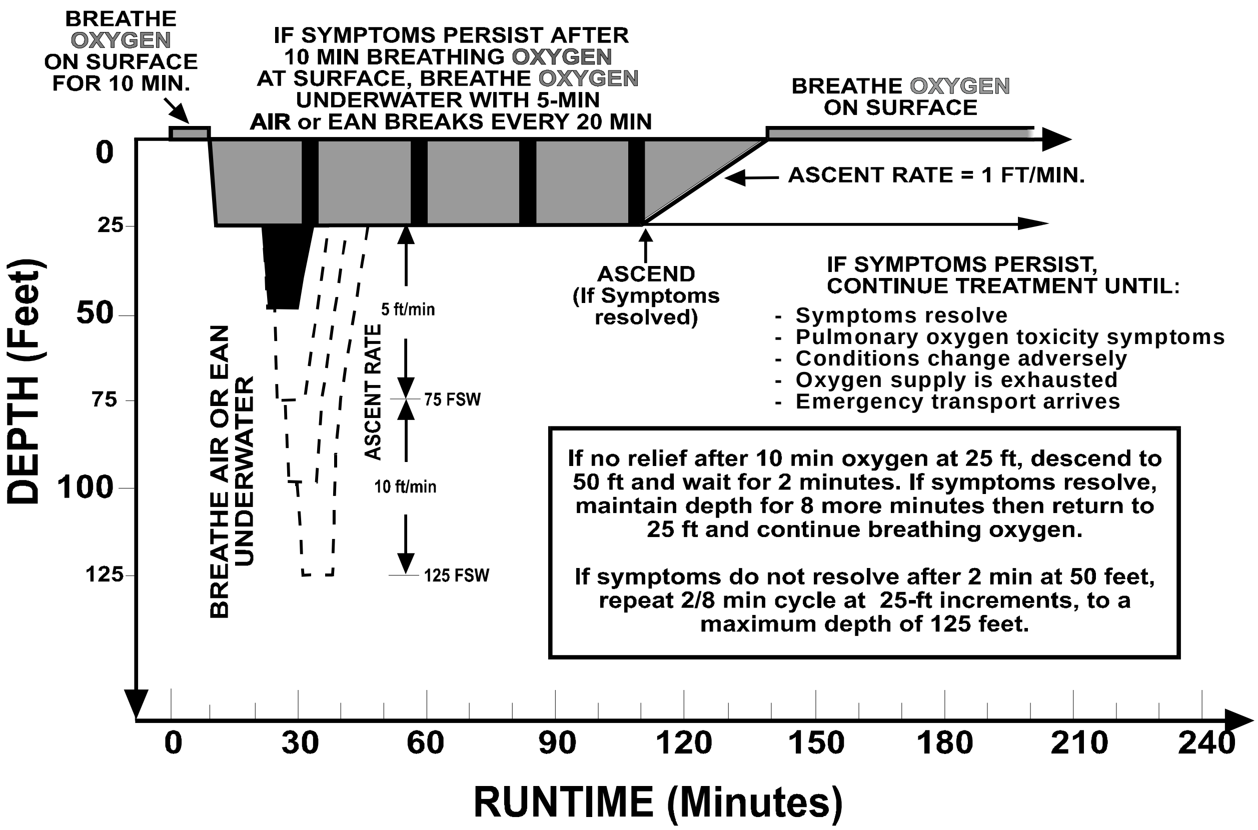
3. If symptoms are resolving after 10 minutes of breathing 100% oxygen at 25 ft (7.5 m), maintain depth and continue breathing oxygen for a period of 90 minutes, interspersed with 5-minute periods breathing air or EAN every 20 minutes.

4. If symptoms persist or continue to progress after the initial 10 minutes at 25 ft (7.5 m), change breathing gas to air or appropriate EAN, descend to a depth of 50 ft (15 m) and assess symptom progression for 2 minutes. If symptoms are resolving, maintain depth for 8 additional minutes, then ascend at a rate of 5 ft/min (1.5 m/min) to 25 ft (7.5 m) and perform step 0.

5. If symptoms persist or continue to progress after 2 minutes at 50 feet, descend to 75 feet and repeat step 0. Continue to repeat step 0 at 25-ft (7.5-m) depth increments until symptoms resolve, or a depth of 125 ft (38 m) is reached. After 10 minutes at maximum "spike" depth return to a depth of 25 ft (7.5 m) at a rate of 10 ft/min (3 m/min) below 75 ft (22.5 m), and 5 ft/min (1.5 m/min) above 75 ft (22.5 m), and perform step 0.

6. After 90 minutes of 100% oxygen with air or EAN breaks, if symptoms have resolved, ascend to surface at a rate of 1 ft/min (0.3 m/min) and continue breathing oxygen at surface until emergency evacuation transport arrives, diver suffers pulmonary oxygen toxicity symptoms, or 3 hours.

7. If symptoms persist or continue to progress after 90 minutes of 100% oxygen with air or EAN breaks, maintain depth and continue 20-min oxygen / 5 min air or EAN cycle until oxygen supply is exhausted, emergency evacuation transport arrives, diver suffers pulmonary oxygen toxicity symptoms, environmental or diver conditions change adversely, or symptoms resolve, then ascend at a rate of 1 ft/min (0.3 m/min).



Discussion

PETAR DENOBLE: Technical divers frequently ask if the depth of a dive on which a diver develops DCS would influence the best recompression depth. Richard, would you comment on the depth of in-water decompression?

RICHARD PYLE: The depth of relief for in-water recompression is generally within six feet of the surface, and by 30 fsw, the symptoms are usually gone in the majority of cases. Only a very few people need to recompress deeper than 30 fsw for relief. The “spike” I mentioned in my talk is the depth of relief plus “X” feet. It is probably best to omit the spike because it introduces additional complexity (such as a gas other than oxygen) with uncertain benefit. Information on in-water recompression can be found at the Rubicon Foundation website (http://rubicon-foundation.org/).

RICHARD MOON: That was a very nice presentation, but I would like to caution the audience that Frank Farm's data is impressive until you read it. Not one of the 500-odd cases was actually observed by someone who knew diving medicine. They were all self-reported. The old case literature from the early part of the 20th Century indicated that the success rate for treatment of bends without recompression approached 90%. This was also self-reported without neurological examination. The guys just wanted to get back to work. Are there any published cases in which a dive physician actually examined the diver before and after in-water recompression to document the clinical improvement?

RICH PYLE: You are correct. Don't believe the Farm data that were from interviews with diving fishermen. These guys have been diving for 40 years and know if they feel better or worse. Their symptoms usually resolve immediately upon hitting the water, not hours later as they often do with the beer approach, which is their alternative treatment. I believe Bob Overlock published some cases (1), but I don't know if he examined the divers before and/or after in-water recompression. Dave Youngblood and I published 10 or 12 cases with very detailed information (2), but I don't believe they were examined by a diving physician on the scene. Even though the divers were not physicians, they seemed to understand the issues well enough that I think warrants more faith in their answers than Frank Farm’s 527 diving fishermen. It's not a clinical study, but it's better than nothing. I don't know quite how you would get the clinical data you want unless Simon got bent trying in-water recompression. Physicians aren’t on-site very often, and I doubt the physician would let the patient get back in the water. I would take the data with a grain of salt but not ignore it completely.

TOM MOUNT: I'm glad we're getting in-water recompression out of the closet. I ran the chamber at the University of Miami from 1968 to 1976. We were the only chamber that treated people in Florida, and we had more than 120 cases. I have also treated about 15 people in the water, 10 with neurological symptoms, including my own wife – twice. I treated a cave diving buddy from Czechoslovakia in 1974 because there was no chamber. We were too dumb to realize that we could have gotten in trouble if it hadn't worked. I've treated myself twice, as Richard has, from my own screw-ups. All had complete recovery. I think in-water recompression is a great capability, but if you're going to do it, you need to have the right equipment on hand. If you use a re-breather, I would stick to a 1.4 atm PO_2. I wouldn't go to 1.6 atm.

SIMON MITCHELL: The remote DCI Workshop Proceedings that I talked about concerning whether everybody needs recompression is available for downloading on the Rubicon Foundation website (http://rubicon-foundation.org/). DAN, who funded that workshop and Gene Hobbs who created Rubicon, made it available as well as many other documents about diving medicine and physiology. Thanks very much, DAN. It's a marvelous contribution to the diving community.

SPEAKER: Rich, your talk on the case for in-water recompression, was very, very good. Where can we get more information?

RICH PYLE: I have a website with my article:
http://www.bishopmuseum.org/research/treks/palautz97/deepstops.html/
If you Google in-water recompression, there's a million conversations on the various discussion lists. I don't think there's any one particular site you can go to get it all. I wish there was a repository for it, hint, hint.

SIMON MITCHELL: The manuscript we produced for this meeting will have some of the information, but Richard is not going to blow his own trumpet so I will. The article he wrote with David Youngblood on his website cited above is one of the best that I've seen. It's well worth reading.

References

1. Overlock, R.K. 1989. DCS case reports involving dive computers. In: M.A. Lang and R.W. Hamilton (Eds.) Proceedings of the American Academy of Underwater Sciences Dive Computer Workshop. USCSG-TR-01-89. American Academy of Underwater Sciences, Costa Mesa, CA, pp. 197-201.

2. Pyle R.L. and D. Youngblood. 1997. In-water recompression as an emergency field treatment of decompression illness (Revised). SPUMS J. 27(3):154-169.

REBREATHER WORKSHOP: CHAIRMAN'S SUMMARY

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This workshop is divided into two parts. The first is presentations on respect of testing standards, giving a Trans-Atlantic comparison, and on the investigation of rebreather incidents. The second is a panel discussion of nine rebreather manufacturers to discuss their views and initiate debate.

Rebreathers have become an essential part of technical diving allowing divers to readily extend both the depth and endurance of their dives; they have also given the diver the enjoyment of, as Cousteau titled his book, "The Silent World." The introduction of rebreather technology has also brought new challenges in ensuring that the apparatus are fit for purpose and provide the diver with life-support for the full duration of the dive. This workshop has considered the transatlantic development of performance goals and standards for diving rebreathers, together with lessons learnt from incidents and manufacturers' experiences.

Dan Warkander outlined the standardized sequence of testing for rebreathers used by the US NEDU, which encompasses both unmanned and manned testing. In support of this he has described the respiratory loads that a diver will experience when using a rebreather, and presented both an historical and contemporary, physiologically based, view of the required performance standards for diving rebreathers; acceptable levels of the respiratory loads for rebreathers were proposed. The conference recognized that carbon dioxide toxicity is a major concern in technical diving and particularly with rebreathers; a technique, by thermally monitoring a rebreather carbon dioxide absorbent canister, was described to provide a 'scrubber gauge' that gives the absorption status of the canister.

Gavin Anthony described the requirement in Europe for Personal Protective Equipment (PPE), including diving breathing apparatus, to be certified as fit for purpose and 'CE' marked. The test techniques used in Europe and in support of the 'CE' marking of rebreathers were described. The principle of using unmanned and manned test techniques and data to identify required performance limits was presented. The current European standard for rebreathers (EN 14143) has over 50 individual tests and associated performance limits. Some of these limits are at variance with physiological principles. An ongoing process of dialogue between interested parties and standard development organizations continues to improve standards and test procedures.

John Clarke compared aircraft incident investigation with that of diving incidents and indicated that in diving, the investigations are often poorly funded and *ad hoc* in nature. He outlined the approach taken by the US NEDU in investigating the equipment from diving incidents. The techniques used, both practical and computer based analysis, were described and graphically illustrated by examples from actual investigations. The requirement, in respect of competency and testing capability, of an investigative body was described. The future of rebreather incident investigations in the US was uncertain as no independent federal agency is likely to be responsible for investigating diving accidents.

A panel discussion, involving nine rebreather manufacturers, addressed many key aspects relating to the design, manufacture and use of rebreathers. The panel responded to pre-prepared and briefed questions; the discussion included comment and discussion from both the panelists and the audience. As may be expected a range of views were tabled on essential elements of rebreather design, semi-closed and closed-circuit systems, bail-out systems, safety assessment and testing. The conference had not planned to achieve any consensus. However, as a result of participation of both the rebreather panel members and the audience, a consensus was achieved with a unanimous vote by all persons in the auditorium.

Consensus Statement[1]

Diving rebreathers should be designed and fitted with an Automatic Diluent Addition Valve (ADV) to maintain a volume of breathable gas within the breathing loop at all phases of a dive.

1 Although the conference had not planned to achieve any consensus, this arose from the discussion within the Rebreather panel and as a result of participation of both the panel members and the audience. The Consensus was as a result of a unanimous vote by all persons in the auditorium.

TESTING DIVERS' UNDERWATER BREATHING APPARATUS: THE U.S. NAVY PERSPECTIVE

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Purpose

The purpose of testing a new or modified underwater breathing apparatus (UBA) is to avoid unsafe equipment at a minimum risk to people. Testing can be done with test divers (manned testing) and with a breathing simulator (unmanned testing). The breathing simulator should breathe the same way a person does in terms of amount of gas breathed (minute ventilation) and its flow profile, it should exhale warm, moist gas and should be able to consume O_2 and produce CO_2.

Testing should be done in standardized ways so that results from different facilities worldwide can be compared to each other and repeated. One advantage of unmanned testing is that it can exceed human capabilities. For instance, tests with a breathing simulator can continue with no concerns for decompression obligations: after such testing, the chamber can be brought to the surface very quickly and another test started. Similarly, tests of whether a scuba regulator will freeze up in very cold water are best done with a breathing simulator. The final determination is, of course, based on manned testing.

Sequence of testing

Tests of UBAs for the U.S. Navy are typically done at the Navy Experimental Diving Unit (NEDU), where they are done in four phases: (1) unmanned, (2) shallow manned, (3) deep manned, and (4) open water diving.

1: Unmanned testing.

Tests can be done in water temperatures ranging from –2 °C (salt water) to more than 40 °C (28 to 104 °F). Depths can exceed 600 msw (2,000 fsw). Commonly, we determine the work of breathing, the O_2 control and the endurance of CO_2 scrubbers.

2: Shallow manned testing.

If a UBA passes the unmanned tests, divers will perform form, fit, and function tests on it in a test pool that is 4.5 msw (15 fsw) deep. Such tests generally include fit of mask or mouthpiece and placement of valves and controls.

3: Deep manned testing in a hyperbaric chamber.
The next phase is to dive the UBA with test divers at depths suitable for the UBA being tested. Commonly, the UBA is monitored during the dives: e.g., by measuring O_2 levels or pressures.

4: Manned diving in open water.
The final phase is to have test divers use the UBA in the open ocean.

Respiratory loads imposed by the UBA
A UBA is certainly a versatile device that allows a diver to stay in a hostile environment for long periods of time. However, this ability does not come for free, in terms of either financial cost or a toll on the diver. As divers well know, it is harder to breathe with a UBA than without one. The questions are how much harder is it, and when is it too hard?

Origin of the respiratory loads
Several respiratory loads are imposed on a diver (Figure 1): breathing resistance, static lung loading (hydrostatic imbalance), and elastance. In addition, CO_2 from the breathing gas or mouthpiece enlarges the effects of the respiratory loads.

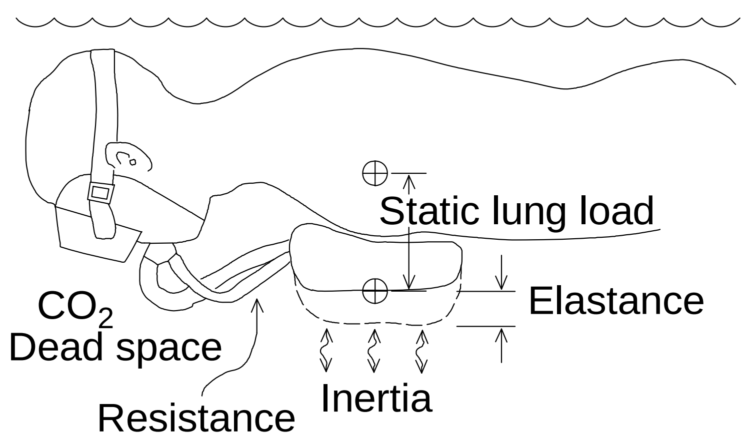

Figure 1. Respiratory loads imposed on a diver using a Rebreather with the breathing bag (counter volume) on the chest. The inertial load is generally small enough to be ignored.

<u>Breathing resistance</u>
The breathing resistance in a UBA is imposed by hoses, narrow passages, and valves and is generally the most intuitive load. The effort required to overcome the breathing resistance generally increases with depth and minute ventilation.

Static lung load

A static lung load (hydrostatic imbalance) is generally one that is hard to understand. It is imposed by the difference in depth between the lung pressure centroid (an imaginary point that can be thought of as the center of the lungs inside the chest) and the breathing bag. Consider a diver standing upright in the water with a scuba regulator (Figure 2). The vertical distance between the regulator and the lung centroid is about 30 cm (12 inches). Since the regulator is at a depth shallower than the lungs, the air inside the lungs is at a pressure lower than that outside the lungs. Therefore, the lungs are subjected to a negative pressure — a so-called a negative static load also called negative hydrostatic load or negative pressure breathing. Such a negative pressure tends to make people breathe at lung volumes lower than they would breathe on dry land. A rebreather diver swimming face down with a rebreathing bag mounted on the back would also experience a negative pressure (Figure 3).

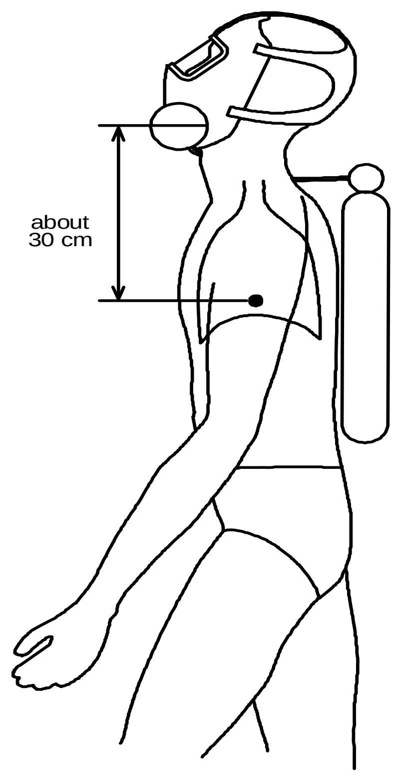

Figure 2. Upright diver with a mouth-held regulator.

The opposite of a negative pressure would, of course, be a positive one. It will be imposed if the scuba diver in Figure 2 were to be head down instead. It will result when a rebreather diver swims face down with a chest-mounted rebreathing bag (Figure 4). A positive pressure will make people breathe at elevated lung volumes.

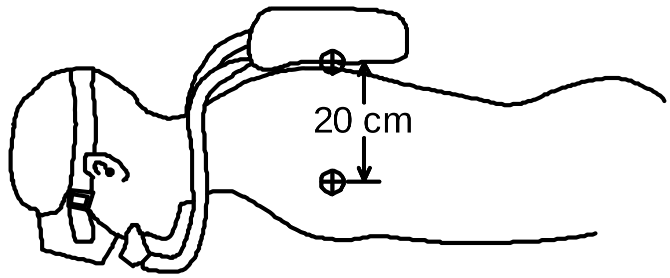

Figure 3. Diver with a back-mounted breathing bag.

To allow breathing, the chest wall and lungs are elastic. The elastance is such that a pressure change of 10 cm H_2O (1 kPa, 10 mbar, 4 in H_2O) will change the lung volume by about one liter. A person's maximum volume change depends on age, height and sex but tends to be in the 3 to 5 L range. Thus, even a pressure change of 1 kPa can change the lung volume significantly. Divers tend to oppose the imposed volume change by muscle activity, which makes the muscles tired.

Anatomical limits

Typically, the minimum distance between the lung centroid and the back is some 20 cm, Figure 3. Therefore, for a rebreather with a back-mounted breathing bag it is hard to have a negative hydrostatic imbalance that is less than 20 cm H_2O (2 kPa).

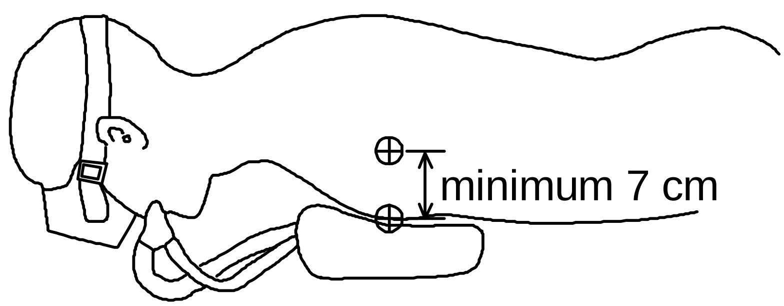

Figure 4. Diver with a chest-mounted breathing bag.

Similarly, the minimum distance between the lung centroid and the front of the chest is some 7 cm in adults. Therefore, a diver who is swimming face down with a front-mounted breathing bag (Figure 4) is likely to a have positive hydrostatic imbalance of some 7 cm H_2O (0.7 kPa).

A solution sometimes used to try to minimize the hydrostatic imbalance is that of over-the-shoulder breathing bags. With the right amount of gas in such bags, the bottom of the bags (which determines their pressure) can be very close to the lung centroid. However, if the breathing bags are also used for buoyancy adjustments, then the hydrostatic imbalance cannot be assured. A diver with over-the-shoulder bags may get surprised: when swimming sideways, he may have the bag volume such that his exhalation fills the upper bag and then has to start filling the lower bag. The diver will then have to generate a relatively large extra pressure just to start breathing on the lower bag.

Another scheme to reduce any hydrostatic imbalance is to have a bellows instead of a bag on a back-mounted bebreather. With extra weights mounted on the bellows to help increase its pressure for a diver who is swimming face down, the negative hydrostatic imbalance will be reduced. If the diver is swimming face up instead, the weights will reduce the pressure and the positive imbalance. For a vertical diver, the weights will not really make a difference.

Elastic loads

The presence of elastic loads is generally not obvious. As a diver exhales into a breathing bag, the bag will get bigger and will be pushed deeper. This increased depth increases the bag pressure. Since the pressure in the bag changes with volume, by definition, an elastic load is present. Is this a workload for the respiratory muscles? Consider a rubber band. As a rubber band is stretched, energy is stored in the band. This energy is released as the band is allowed to resume its original size. Therefore, the net work is zero. That is correct for physical work. However, muscles need to burn energy both when a rubber band is stretched and when it is released: Muscles are forced to work in both ways.

Carbon dioxide

The primary signal for a person's control of breathing is the partial pressure of CO_2. When a muscle works, it consumes O_2 and produces CO_2. Other sources of CO_2 can be the breathing gas (contamination and partly spent scrubber) and the UBA's mask or mouthpiece. All such CO_2 needs to be removed from the body, a removal accomplished by diluting it with fresh air — a process we call breathing.

Effect of inspired CO_2

If CO_2 is present in the inspired gas, it is possible to calculate the extra amount of breathing required to keep the body's CO_2 level at a desired value:

$$V'_E\text{factor} = PCO_2 / (PCO_2 - P_{in}CO_2),$$

where PCO_2 is the CO_2 level in the body and $P_{in}CO_2$ is the partial pressure of CO_2 in the inspired gas. The typical PCO_2 value given for people on dry land is 40 mm Hg (5.3%, 5.3 kPa, 53 mbar). However, studies have shown that divers tend to breathe somewhat less than they do on dry land and that they typically maintain 45 mm Hg (6%, 6 kPa). The outcome of this equation is presented in Figure 5. It shows that for low levels of inspired

CO_2, the increase is fairly small, but the need to breathe increases drastically with elevated levels of CO_2.

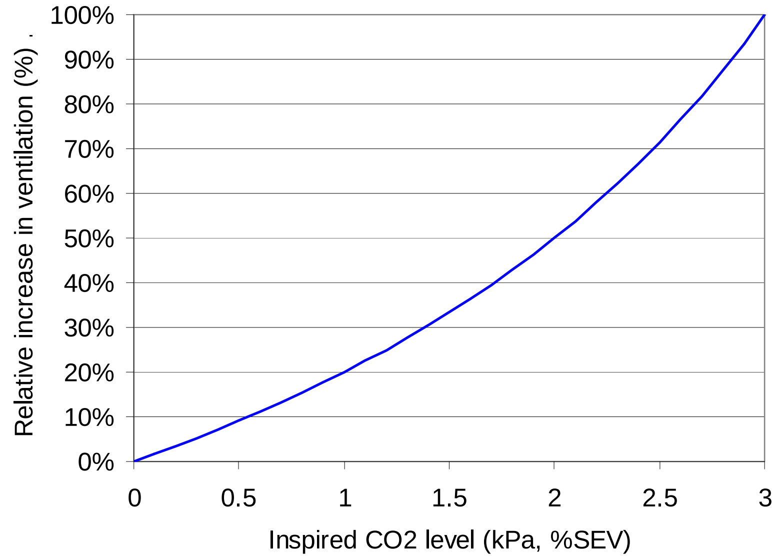

Figure 5. Relative increase in minute ventilation plotted for different levels of inspired CO_2. Calculations are based on a PCO_2 of 6 kPa.

Effect of dead space

The dead space in a mask or mouthpiece traps some of the exhaled, CO_2-rich gas and returns it in a later inhalation. A snorkel is a good example of a dead space. The gas at the end of an exhalation into a snorkel is the first gas that gets inhaled. To get the same amount of fresh air, a diver would have to increase the size of every breath with the size of the dead space. Similarly, mouthpieces, full face masks and helmets have dead spaces. It has been shown empirically (1) that the minute ventilation increases by the factor $1 + 0.58 * V_D$, where V_D is the dead space volume (in liters).

A typical mouthpiece with a dead space of 0.05 to 0.1 L would increase the minute ventilation by 3 to 6%. A full face mask with a well fitting oro-nasal cup may have a dead space of 0.2 to 0.25 L which will raise the minute ventilation by 12 to 14%. A full facemask with a leaky oronasal cup may have a dead space in the range 0.3 to 0.5 L, which would require an increase in minute ventilation of 17 to 29%. A diving helmet may have a dead space that ranges anywhere from 0.3 to 1 L, a dead space that will likely vary according to minute ventilation and depth. Such a helmet may require an increase in minute ventilation of 17 to 58%.

Increases in minute ventilation will use up a scuba diver's gas supply much faster than if no increases were necessary. Such increases are less of a problem for a rebreather diver, where the O_2 replacement is based on actual consumption. However, the life of the scrubber may be decreased, since increased minute ventilation gives the scrubber less time to absorb the CO_2. Independently of what type of UBA is used, any increase in minute ventilation magnifies the effects of other respiratory loads.

Oxygen control

An important parameter for rebreathers is the UBA's ability to maintain oxygen partial pressure (PO_2), which needs to be determined during three phases of a dive: descent, on bottom and during ascent. The deviation from the set point should be determined, for if the actual PO_2 goes too high, the risk of O_2 toxicity increases, and if it goes too low, the decompression obligations will change.

During descent, any O_2 present in the diluent gas gets added to the breathing loop as the breathing bags shrink. This added O_2 raises the PO_2, possibly to dangerous levels. During ascent, the PO_2 decreases as the ambient pressure decreases. So the UBA's ability to add and maintain the desired PO_2 has to be determined.

Unmanned tests of O_2 control can be done without any injection of CO_2 to determine the performance of the O_2 algorithm and to determine how well the O_2 gets mixed. However, tests should also be run with CO_2 injection and CO_2 absorbent present. The chemical reaction produces heat and moisture, and the O_2 sensors tend to be sensitive to both: thus, O_2 control is likely to be affected.

Endurance of the CO_2 scrubber

Tests of the scrubber endurance in a rebreather are best done in unmanned tests, particularly for long-duration UBAs. Typically, such tests are done worldwide at one workload (40 $l \cdot min^{-1}$, 1.6 $l \cdot min^{-1}$ of CO_2) and at one or more water temperatures. The chemical reaction is sensitive to temperature, and, depending on scrubber geometry and insulation, the endurance may vary drastically. A change in temperature from 4 to 30 °C (39 to 86 °F) may double the endurance. The change in the workload can have similar influence on the endurance.

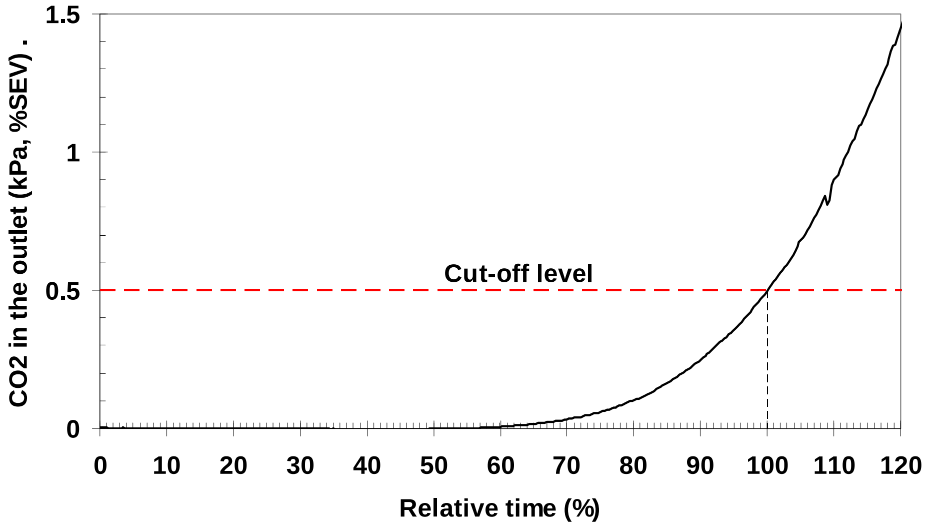

Figure 6. Commonly seen trace of the PCO_2 during an endurance run of a CO_2 scrubber.

Figure 6 illustrates how the CO_2 level in the scrubber outlet commonly varies during a test. The endurance is given as the time when the CO_2 in the gas leaving the scrubber reaches 0.5 kPa (0.5% surface equivalent). This may seem like a low level of CO_2; after all, the minute ventilation has gone up by only about 9%. However, as Figure 6 shows, the CO_2 increases very fast at that point. Figure 6 also shows that going beyond the endurance time by only 10% has doubled the CO_2. Therefore, setting the limit fairly low allows an extra safety margin.

Monitoring the CO_2 scrubber

Ideally, by monitoring the CO_2 scrubber it should be possible to dive longer. After all, the diver has gauges for the gas supplies. The obvious choice of a monitor would be that of a CO_2 sensor in the gas that the diver is about to inhale. However, this type of sensor presents many technical difficulties. The diving environment is harsh: salt water is corrosive, and the gas is humid and of varying temperature. Field calibration may be needed, and power consumption must be considered. Infrared sensors are often used for CO_2 monitoring, but they rely on lenses and/or mirrors. Any condensation or flooding will divert the light. In addition, the infrared absorption of CO_2 changes with depth. All these are design considerations that may be resolved. However, even if a perfect CO_2 can be found, the CO_2 sensing technique will still be limited because no CO_2 can be sensed until 60 to 80% of the absorbent is spent (Figure 6): the gauge will read "0" most of the time. Such a reading, of course, would be good news, but it does not permit any planning: 90% of the absorbent may be left, or only 30%. The diver cannot know.

Another technique that is starting to be used is based on the well-known fact that the absorbent releases heat when it absorbs CO_2. Figure 7 shows the typical changes in temperature. At the start of the test, the absorbent around probe A warms up quickly. The other temperature probes indicate a sequential increase. Fairly quickly, probe A indicates a drop in temperature again: *i.e.* the absorbent is less active. The other probes follow in sequence. This pattern of temperature changes is consistent even at different water temperatures, diver workloads and depths.

What is needed is a technique for turning these temperature changes into a reading that is obvious to, and meaningful for the plans of, the diver.

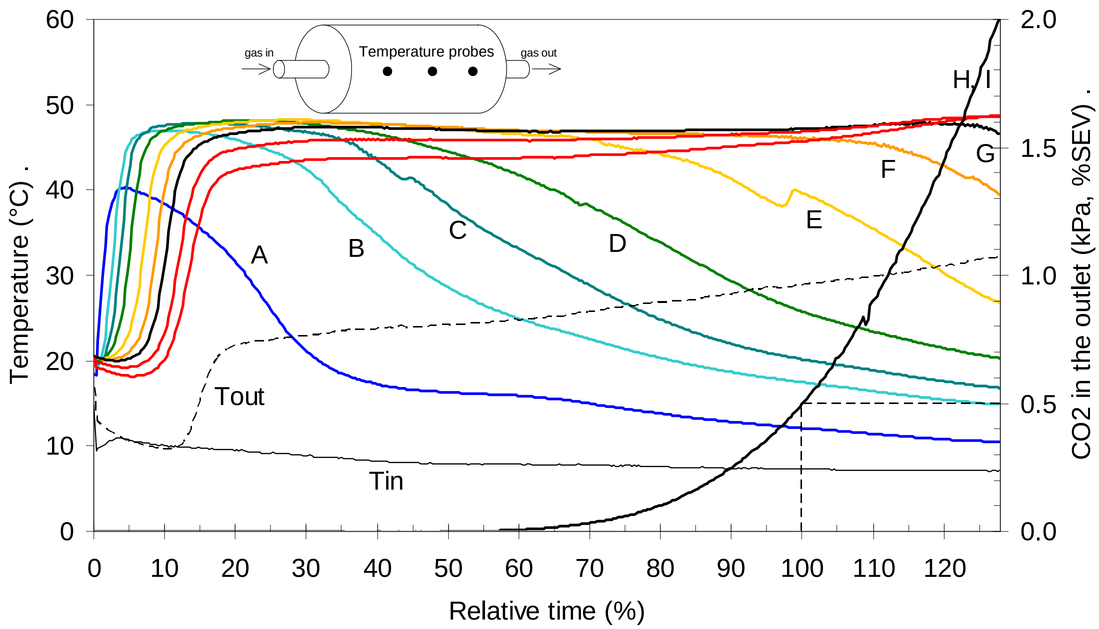

Figure 7. Typical pattern of temperature change inside the absorbent throughout an endurance test. The letters A through I refer to placements of probes inside the absorbent, with A as the probe closest to the gas inlet and I as that closest to the outlet.

To date, two methods for this conversion exist. One is used by AP Diving, Cornwall, UK, in its Inspiration UBA (2). It provides a reading of "scrubber health" throughout the dive. Another method for a scrubber gauge has been developed after more than 1,000 hours of diving at NEDU [3]. With this method, readings presented to the diver are similar to those of a pressure gauge or a car's fuel gauge. A working proof-of-concept unit has been tested both in unmanned tests and with divers. The readings of the scrubber gauge are essentially independent of water temperature, diver work load, depth and previous use (multiple dives are allowed). No field calibrations are needed. The cost for the hardware is about the same as two buckets of CO_2 absorbent. The current version will not detect channeling of the absorbent, but a patent for a simple method is pending.

Acceptable levels of the respiratory loads

Historical background

Breathing resistance was the first respiratory load to which limits were assigned. Two sets of limits have been used worldwide: one is based on findings by Morrison and Reimers (4), and another on findings by Middleton and Thalmann (5). The common approach by both sets of authors was to look at what was commercially available at the end of the 1970s.

Morrison and Reimers set two limits for the external work of breathing: comfort and tolerance. For the comfort limit, the maximum work of breathing (in $J \cdot l^{-1}$) should not exceed $0.5 + 0.02 * V'_E$, and for the tolerance limit it should not exceed $0.5 + 0.04 * V'_E$, where V'_E is the minute ventilation. These authors stated that there were "inadequate physiological data on which to base reliable performance standards for underwater breathing apparatus" and that "suggested standards can only be regarded as an interim measure and subject to change as more appropriate data become available." The tolerance limits (with minor modifications) have become the limits for commercial diving in the North Sea [6] and the European Standards for open circuit diving (7).

In 1981, Middleton and Thalmann set limits that vary according to what type of UBA (*e.g.* open circuit scuba, umbilical supplied rebreather) is used. Their limits were set so that only the best UBAs around 1980 were deemed acceptable, and these limits shaped those for testing by the U.S. Navy (8).

Recently, NATO (9) and the U.S. Navy has decided to adopt limits for breathing resistance and the other respiratory loads based on diver tolerance (10). These new limits are based on experiments with divers exposed to varying levels of these loads, either one load at a time or in combination. Many years and more than 1,000 manned dives have been required to obtain these results (11). In most of these experiments the divers were exercising fairly hard (60% of their maximum O_2 consumption) for 25 minutes.

Breathing resistance

The effort required to move gas from the mouth to the lungs and out again will increase as depth increases. However, the work capability of the respiratory muscles does not change with depth. Therefore, the effort that can be allowed by the UBA has to decrease as depth increases. This means that a UBA that can be used only for shallow diving (*e.g.* an O_2 rebreather) can have a higher breathing resistance (*e.g.* thinner hoses) than one intended for use at great depths. The new limits allow less breathing resistance as depth increases. Levels of breathing resistance are generally calculated as the amount of work required to take a certain sized breath divided by the volume of that breath (WOB/V_T). Strictly speaking, this is the volume-averaged pressure. However, the terms commonly used are "work of breathing" and "resistive effort."

The resistive effort should not exceed:

$WOB/V_T = 2.49 – 0.016 * depth$ (depth in msw, effort in kPa)
$WOB/V_T = 2.49 – 0.00485 * depth$ (depth in fsw, effort in kPa)

<u>Hydrostatic imbalance</u>
The maximum tolerable hydrostatic imbalances, relative to the suprasternal notch, should be in the range +0.4 to +2.9 kPa for a vertical diver and in the range –0.3 to +1.7 kPa for a horizontal diver.

<u>Elastance</u>
The elastance should not exceed 0.7 $kPa \cdot l^{-1}$ independent of depth and ventilation.

<u>Respiratory loads acting together</u>
The total acceptable respiratory load can be calculated by adding the relative value for each load (measured value / maximum allowed):

Total load = %R + %E + %HI,

where %R is the relative resistive load, %E is the relative elastic load and %HI is the relative hydrostatic imbalance.

<u>CO_2</u>
Any CO_2 presented to the diver forces an increased minute ventilation that magnifies the effect of the other respiratory loads imposed by the UBA.

References
1. Warkander DE, Lundgren CEG. Dead space in the breathing apparatus: Interaction with ventilation. Ergonomics, 38(1995):1745–1758.

2. Parker MJ. Carbon dioxide scrubber for breathing apparatus. U.K patent number 2,382,572. Filed 30 Nov 2001. Also a European patent.

3. Warkander D. Temperature-based estimation of remaining absorptive capacity of a gas absorber. U.S. patent number 6,618,687. Assigned to the United States of America as represented by the Secretary of the Navy (Washington, DC). Filing date 16 October 2001. Also patented in Russia and Australia. A European patent is pending.

4. Morrison JB, Reimers SD. Design principles of underwater breathing apparatus. In Bennett PB. and Elliott DH., eds. The physiology and medicine of diving, 3rd edition. San Pedro, CA: Best Publishing Company, 1982. Pp. 55–98.

5. Middleton J, Thalmann ED. Standardized NEDU unmanned UBA test procedures and performance goals, Navy Experimental Diving Unit, NEDU TR 3-81, Jul 1981.

6. Norwegian Technology Standards Institution. Diving respiratory equipment standard, NORSOK, U-101 rev 1. Oslo, Norway. Aug 1999.

7. European Committee for Standardization. Respiratory equipment — open circuit self-contained compressed air diving apparatus, European Standard EN 250:2000, European Committee for Standardization, ISBN 058035713-9, Apr 2000.

8. Navy Experimental Diving Unit. U.S. Navy unmanned test methods and performance goals for underwater breathing apparatus. Navy Experimental Diving Unit, NEDU Tech Man 01-94, Jun 1994.

9. North Atlantic Treaty Organization. Standard unmanned test procedures and acceptance criteria for underwater breathing apparatus, NATO Standardization Agreement (STANAG) 1410, 2nd edition, North Atlantic Treaty Organization, Oct 2005.

10. Warkander DE. Comprehensive performance limits for divers' underwater breathing gear: Consequences of adopting diver-focused limits. Navy Experimental Diving Unit, NEDU TR 07-02, Jan 2007.

11. Warkander DE, and Lundgren CEG. Development of comprehensive performance standards for underwater breathing apparatus. Final report to the United States Navy, Naval Sea Systems Command, Deep Submergence Biomedical Development Program and the Office of Naval Research, 2000.

Discussion

SPEAKER: Dan, you quoted a NATO standard. How did they come about with that? Do we have a lab somewhere or something?

GAVIN ANTHONY: The NATO standard was my responsibility as the lead author, certainly the standard was developed with input from the U.S, Canada and the UK. Dan and I sat down and simplified Dan's work to come up with a NATO standard.

BRUCE PARTRIDGE: Did you come up with any sort of limits for the maximum ventilation under water? Can people ventilate at that rate under water, and did you come up with any maximum consumptions under water? How much oxygen is the most you'd ever need to add to maintain oxygen in the Rebreather?

DAN WARKANDER: The first question is this: How hard can you breathe under water. We had one of our subjects at 57 meters; he did maintain more than 70 liters a minute throughout the 25 minute period, and he was always in good shape. But 70 liters a minute is probably more than most people can do, but testing and decision making is at 62 and a half. So 70 sounds like a lot, but it can be done even at such a great density. As for oxygen consumption, when you build a rebreather, yes, you consume a lot of oxygen, but probably the limit for the valve is probably more how can you keep up with workload, and making sure that the O_2 is maintained high enough when you ascend.

BRUCE PARTRIDGE: It's very easy to calculate how much you need to add when you're ascending. I'm looking for the human part of that calculation.

DAN WARKANDER: If you do breathe 70 liters a minute, you would consume 3 liters a minute of O_2. So, three, four liters is probably enough, plus whatever you need to maintain the O_2.

PAUL HAYNES: Going back to the NATO standard, is there a higher work of breathing resistance allowed for combat divers?

DAN WARKANDER: It's all the same. Combat divers can probably sustain it for longer, but it's not any different.

GAVIN ANTHONY: Just to clarify, the NATO standard has two depth limits, 20 meters and deeper than that, but it doesn't identify the particular swimmer types.

PETER READEY: We took out a patent and received a patent for a similar temperature stick with Michael Cochran in '96 and '97. The reason we didn't use it in our current system is because we couldn't get it to work effectively with our radial flow canister. Have you actually done work on a radial flow design?

DAN WARKANDER: No, I have not done that. But I can't see a reason why it wouldn't work in general. It depends on where you put the sensors, I think. You probably don't have any data to show me right now.

PETER READEY: If you get that solved, I'd like to know.

DIVING REBREATHING APPARATUS TESTING AND STANDARDS UK/EU PERSPECTIVE

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European standards
For diving and other Personal Protective Equipment (PPE) to be sold within the European Union (EU) it has to be of an acceptable performance, and certified as fit for purpose: certified PPE is marked with a 'CE'. Increasingly, diving equipment being sold worldwide has the CE mark, which should also identify the standard it complies with and the Notified Body that certified the equipment (Figure 1).

Figure 1. First stage diving regulator showing CE marking.

Prior to the formation of the EU, diving equipment performance tests in the United Kingdom (UK), and for many European countries, were based on those agreed the between the U.S. Navy (USN) and the Royal Navy (RN) (1). The required performance of the equipment was then generally accepted as that identified in the Norwegian Petroleum Directorate (NPD)/UK Department of Energy (DEn) guidelines (2,3).

In 1989, the EU issued the PPE Directive 89/686/EEC, which over the next decade was amended by 93/95/EEC, 93/68/EEC, 96/58/EC and 98/37/EC. The outcome of the PPE directive, and the subsequent amendments, was to bring some clarity and classification to the requirements and performance of diving PPE. The generic requirements of diving PPE are to:

- Protect the diver from hazards of extreme environment
  e.g. Protect from drowning, temperature and provide ability to work
- Control and protect against inherent hazards with PPE
  e.g. With rebreathers protect against hypoxia, hyperoxia and hypercapnia
- Reduce hazards to So Far As Is Reasonably practical (SFAIR)
  e.g. Cost-effective in terms of providing PPE against cost of testing and certification.

In order to achieve this, PPE is classified at different levels according to the protection it is required to provide (Table 1) and the certification is based on either a 'Technical File' or by complying with a harmonised European Standard (EN – European Norm). In either case, a comprehensive series of tests need to be undertaken. The most pertinent PPE standards for diving equipment are open-circuit demand regulators EN 250 (4), nitrox regulators EN 13949 (5), buoyancy compensators EN 1809 (6) and diving bebreathers EN 14143 (7).

Table 1. Categories of EU PPE

PPE Category	CE marking requirement	Example diving equipment
0	Excluded as PPE. Does not require marking	Equipment for security, police or military applications
I	Self-certified CE marking by manufacturer	Diving facemasks
II	CE marking by Notified Body. Type testing only	Diving suits
III	CE marking by Notified Body. Type testing and product quality control	Diving breathing apparatus – *e.g.* Rebreathers

The testing covers a range of requirements from general configuration and safety systems (*e.g.* gauges, warnings, electrical systems and the requirement for a Failure Mode Effect and Criticality Analysis (FMECA)), mechanical safety and performance (*e.g.* hose bend radii and burst pressures, pressure connections, mechanical integrity and resistance to environmental conditions), marking and instructions and, most importantly, life-support function (*e.g.* gas supply gas concentrations and breathing performance). The rebreather standard EN 14143 (7) has over 50 separate tests. The intention in this text is to present some of the background and requirements for the physiologically significant tests, including those for breathing performance, hydrostatic imbalance, inspired partial pressure of oxygen (PO_2) and the apparatus endurance as limited by a carbon dioxide absorbent canister.

Unmanned and manned testing

Testing of diving rebreathers has for many years been extensively undertaken by some of the major world navies, including the USN and the UK RN. The RN use a progressive series of tests starting with unmanned testing using a breathing simulator, proceeding through manned ergonomic tests in a benign environment, controlled manned tests in a compression chamber to final evaluation in open water in an operational scenario.

Unmanned testing is the essential first step in the process allowing any hazardous shortfalls in apparatus performance to be identified, and if need be rectified, before a manned dive is undertaken. Most comprehensive breathing simulators, such as the QinetiQ Life Support Systems Laboratory (LSSL) (Figure 2), have the ability to test the apparatus immersed, at a range of water temperatures, and in a range of different diver attitudes, typically simulating being horizontal or vertical in the water column, whilst the equipment is breathed at known simulated ventilation rates. The simulator is also capable of heating and humidifying the breathing gas, adding carbon dioxide and removing oxygen. This simulates a diver's exhaled gas and metabolic consumption of oxygen and production of carbon dioxide. The breathing simulator, by design, creates a sinusoidal flow for the respiratory gas and a standard set of test parameters have been identified (Table 2) (3,4,7,8).

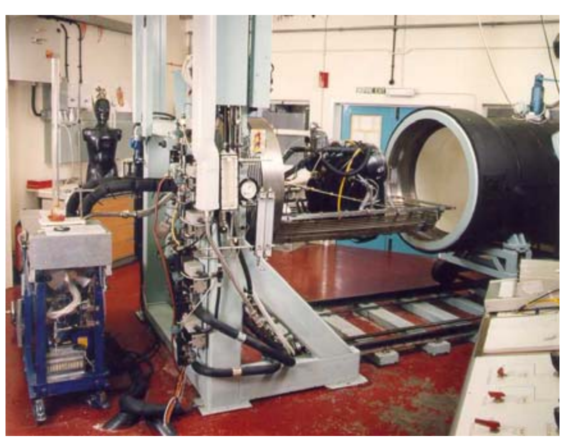


Figure 2. QinetiQ Life Support Systems Laboratory (LSSL).

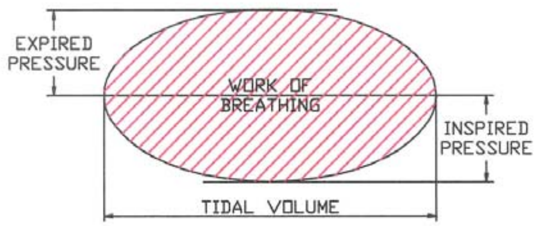
Unmanned testing for breathing performance (*i.e.* work of breathing (WOB) and respiratory pressures) is usually undertaken immersed, in water temperatures from 4 ºC for cold water (to identify any risk of apparatus freezing) to 30 ºC for warm water; with depth increments of 10 m to the expected maximum depth and with the ventilation conditions specified in Table 2.

Table 2. Standard breathing simulator ventilation criteria (8).

Tidal volume ATP litre (l)	Respiratory frequency min^{-1}	Ventilation rate ATP $l\cdot min^{-1}$	Carbon dioxide injection rate STPD $l\cdot min^{-1}$	Oxygen Consumption STPD $l\cdot min^{-1}$
1.0	10	10.0	0.40	0.44
1.5	15	22.5	0.90	1.00
2.0	20	40.0	1.60	1.78
2.5	25	62.5	2.50	2.78
3.0	25	75.0	3.00	3.33
3.0	30	90.0	3.60	4.00

STPD – Standard Temperature and Pressure Dry, 0 ºC and 1013 mbar
ATP – Actual Temperature and Pressure

By monitoring the stroke (*i.e.* tidal volume) of the breathing simulator, and plotting this against the respiratory pressure recorded within the mouthpiece or face piece of the apparatus, a pressure-volume loop (also known as a PV loop) may be created. From the pressure-volume loop, the WOB may be calculated from the area of the loop and the maximum expiratory and inspiratory pressures identified. The characteristics of the pressure-volume loop from open-circuit demand apparatus and re-breathing apparatus are different (Figure 3); loops obtained from re-breathing apparatus slope with a greater respiratory pressure at the start of inhale to that at the start of exhale. The pressure difference between the start of inhale and exhale provides a measure of the compliance and elastance of the breathing circuit.



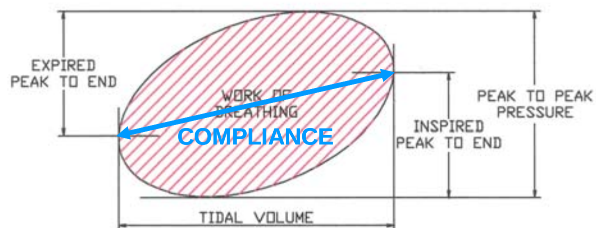


Figure 3a. Open-circuit equipment WOB and respiratory pressures.

Figure 3b. Re-breathing equipment WOB, respiratory pressures and compliance.

When unmanned testing rebreathing apparatus, an added complication arises in that the volume of breathing gas in the breathing loop (*i.e.* degree of inflation of the counterlung) changes the characteristics of the pressure-volume loop and thereby the monitored performance. Currently, for testing to EN 14143, breathing performance is taken when the breathing loop contains an optimal volume of gas. Additional performance data may be gained by analysis of under- and over-inflated loops, and compliance, work is under way to consider the implications of this and for inclusion in future performance standards.

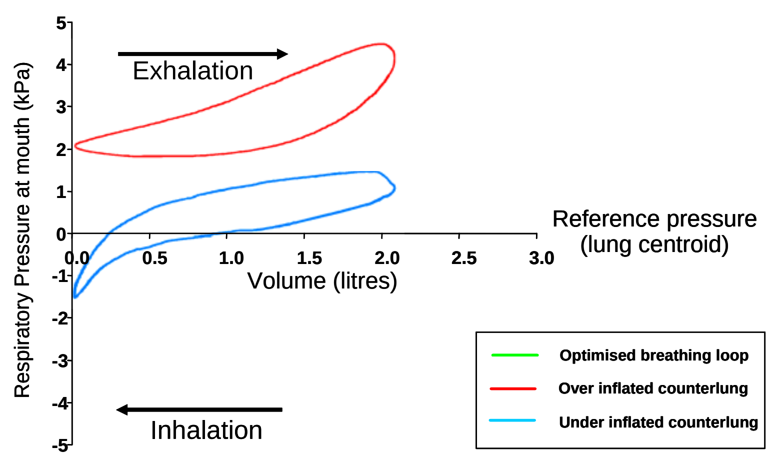


Figure 4. Variation in re-breathing (counterlung) equipment pressure-volume loop with degree of inflation of the counterlung.

Although unmanned testing is a vital first stage for determining equipment performance, controlled manned tests provide a more definitive and relevant measure of an equipment's performance. To conduct controlled manned tests a diver, wearing the equipment under test performs a graded exercise regimen within a wet compartment of a compression chamber, allowing the test to be conducted at depth. This has been achieved in the UK by the diver pedaling on an underwater ergometer where the work rate may be incrementally increased. Standard test protocols (9) require the diver, in both a horizontal (*i.e.* swimming) and vertical (*i.e.* ascending through water) orientation, to undertake three, four minute, work periods at nominal ergometer work rates of either 80, 100 and 125 W or 75, 100 and 150 W, with two minutes rest between each exercise period. The maximum work rate is such as to require the diver to ventilate in the order of 75 $l \cdot min^{-1}$. The diver's heart rate, respiratory pressure, inspired and expired gas composition and ventilation rate are monitored continuously during the test. To enable the diver's ventilation rate, tidal volume and respiratory frequency to be monitored breath-by-breath, QinetiQ uses Respiratory Inductive Plethysmography (RIP), which requires two inductive bands to be placed around the diver's torso, one around the thorax and the other around the abdomen (10). This is non-invasive to the combined diver and rebreather breathing circuit, and provides the ability to create manned pressure-volume loops directly comparable to those obtained, unmanned, using a breathing simulator. In addition to the objective monitoring, to identify if the diver has experienced any dyspnoea, a perceived exertion questionnaire is completed during each of the two minute rest periods and at the and of the graded exercise test. During these tests, a diver will either stop exercising voluntarily, *e.g.* due to dyspnoea, or be instructed to stop if the expired end tidal carbon dioxide ($P_{ET}CO_2$) exceeds 8.5 kPa for five breaths. $P_{ET}CO_2$ is a direct indicator of arterial carbon dioxide level; 8.5 kPa is considered as a point beyond which the diver is retaining carbon dioxide rather than excreting by ventilation and is hypercapnic (11).

Using a combination of unmanned and controlled manned testing provides a means of identifying, within the concept of the PPE directive, if diving equipment is fit for purpose and under what conditions it may be used. It also allows unmanned performance criteria to be identified and included in standards, such as EN 14143 or NATO STANAG 1410 (8). Examining the performance of two anonymous breathing apparatus (apparatus A and B) provides a pragmatic example of this.

Unmanned work of breathing data for the two apparatus obtained at a simulated depth of 40 m are presented in Figures 5a and 5b. It is clear that apparatus A complies with the maximum limit of the NPD/DEn guidelines, just complies with the requirement of EN 14143, and falls short of the requirements of NATO STANAG 1410 and the NPD/DEn preferred guideline. Whereas, at a depth of 40 m, apparatus B fulfils the requirements of all three standards.

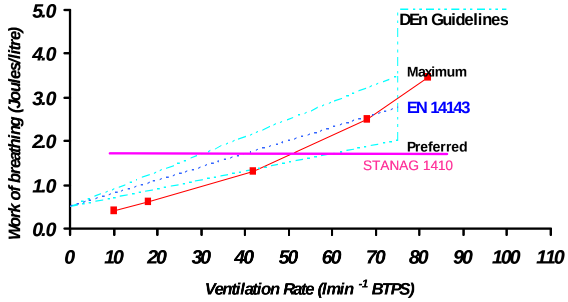


Figure 5a. Nominal apparatus A Unmanned WOB.

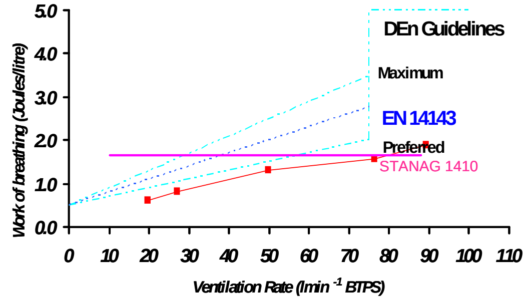


Figure 5b. Nominal apparatus B Unmanned WOB.

Controlled manned testing of apparatus A resulted in the $P_{ET}CO_2$ exceeding the 8.5 kPa termination criterion at the higher work loads (*i.e.* 100 and 125 W) and thus ventilation rates (Figure 6). Under the conditions of test, the equipment performance may be considered as limiting a diver's ability to safely undertake hard work and is thus not fit for purpose. Comparable testing of apparatus B (Figure 7) shows that under all work loads, both horizontal (H) and vertical (V), the $P_{ET}CO_2$ remained less than the 8.5 kPa termination criterion and reached a nominal level of 7 kPa. Thus apparatus B is not workload limited and may be considered fit for purpose.

When the manned WOB data for apparatus A and B (Figures 8a and 8b), obtained during the same tests as presented in Figures 6 and 7, are compared to the unmanned WOB (Figures 5a and 5b) it becomes clear that there are close similarities. Where both the unmanned and manned WOB exceeds some recognized standards, manned trials have also shown that high $P_{ET}CO_2$ values are recorded, indicating that the apparatus may not be considered as physiologically acceptable or fit for purpose. Conversely, where the WOB falls within the requirements of performance standards, manned trials have shown that the apparatus is physiologically acceptable and fit for purpose. By employing procedures such as described here, standards such as EN 14143 and STANAG 1410 have been developed and are being continuously improved. It also demonstrates that with appropriate unmanned testing and standards, equipment may be developed that should be meet the requirements of the PPE directive and on a physiological basis be fit for purpose.

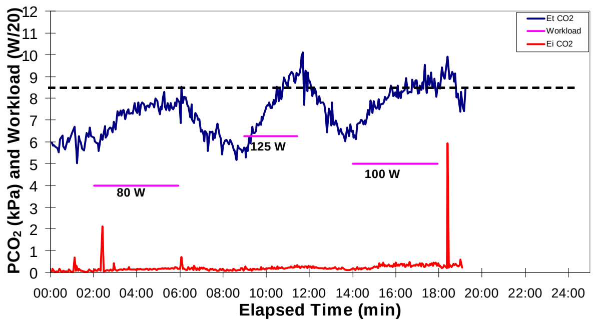


Figure 6. $P_{ET}CO_2$ limiting with work load - nominal apparatus A.

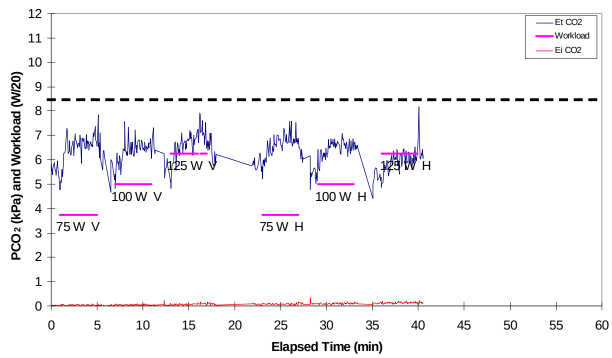
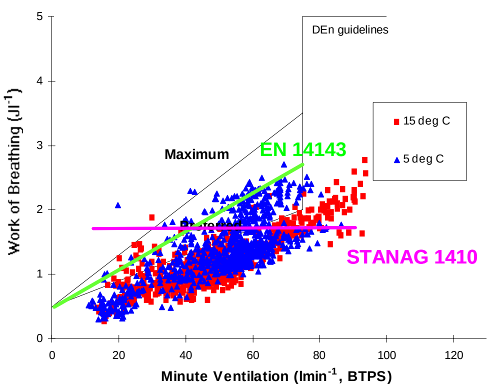


Figure 7. $P_{ET}CO_2$ not limiting with work load – nominal apparatus B.



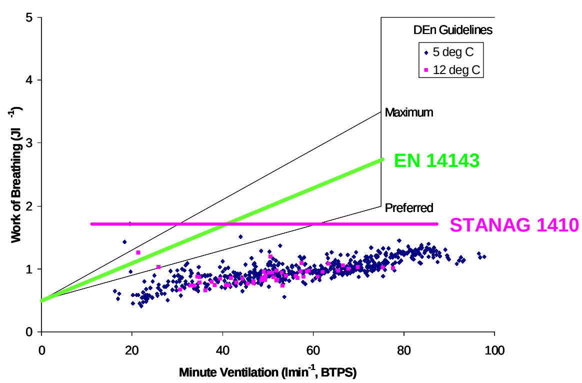


Figure 8a. Nominal apparatus A manned WOB. **Figure 8b. Nominal apparatus B manned WOB.**

The problems of breathing gas at hyperbaric pressures are well known with respect to oxygen toxicity and narcosis. It is also recognized with rebreathing apparatus that hypoxia and particularly hypercapnia are also of concern (12). As breathing gas density and equipment WOB increase, a diver will subconsciously reduce ventilation rate and allow arterial carbon dioxide to levels increase, as illustrated in the manned performance tests described earlier; this is known as carbon dioxide retention and varies from individual to individual. It also causes debate as to what is an acceptable gas density, and hence maximum diving depth for a given gas mixture to avoid carbon dioxide retention and the risk of hypercapnia. Recent manned trials on a closed-circuit rebreather (13) using the same diver subjects provided breath-by-breath $P_{ET}CO_2$ data when breathing nitrox at 30 and 40 m and heliox at 60 m with a 1.3 bar inspired partial pressure of oxygen (PO_2) (Figure 9); it should be noted that dives were terminated when $P_{ET}CO_2$ values exceeded 8.5 kPa.

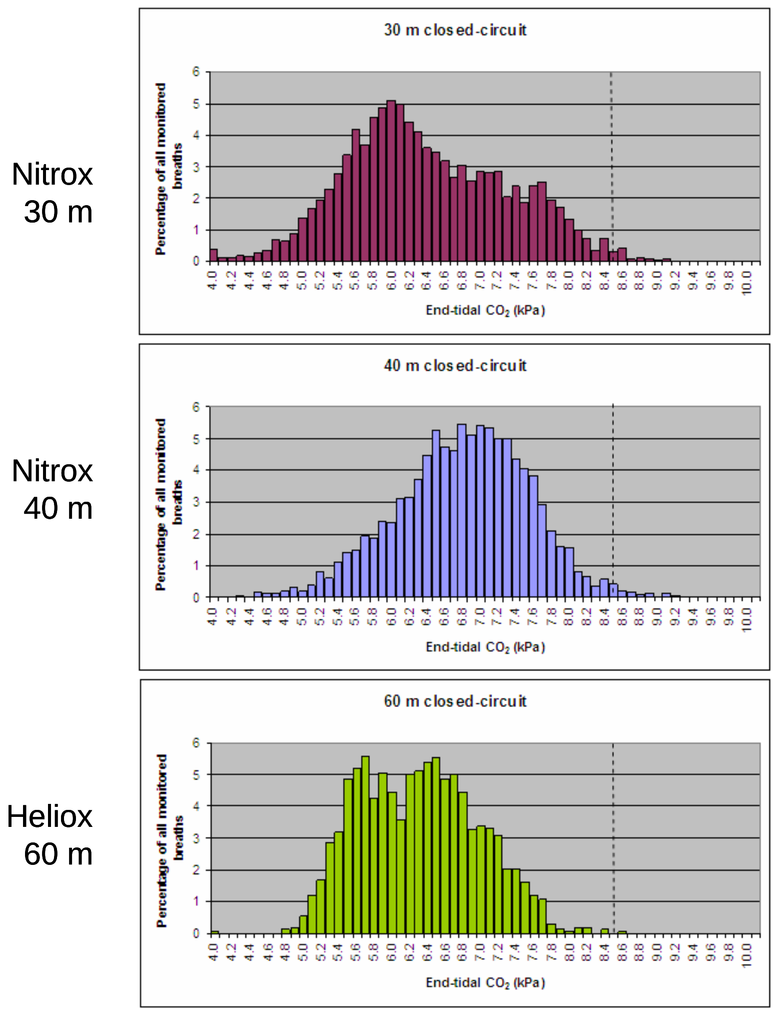


Figure 9. Distribution of individual breath $P_{ET}CO_2$ values with nitrox and heliox (13).

When breathing nitrox, a clear shift occurs in the $P_{ET}CO_2$ modal peak from 6.0 to 7.0 kPa with an increase in depth from 30 to 40 m. When breathing heliox at 60 m, the $P_{ET}CO_2$ distribution is reduced with bimodal peaks at 5.7 and 6.5 kPa. This and similar studies (13,14) have resulted in the maximum depth for using nitrox in rebreathers to be limited to

40 m in EN 14143. To increase operational performance and safety, the RN now limit diving with nitrox in rebreathers to 30 m. The reduction in gas density with heliox allows greater depths to be safely achieved. The maximum depth with trimix gas mixtures will be greater than 40 m and depend on the relative density of the mixture when compared to nitrox.

Hydrostatic imbalance

Breathing performance in respect of WOB and respiratory pressures is not the only factor of design and performance that may affect a diver's ability to undertake sustained work. Hydrostatic imbalance, the difference in pressure between the gas located in the counterlung and the diver's physiological lung centroid pressure (also known as static lung load), will also affect a diver's performance; an ideal hydrostatic imbalance would be a positive pressure of 1 kPa (15).

Hydrostatic imbalance depends on the equipment design, volume of gas in the breathing circuit and the diver's attitude in the water. Unmanned tests for hydrostatic imbalance (7) may be conducted by using a breathing simulator connected to a rotating mannequin. Although lung centroid is the correct physiological reference point, tests are much easier to conduct referencing respiratory pressure to the pressure at the suprasternal notch. The data may then be referenced to lung centroid by simple trigonometry. Once the test is started, the apparatus is breathed at a ventilation rate of 62.5 $l \cdot min^{-1}$ and rotated through pitch or roll angles (8) without adding, or removing gas, from the breathing circuit: the hydrostatic imbalance is taken as the pressure difference between the reference point (*e.g.* suprasternal notch) and the respiratory pressure at the end of exhalation no-flow point (1,8,16).

The affect of diving rebreather configuration on hydrostatic imbalance and with diver pitch and roll is presented in Figure 10 (17). It is clear that simple front and back-mounted counterlung systems may cause extremes of hydrostatic imbalance as a diver changes orientation in the water. Equipment designs incorporating over the shoulder (OTS) counterlung systems have the potential to reduce hydrostatic imbalance, and the changes thereof that occur when a diver moves to a different orientation in the water. Rebreather manufacturers have also used a range of design configurations, such as balance weights, to reduce the effect of counterlung position on hydrostatic imbalance.

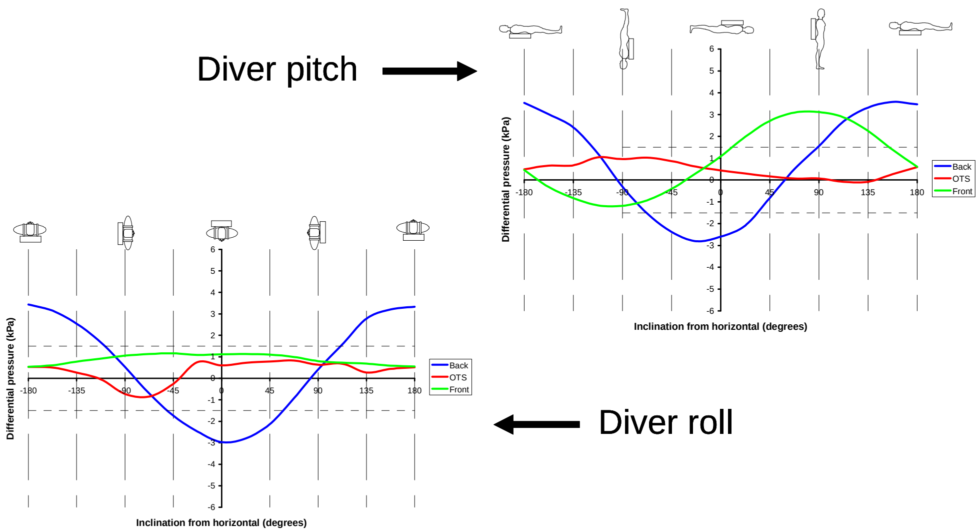


Figure 10. Hydrostatic imbalance of closed-circuit Rebreather designs.

Solving the problem of hydrostatic imbalance in closed-circuit Rebreathers may also introduce additional problems, particularly with split OTS counterlung systems with inlet and exhaust valves in separate counterlungs. A pressure difference between these valves may cause a free-flow of gas through the breathing loop releasing large volumes of gas compromising endurance and thus safety. Figure 11 illustrates a system that complies with the current requirements of EN 14143, but releases large volumes of gas as a diver rotates to the right (+ve roll). As more data become available, standards will be improved to reduce the hydrostatic imbalance and the risk of gas loss.

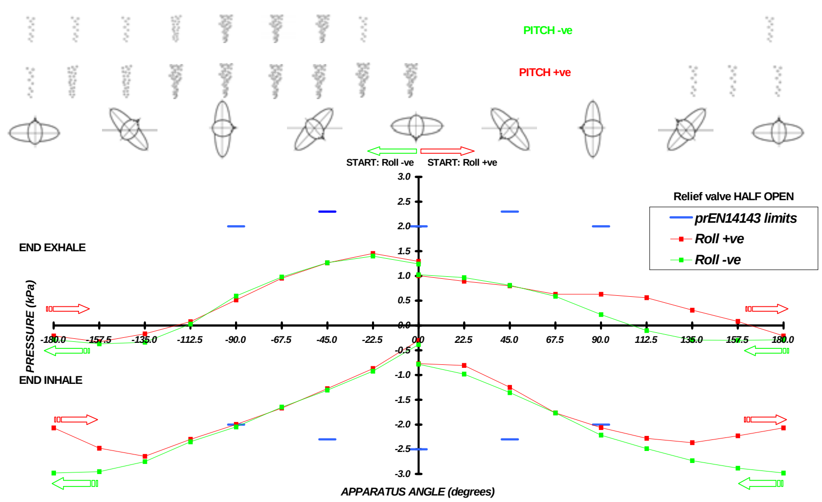


Figure 11. Gas loss during diver roll with split counterlung system.

Oxygen control

One of the greatest advantages of diving rebreathers is the ability to control inspired oxygen levels and thereby optimize decompression requirements. Different rebreather configurations provide for a range of oxygen control possibilities. In simple terms these may be considered as either mechanical, *i.e.* semi-closed control systems, or electronic systems that use oxygen sensors to monitor and control oxygen injection to maintain oxygen levels around a nominal PO_2 set point. By their nature, mechanical (semi-closed) systems allow greater variability in inspired PO_2 than electronic systems; the inspired PO_2 varying with both depth and diver workload (Figure 12).

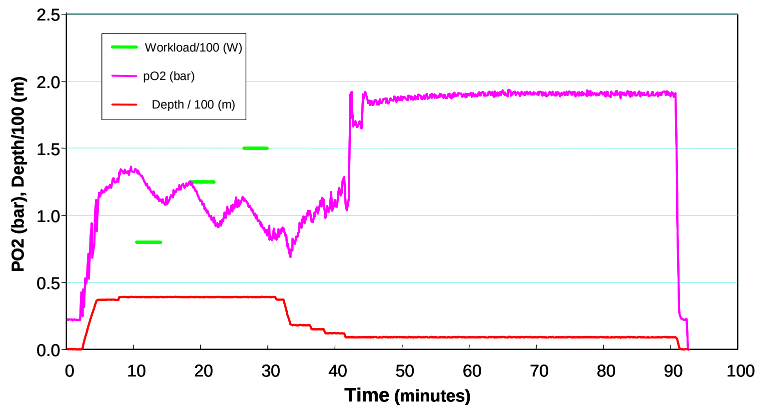


Figure 12. Example semi-closed circuit Rebreather inspired PO_2 with depth and work rate. Note: Diver switched to pure oxygen at 12 m following two flush-through procedures.

Producing standards and associated test methods for both systems has proved challenging as they respond and work differently. The basic concept employed in the UK and EN 14143 has been to identify physiologically-based inspired PO_2 levels within which a Rebreather must control the level to prevent a diver suffering hypoxia or hyperoxia, *i.e.* inspired PO_2 to remain between 0.2 and 1.6 bar. In addition, limits are placed on the maximum PO_2 deviation that may occur during initial descent on a dive; PO_2 may exceed 1.6 bar for a maximum of 1 minute but at no time exceed 2.0 bar. The derivation of these levels is beyond the scope of this paper. The second aspect of standardisation and testing is that rebreathers designed to maintain a constant inspired PO_2 around a declared setpoint are to do so within a tolerance of less than ±0.1 bar.

Testing of PO_2 control may be undertaken during both unmanned and manned dives. If performed during unmanned testing using a breathing simulator, it is vital that the conditions within the breathing loop are as close as possible to those that may be experienced during a manned dive. Tests at QinetiQ have shown (Figures 13a and 13b) that the oxygen control of an electronic closed-circuit rebreather may be significantly affected by the temperature and humidity of the gas within the breathing loop.

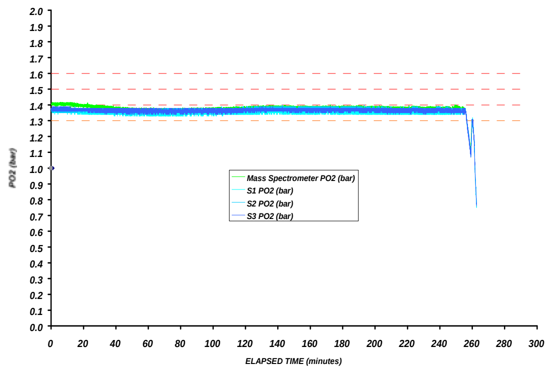


Figure 13a. Unmanned PO2 control Without gas heating, humidification and active CO_2 absorption.

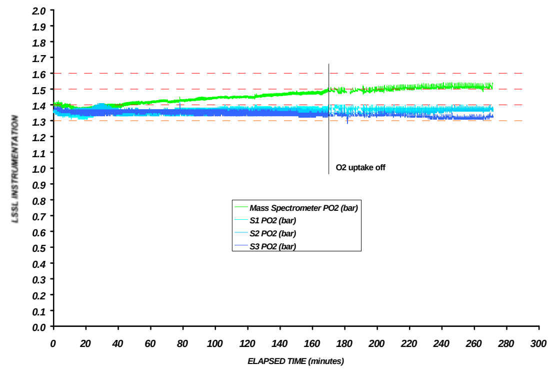


Figure 13b. Unmanned PO2 control With gas heating, humidification and active CO_2 absorption.

Investigations have shown that oxygen sensor output may be affected by temperature differences and if water condenses on the sensing surface. This reduces the cross sectional area of the sensor available to detect oxygen, resulting in a reduced output voltage for a given PO_2. The control circuit assumes this to be a reducing PO_2 and, accordingly, adds more oxygen to achieve the nominal set point resulting in an increase in the actual inspired PO_2. Thus when testing the oxygen control of rebreather systems it is essential that the exhaled gas from the breathing simulator is heated and humidified, it should also contain carbon dioxide with an active carbon dioxide absorption system within the rebreather; this then provides an appropriate test condition.

Simulated oxygen consumption may be obtained by using either a metabolic simulator (18) or by simple gas exchange that removes oxygen containing gas from the breathing loop at an appropriate rate and injects an equivalent volume of pure diluent gas. When the oxygen control of a closed-circuit rebreather is determined in different water temperatures with appropriate unmanned test procedures, the variation in inspired PO_2 that may be observed is presented in Figure 12.

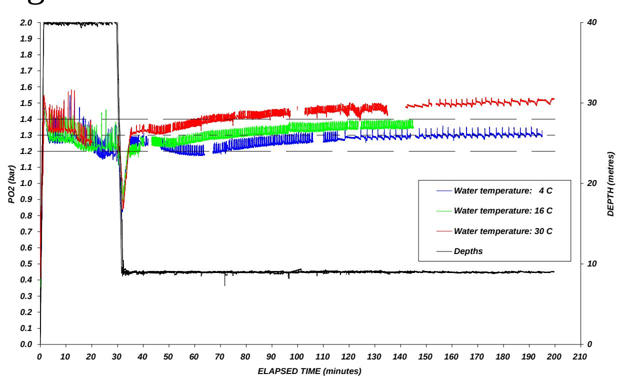


Figure 12. Example unmanned test data showing variation in inspired PO_2 with water temperature.

Carbon dioxide absorption

In 1889 Arrhenius (19) showed that rate of a chemical reaction is affected by temperature, the rate of reaction reducing as the temperature is reduced. This is directly applicable to the absorption of carbon dioxide by alkali metal hydroxides such as those in soda lime. Work undertaken in the early 1980s also showed that the absorption of carbon dioxide by soda lime was affected by pressure (20); an increase in pressure from 1 bar (0 m) to 11 bar (100 m) caused a three quarters reduction in the absorption capacity (Figure 13).

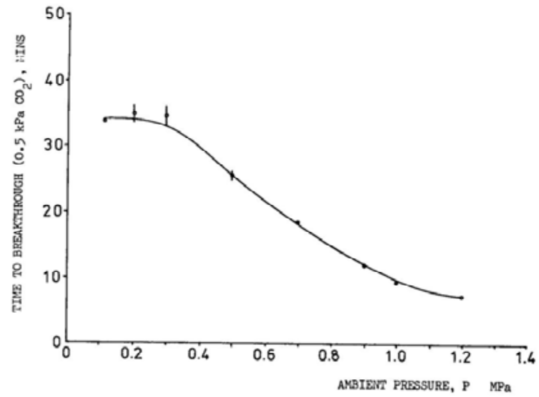


Figure 13. Affect of pressure on the efficiency of a carbon dioxide absorption system [20].

When testing the efficiency and endurance of a diving rebreather carbon dioxide absorbent canister, it is necessary to test at an appropriate temperature, *i.e.* in the lowest expected water temperature and with the exhaled gas from a breathing simulator heated and humidified to physiological relevant levels. As a minimum requirement, EN 14143 calls for tests to be conducted in water at 4 ºC with an exhale gas temperature in the range 32 °C ±4 °C and a relative humidity greater than 80 %. A 10 ºC change in water temperature can have a dramatic affect on absorbent canister endurance (Figure 14).

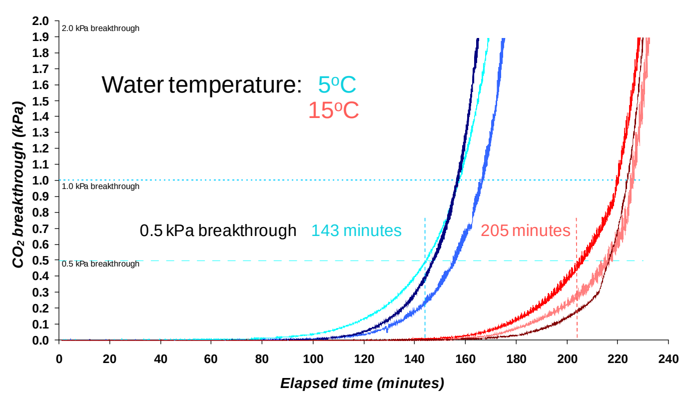


Figure 13. Sixty minute reduction in absorbent canister endurance with a 10 ºC reduction in water temperature; n=3 runs at each temperature.

Similarly, to anticipate the effect of pressure (depth) on the endurance of a rebreather it should be tested for dive profiles to the maximum expected depth of use and for each gas mixture *i.e.* nitrox, heliox or trimix. If intended for use at a constant shallow depth, such as with oxygen rebreathers, this should also be tested. A given mass of soda lime will have a limited carbon dioxide absorption capacity, thus the greater the work rate of the diver and associated increased carbon dioxide production (Table 1), the lower the endurance of the absorbent canister will be. For standard unmanned tests, to simulate an average moderate work rate, a ventilation rate of 40 $l \cdot min^{-1}$ is used with a carbon dioxide production (breathing simulator injection rate) of 1.6 $l \cdot min^{-1}$. It has been recognized that during periods where an increased work rate is required, or an emergency occurs, a diver's ventilation and carbon dioxide production rates will increase. To address this, consideration is being given to including five-minute periods of heavy work during absorbent canister tests and specifically when a canister is nearing exhaustion.

Unfortunately, there is often a wide distribution of the endurances recorded during absorbent canister tests (Figure 14). In an ideal world, sufficient endurance runs would be undertaken to apply a valid statistical analysis, identify the standard deviation (SD) and declare an operational endurance of the mean minus 2 SD. This was a requirement in the original NPD/DEn guidelines (2) with six endurances being conducted under each test condition. In practice this is too time consuming and costly, particularly with the number of variables of water temperature, depth and depth profiles and work rates. As a result, a range of reduced requirements has emerged with the minimum (as per EN 14143) being three runs under each test condition.

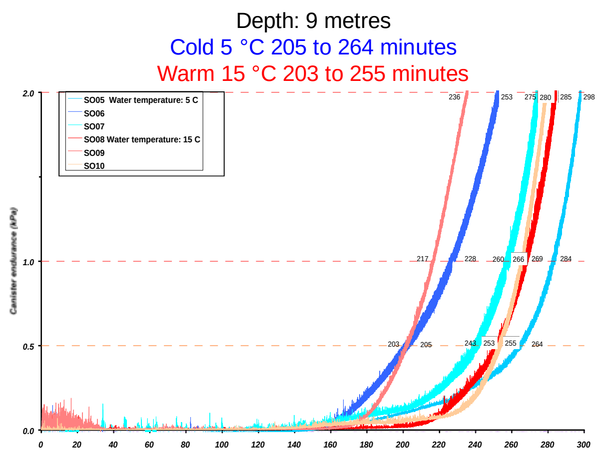


Figure 14. Large variation in recorded absorbent canister endurance in water at 5 and 15 ºC.

Summary

Within the EU and therefore the UK, legislation, as per the amended PPE Directive 89/686/EEC, has endeavored to improve the safety and performance of diving rebreathers by defining a harmonized performance standard, EN 14143 (7). Within the standard, over

50 individual tests are required and performance limits set. Some of these limits are at variance with simple physiological principles and those in other standards such as NATO STANAG 1410 (8). An ongoing process of dialogue between interested parties and standard development organizations continues to improve standards and test procedures for rebreather performance and safety.

Standards and associated test procedures for rebreathers have been developed for two main reasons:

- To give manufacturers design goals such that they may produce and sell rebreathers that may be considered as ‘fit for purpose’.
- To give the user some guarantee that a rebreather they are purchasing is of a known performance and is safe for them to use.

References

1. Middleton J, Thalmann ED. Standardized NEDU unmanned UBA test procedures and performance goals, Navy Experimental Diving Unit, NEDU TR 3-81, Jul 1981.

2. Draft guidelines for minimum performance requirements and standard unmanned test procedures for underwater breathing apparatus. Norwegian Petroleum Directorate/UK Department of Energy, 1984. ISBN 82-7257-167-6.

3. Guidelines for the evaluation of breathing apparatus for use in manned underwater operations in the petroleum activities. Norwegian Petroleum Directorate/UK Department of Energy, 1991. ISBN 82-7257-308-3.

4. EN 250:2000. Respiratory equipment – Open-circuit self-contained compressed air diving apparatus - Requirements, testing and marking.

5. EN 13949:2003. Respiratory equipment - Open-circuit self-contained diving apparatus for use with compressed nitrox and oxygen - Requirements, testing, marking

6. EN 1809:1998. Diving accessories Buoyancy compensators, Functional and safety requirements, test methods.

7. EN 14143:2003. Respiratory equipment - Self-contained re-breathing diving apparatus.

8. North Atlantic Treaty Organization (NATO). Standard unmanned test procedures and acceptance criteria for underwater breathing apparatus. NATO Standardization Agreement (STANAG) 1410, 2nd edition, NATO, Oct 2005.

9. Dobbins TD, Gilbert M.J, Gay LA, Anthony TG. Procedures for the evaluation of diving life support systems. DERA/CHS/PPD/CR980144/1.0. March 1999.

10. Gay LA, Searle SL. The measurement of manned work of breathing using respiratory inductive plethysmography. DRA/Mar/TM(MTL)91719, October 1991.

11. UK Ministry of Defence. Schedule of Approved Procedures, Research Ethics Committee, Version 1.2, 29 November 2006.

12. Elliott DH, Bennett PB. Underwater accidents. In: Bennett PB, Elliott DH, eds, The Physiologigy and medicine of Diving. 4th edition, Saunders, 1993:238-252. ISBN 0-7020-1589-X.

13. Gilbert MJ, Fisher AS, Evans MA, Stansfield M, Searle SL, Fraser R. Manned Evaluation of Clearance Divers Life Support Equipment (CDLSE). QINETIQ/07/02631/1.0, November 2007.

14. Gilbert MJ, Gay LA, Evans MA, Anthony TG. Manned evaluation of candidate mine countermeasure/explosive ordnance disposal diver life support equipment for RN use: Set 'Delta', DRA, DRA/SSES/CR/951021, April 1997.

15. Warkander DE, Clarke JR, Lundgren CEG. Undersea and Hyperbaric Medicine Society, Summer meeting 2001:28(supp.)(Abstract)150.

16. Navy Experimental Diving Unit. U.S. Navy unmanned test methods and performance goals for underwater breathing apparatus. Navy Experimental Diving Unit, NEDU Tech Man 01-94, Jun 1994.

17. Dobbins TD, Gilbert MJ, Blatherwick SP, Anthony TG. Hydrostatic load characteristics of breathing apparatus. Undersea and Hyperbaric Medicine Society, Summer meeting, 1999:26(Supp.)(Abstract)112.

18. Loncar M, Örnhagen H. Testing and performance of Rebreathers. South Pacific Underwater Medicine Society. 1997, Volume 27, Number 1.

19. Arrhenius S. Uber die Reaktionsgeschwindigkeit bei der Inversion von Rohrzucker durch Sauren. Zeitschrift für Physik Chemie 4, 1889, 226–248.

20. Anthony TG. Methods of determining the efficiency of a soda lime absorption system. Ocean Science and Engineering, 1983, Vol. 8, 99-112.

Discussion

ALEX DEAS: One thing you didn't cover is the elements in EN 14143 on electrical and software safety. Any comments on that?

GAVIN ANTHONY: The approach I've used in this presentation is that there are 50 separate tests within EN14143. In addition to the 50 separate tests, there is one nice little clause, in the standard, which actually says you have to make sure the electrical systems meet another European standard. It is a requirement to help with safety. I haven't avoided it here. It's just I haven't covered a lot of the other tests as well.

RICHIE KOHLER: Regarding the Royal Navy using heliox deeper than 30 metres in their rebreathers, my question is, what mixture are you using and are you affecting slower ascent rates using heliox?

GAVIN ANTHONY: The Royal Navy is in the process of switching between two rebreathers. But I can answer the question really with respect to both of them. Both rebreathers have a nominal 1.3 bar PO_2 set point and the balance is helium; so that is the mixture. As far as how it's controlled, the diluent gas in one is 16:84 O_2:He, the gas in the other is 20:80, but as far as the gas that you breathe, it doesn't make much difference. The Royal Navy have for their rebreathers dedicated decompression tables. And, yes, if you look at it, the overall ascent is slightly more than the typical technical diving decompression profiles that you would use.

BRUCE PARTRIDGE: You mentioned that the maximum acceptable density was 30 metres on nitrox. Is it 1.3 PO_2 so if you were mixing gases with helium and wanted to match the density?

GAVIN ANTHONY: For air, oxygen and nitrox, the density difference between these are small. So when you're looking at a density, then you would take the density of whatever the nitrox is and then that should be considered for your heliox.

PAUL HAYNES: Paul Haynes, Scotland. Gavin, the standard requires tests on the scrubbers at 4 °C, and that is the only temperature. This in reality is not what divers are regularly doing. What's your feelings on testing at a range of temperatures to provide divers with an envelope to make a choice in terms of the scrubber duration?

GAVIN ANTHONY: It is a perfectly valid thing to do. You've seen at the conference CO_2 is a problem, and if we're getting a message over to you that you can probably take away from this conference, CO_2 is a problem and you need to be safe on your canister endurances. So the standard is designed to actually try and run at the safe, conservative end, and that's what it's intended to do. However, if you can guarantee the equipment is only going to be dived in, say, the Caribbean, in warm water temperatures, and the manufacturer tests and quotes that. I see no reason why you can't provide that data and allow it to go longer. My concern is how many people read the instruction manual.

PAUL HAYNES: Point noted, but the reality is divers are exceeding the recommended scrubber durations. By providing extra tests at different temperatures, they can then make an informed decision about what to do in the environment they find themselves in for that particular dive.

GAVIN ANTHONY: Yes, they can do that. It's not the harmonized condition in the standard, but it is allowed within the European standard. If a manufacturer tests for that 20 °C and quotes it for 20 °C and it goes into the technical file, then it can be CE marked for that condition to give the divers an advantage.

KARL HUGGINS: Karl Huggins, Catalina. You mentioned that the Royal Navy divers use set tables, but in the units that have decompression algorithms in their software are there any standards that are set for those?

GAVIN ANTHONY: No. However, let's deal with it from a European point of view and then a Royal Navy point of view. From the European point of view there are standards for depth/time monitoring equipment. But that only looks at the performance of the time keeping and the depth/time accuracy. There is no standard for dive computers, or the algorithms, or the safety of them. As far as the Royal Navy goes, and I think this is also appropriate to the U.S. Navy and several others, the technical diving world and the recreational world generally have shown the diving world that computers are a damn good way of going forward. They are now looking at how they embrace them. But the challenge would come, and it may be that this is where standards for computers come out, is how you embrace them in the type of corporate safety that the Navy would want to look at for its users.

SPEAKER: Earlier you mentioned EN 61508 on electronics and that comes from Europe, but it can apply to anything involving electronic equipment.

GAVIN ANTHONY: EN 61508 could apply to dive computers but there isn't a specific harmonized standard. So the computer information would have to go into a technical file and be addressed in that manner. I think at that point I'm going to call a halt to the discussion.

ACCIDENT INVESTIGATION

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Approach

Compared to aircraft accident investigations, diving accident investigations are often *ad hoc* in nature, poorly conceived and poorly funded. Nevertheless, these investigations are just as important for the safety of the diving public as are similar investigations **for** the flying public. Unfortunately, no national regulations presently address how investigations of diving accidents should be conducted: volunteer investigators have no legal status for extracting information about an accident, and they have no legally binding protection from litigation based on the conduct of their investigation or on its results. That is, no business case can be made for conducting diving accident investigations, in spite of the moral authority for conducting them.

With the conviction that this untenable situation must eventually change, this presentation will describe the U.S. Navy's approach to diving accident investigations with particular emphasis on rebreathers and will draw some comparisons to aviation accident investigations by the National Transportation Safety Board (NTSB).

Initiators of accident investigations

The involvement of the Navy Experimental Diving Unit (NEDU) in an accident investigation begins with a request from a governmental or quasi-governmental agency such as regional medical examiners, police departments, the U.S. Coast Guard, and occasionally the U.S. Navy itself. We do not respond to requests from lawyers or family members for an accident investigation. In fact, with the exception of subject matter experts, personnel not directly involved in an accident are excluded from all phases of an investigation — a policy vigorously pursued as well by the NTSB. Furthermore, NEDU's Report of Investigation is delivered solely to the requesting agency. A mechanism for publicly disseminating diving accident reports is not currently established, but should be pursued for the benefit of the entire dive community.

Aircraft accident investigations

Pilots know that if they are involved in a fatal crash, the NTSB will investigate the accident by examining in excruciating detail everything those pilots did for hours, perhaps even days or weeks, leading up to that accident. It will investigate how often they called flight service to check on the weather. The NTSB will go through those pilots' personal logbooks to check on their currency and proficiency, and it will check Federal Aviation

Administration (FAA) records for a history of violations. NTSB investigators will also examine an aircraft's logbooks to scrutinize its maintenance records. They will play back voice and radar data, and if a data recorder is available, they will analyze its contents.

Then they get personal. The NTSB and its FAA counterparts will talk to mechanics, surviving passengers, and friends to ask questions such as, "What were the aviators' attitudes toward flying? Were they cavalier? Did they take unnecessary risks, or were they careful and methodical?"

Due to the detailed, scripted nature of NTSB procedures, the investigation may take up to a year to complete.

In a recent accident, a pilot was forced to make a water landing just off the beach in Panama City, Fla. The ditching should have been survivable, but he lost consciousness on impact and sank with the airplane as it settled to the bottom in relatively shallow water. He drowned.

If he had been a diver, that would have been the end of the story. The public judgment would have been, "A diver drowned. He tried to breathe underwater; this is what happens." But this victim happened to drown inside an airplane. So instead of the medical examiner simply saying that he drowned, the NTSB started its very thorough investigation procedures.

Fortunately, the pilot also had a surviving passenger. From the survivor's statement, the aircraft's maintenance records, and the mechanic's testimony, an ugly story of reckless disregard for the most basic safety rules of flying began to emerge.

Do divers ever show a reckless disregard for basic safety rules? You bet. It's unfortunate that the pilot died, but the events leading to his death were a useful reminder that the media in which we work and play, high-altitude air and water, are not forgiving. Humans are not designed for flying or diving, and nature only begrudgingly lets us trespass — on its terms.

The U.S. Navy (1) and Coast Guard are chartered to investigate diving accidents. Unfortunately, there is a huge discrepancy in the number of personnel and the amount of funding for aviation accident investigations compared to diving accident investigations. The NTSB has hundreds of personnel and tens of millions in funding available, whereas the entire U.S. Navy has at most a handful of investigators with no investigation-specific funding.

Navy investigation procedures

Because of resource and funding constraints NEDU restricts itself to only investigating diving equipment (2). We are never given the opportunity to investigate the diver's frame of mind, training, or drug status. We examine only the physical evidence in front of us, such as the SuperLite 17 helmet in Figure 1 or the three similar helmets in Figure 2. All these helmets were involved in commercial diving accidents occurring within a short time.

Figure 1. A SuperLite 17 diving helmet involved in a diving mishap.

Unfortunately, NEDU typically has a backlog of equipment to be tested, so an investigation can take a year or more to complete, just as it does for the NTSB.

Figure 2. Three SuperLite helmets awaiting study.

The simplest pieces of equipment to investigate are scuba regulators. We may need to do nothing more than place a regulator on a test bench like that in Figure 3 to determine how the accident regulator functions. Figure 4 shows a typical report from dry bench testing.

Figure 3. NEDU's scuba regulator dry test bench and NEDU lead Investigator for Diving Accidents, David Cowgill.

NAVY EXPERIMENTAL DIVING UNIT
SCUBA REGULATOR
DRY BENCH INVESTIGATION REPORT

Date Tested: **24 Oct. 2007** NEDU Tracking #: **02-07 Encl 3**

Task #/Agency/Command: **California OSHA** Test Plan #:

Point of Contact: [redacted] Case #: **310544614**

Manufacturer Specifications:

Intermediate / Over-bottom Pressure **135-150** psi at **3000** psi Supply Pressure

Cracking **- 0.9** Inches of H_2O (if provided by manufacturer)

REGULATOR MANUFACTURER: **Sherwood** MODEL: **Magnum Blizzard**

SERIAL # 1st STAGE: **Not Marked**
SERIAL # 2nd STAGE: Primary **Z116218**
SERIAL # 2nd STAGE: Octopus **ScubaPro Air 2 / Boyancy compensator inflation device SN 0401013029**

TEST RESULTS:

Intermediate / Over-bottom Pressure 128 psi @ 3000 psi 130 psi @ 1500 psi 128 psi @ 500 psi

Maintains Set Pressure? ☒ Yes ☐ No (If no, explain in comments)

Second-stage Free Flow? ☐ Yes ☒ No (If yes, explain in comments)

Exhalation Crack Pressure 0.3 Inches of H_2O

Inhalation Crack Pressure 0.5 Inches of H_2O

Evaluation Pressure Supplied to First Stage 2800 psi

Apparatus performs per manufacturer's specifications ☐ Yes ☒ No (If no, explain in comments)

Visual Examination

Corrosion Present	Moderate
Filter Particulate	Moderate
Hose Damage	Minor
Mouthpiece Damage	Moderate
Exhaust Valve	Moderate
Condition Key:	None – appears as if new Minor – normal use, maintained and in serviceable condition Moderate – heavy use, needs maintenance Excessive – gross lack of maintenance, unserviceable condition

Figure 4. NEDU's Dry Bench Investigation Report (2).

Figure 5 shows a typical bench testing result with the primary regulator venturi generating positive pressure at high flow rates and the secondary regulator (the "octopus") showing its expected non-venturi driven behavior that minimizes the risk of free-flow.

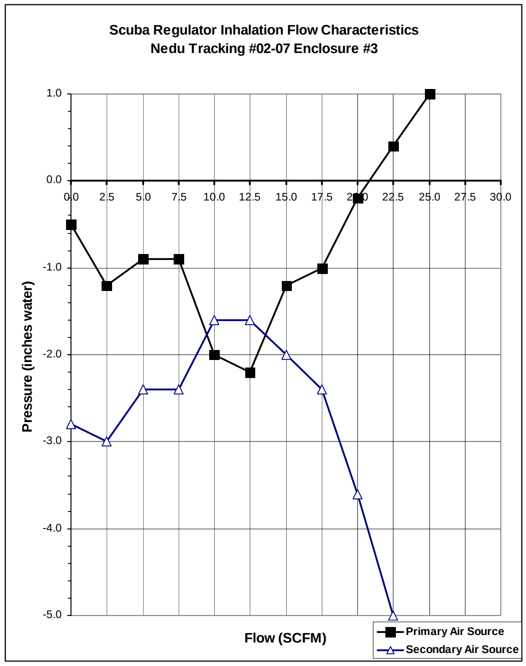

Figure 5. Graphical results from dry bench tests of primary and secondary (octopus) regulators.

When bench test results show anomalous behavior, NEDU may place the helmet or regulator in a test chamber (Figures 6–8) and drive it with a breathing machine (Figure 9) to dynamically reproduce the respiratory and environmental conditions encountered during the accident. This testing uses procedures described in reference (3).

Figure 6. One of NEDU's unmanned test chambers.

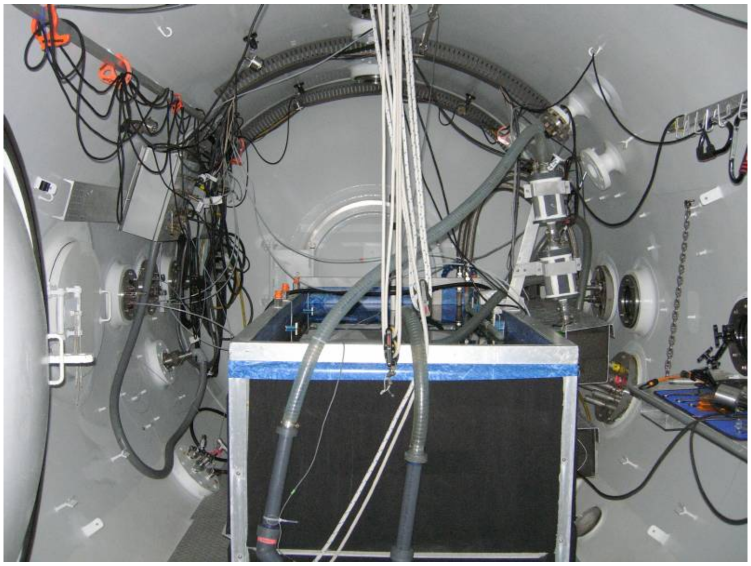

Figure 7. Water-filled ark inside a pressure chamber for immersing underwater breathing apparatus (UBA) during equipment tests.

Figure 8. Control console for unmanned equipment testing.

Figure 9. Dual-headed breathing machine used to simulate two divers breathing on two UBA simultaneously.

In rare cases, such as that of a recent Coast Guard tragedy, NEDU may even conduct an accident re-enactment in our 15-foot deep test pool (Figure 10), particularly when buoyancy or diver weighting is of interest.

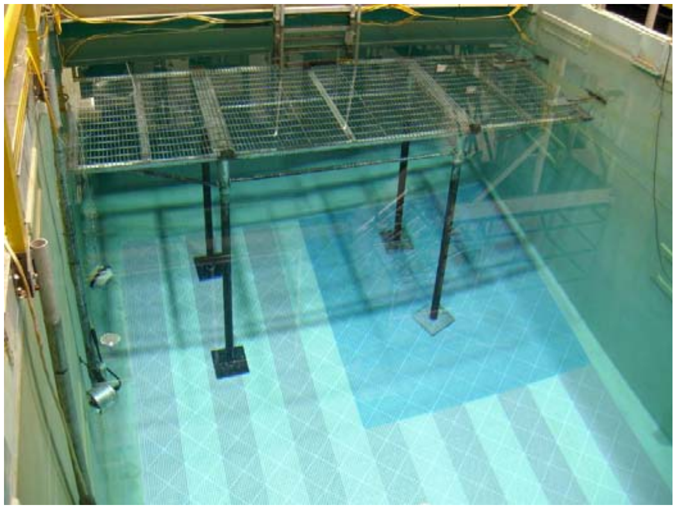

Figure 10. NEDU's test pool.

Rebreathers are troublesome

In accident investigations, rebreathers are problematic because they can kill in ways that may not be detectable post-accident. They may leave no evidence, because the diver may have been improperly using a perfectly functioning UBA.

Hypercapnea

Should a CO_2 scrubber canister become compromised due to poor absorbent packing or water intrusion, the result can be premature canister breakthrough, where recirculating CO_2 rises precipitously (Figure 11). Whereas a resting diver might notice his breathing becoming increasingly labored as inspired CO_2 increases, a working diver may not notice this. As a research subject in a CO_2 exposure study, I have personal experience that judging one's level of impairment from high inspired CO_2 concentrations is difficult during exercise. Without being aware of his predicament a diver might become physically or mentally compromised, with potentially tragic consequences.

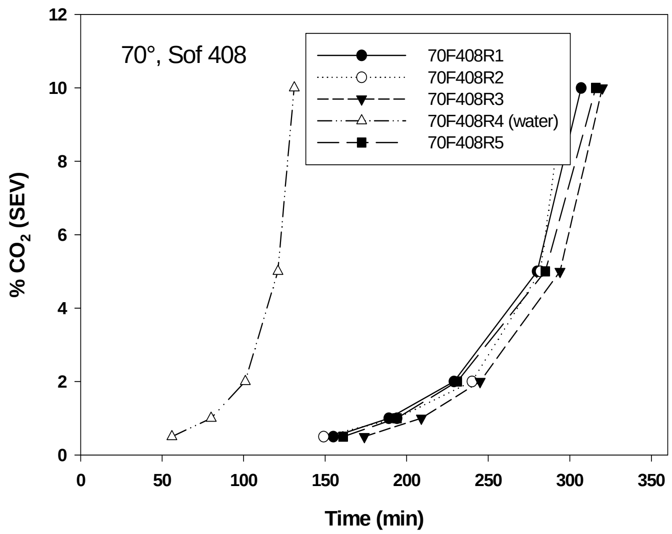

Figure 11. Of five tests of CO_2 absorption in rebreather scrubber canisters, one had a remarkably short canister duration. Post dive examination revealed more water than normal in that canister.

Regardless of how well his UBA may be functioning, a diver can become toxic with elevated levels of CO_2 in his bloodstream. All it takes is for him to under breathe, or hypoventilate. A research subject at the Naval Medical Research Institute in Bethesda, MD, once developed a bizarre breathing pattern at a pressure of 100 meters of seawater (msw) that helped him avoid an imposed respiratory load but interfered with his body's CO_2 washout so much that he lost consciousness. If he had been in the open sea, his exaggerated pattern of skip breathing would have killed him. Likewise, deep divers who use rebreathers can encounter high respiratory loads that can, in extreme cases, result in fatal hypercapnea.

Deducing the cause of fatalities from hypercapnea (CO_2 intoxication) by examination of the diving equipment alone can be exceedingly difficult. Since a rebreather frequently floods during or after an accident, there is no way to know whether water in the canister contributed to the accident.

In the second example of hypercapnea, the equipment may have been functioning correctly, but the diver may have been using it incorrectly or beyond its intended limits. Those limits, of course, may be as much physiological as physical. The diver's physiological status will not be known to the investigator unless revealed by autopsy results or deduced from the diver's reported behavior prior to the accident. Unfortunately, autopsies typically list drowning as the cause of death with little or no insight into the physiological events leading up to the drowning.

Hypoxia

Fatal hypoxia may also occur without an equipment anomaly being detected, especially in semi-closed-circuit UBA (Figure 12) (4-7). Figure 13 shows plots of oxygen fractions seen in divers monitored in the NEDU test pool and performing what was supposed to be light to moderate work. The horizontal dashed lines represent the fractions of O_2 expected to be in the UBA breathing bag at rest (0.5 $l \cdot min^{-1}$ O_2 consumption) and at work (2.0 $l \cdot min^{-1}$ O_2 consumption). The dives were aborted when the fraction of inspired oxygen (FIO_2) reached that for air (21%), rather than the expected oxygen-enriched nitrox gas mixture.

Figure 12. A LAR V Nitrox (LAR VII) semi-closed UBA.

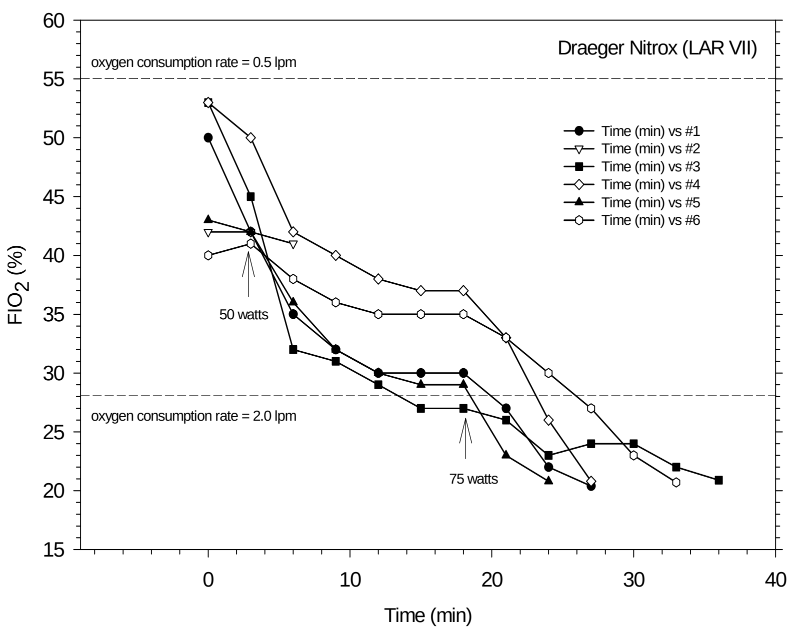

Figure 13. The time course of falling FIO_2 in five divers using the LAR V Nitrox (LAR VII) Rebreather (Figure 12.)

Something as simple as inappropriately adjusting a semi-closed UBA's variable exhaust valve can result in hypoxia during moderately heavy work (Figure 14.)

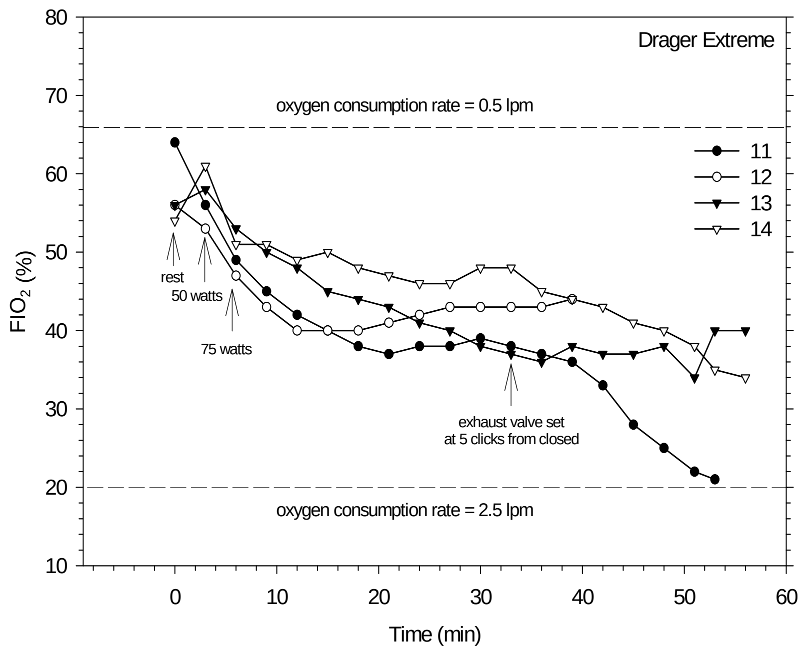

Figure 14. Changing an exhaust valve setting in one semi-closed UBA caused the diver's inspired oxygen to plummet 40 minutes into the dive.

Detecting such potentially fatal events without O_2 sensors and data loggers is virtually impossible. Semi-closed UBA typically have neither sensors nor loggers.

Computer simulators

Computer simulations are useful tools for analyzing diving accidents, especially for those involving semi-closed UBA where inspired oxygen concentrations are a complex function of UBA design, gas mixture, and dive and exercise profiles (4-7). An example of such a simulator is the *Semi-closed* software written by NEDU to help in its investigations.

Figure 15 is a screenshot of a *Semi-closed* depiction of an hypoxic episode caused by an improperly adjusted exhaust valve. Hypoxia resulted in loss of consciousness, with eventual recovery due to the presence of a simulated full face mask. The heavy line at the bottom is the diver's inspired partial pressure of oxygen (PO_2), which reaches a critically low value (bottom dashed line) about three-fourths of the way through the dive. The oscillating waveform is the diver's mouth pressure (*e.g.* breathing pattern).

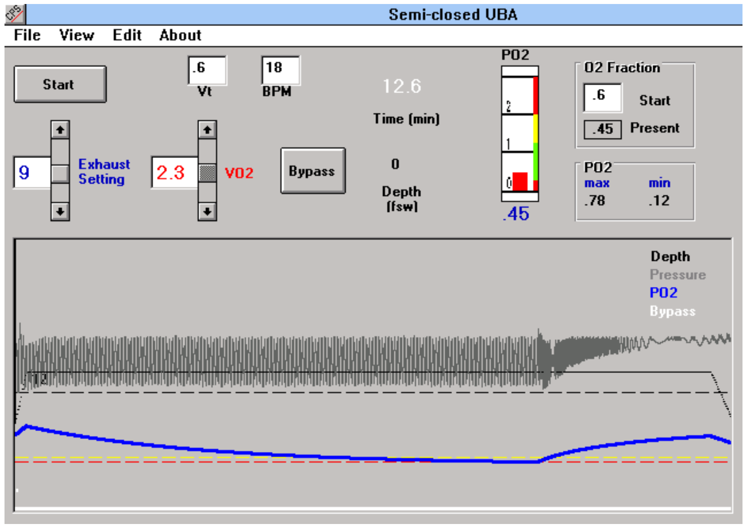

Figure 15. A computer simulation of hypoxia due to improperly setting a variable exhaust valve in a semi-closed UBA.

Constant PO_2 Rebreathers

Much of NEDU's research and training time is spent with Carleton's MK 16 constant PO_2 bebreather (Figures 16 and 17), currently used by both U.S. Navy SEALS and Explosive Ordnance Disposal divers (called Clearance divers in some other navies.)

Figure 16. A Navy SEAL with MK 16 before a chamber dive.

Figure 17. MK 16 diver entering NEDU's Ocean Simulation Facility chambers.

NEDU has also investigated the occasional MK 16 accident. In 1995, due to mechanical damage or improper seating during installation, a loss of Viton O-ring integrity in a Bendix cable connector extending between the UBA's primary electronics assembly and the O_2 add solenoid initiated a fatal chain of events (Figures 18–20). The last event in the chain was the diver's failure to notice problems in the primary and secondary displays and abort the dive on open circuit; the standard emergency procedure for electrical failure in the MK 16.

Figure 18. MK 16 solenoid.

Figure 19. MK 16 Bendix connector.

Figure 20. A damaged O-ring in this connector contributed to a fatality.

Recently a Navy MK 16 diver lost consciousness because a connection between the UBA battery and the electronics module (Figures 21–22) had been improperly repaired. Thanks to the quick action of diver tenders, he survived.

Figure 21. Improperly spliced connectors in an electronics pod.

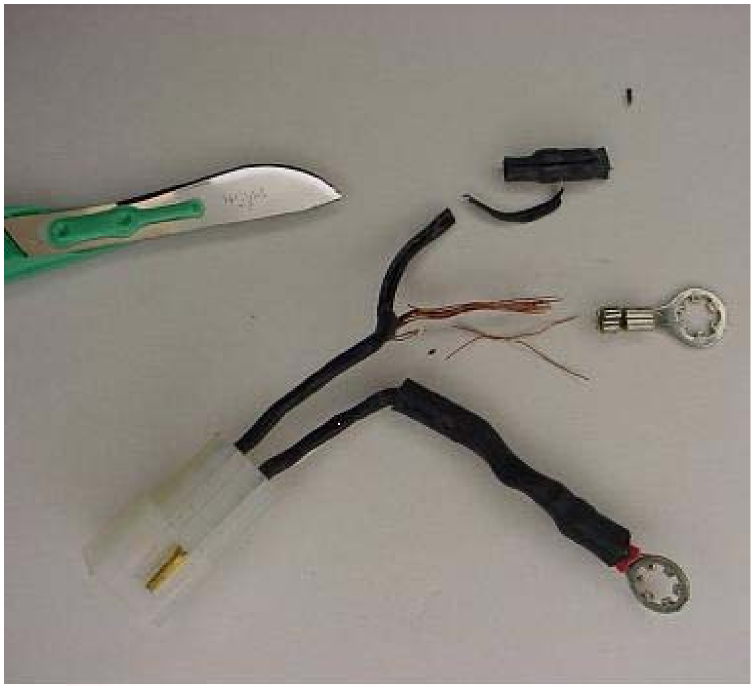

Figure 22. Connecting wires damaged by improper repair.

Computer-controlled rebreathers

Modern, fully closed-circuit rebreathers (CCR) that control inspired O_2 provide a versatile means for managing a rebreather's life support function. They also provide new opportunities for accidentally killing a diver.

In the 1990s following a nearly fatal NEDU accident with one of the world's first computer-controlled rebreathers, NEDU developed the ability to examine software logic for sensor status and alarms [3] (Figure 23). We were able to test oxygen control and alarm algorithms both isolated from and interfaced with the UBA.

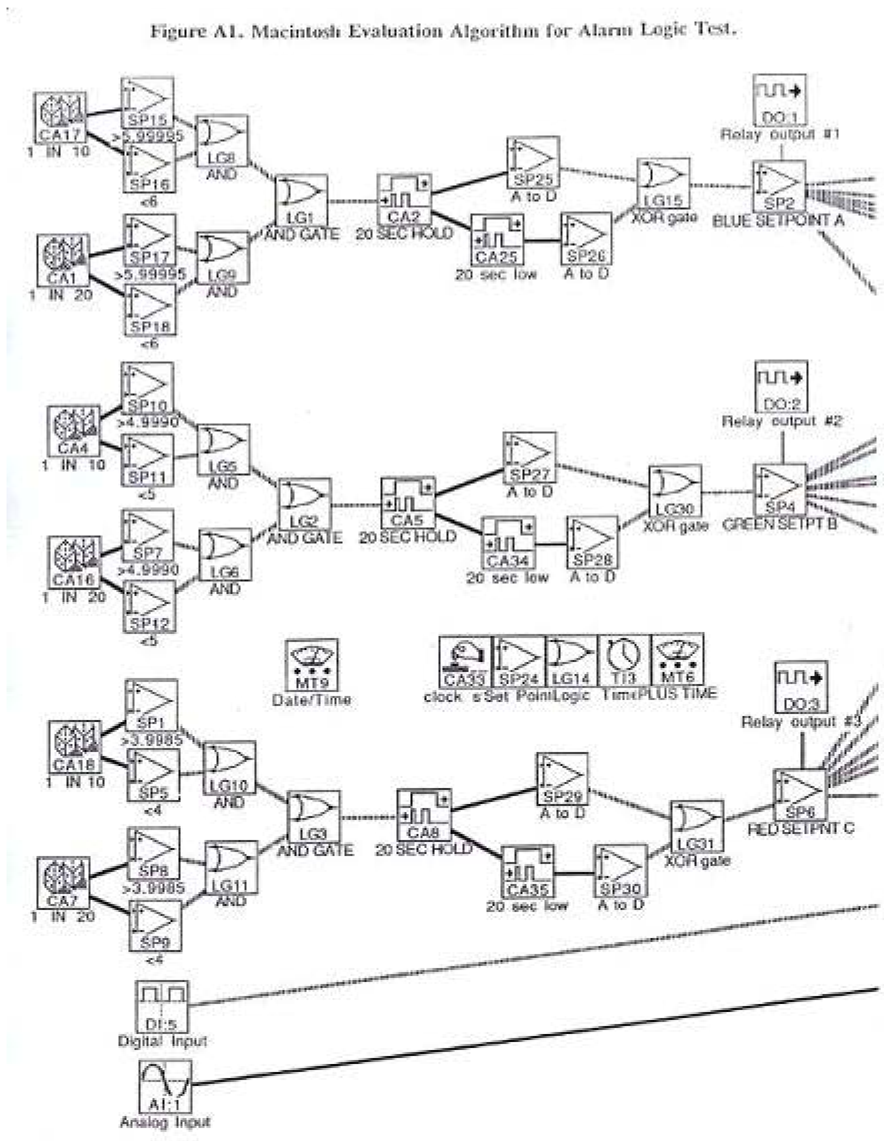

Figure 23. A graphical representation of a program used to test O_2 control function in the EX-19 rebreather through random changes in sensor outputs.

In recent years formal Independent validation and verification (IV&V) procedures for life-critical software (8) and a commercial industry to take advantage of that quality control function have been developed. Software IV&V (or alternatively, VV&A — verification, validation, and accreditation) is a systems engineering process using rigorous methodologies for evaluating the propriety and integrity of the software product (9). Nevertheless, that industry would be hard-pressed to show that applying IV&V procedures to rebreather software analysis is any more advanced than methods used by NEDU almost 20 years ago. Lately NEDU has seen multiple software and hardware failures in developmental rebreathers, failures that occurred despite control and display algorithms having passed formal IV&V inspection.

When investigating a diving accident, investigators should certainly be prepared to explore the operating and logical details of both the software and the electronic black box, details commonly hidden from investigators under the pretext of "proprietary information." Investigators should use whatever tools are available to them and not shirk their responsibility by assigning tasks to an independent IV&V laboratory that may know nothing about diving equipment and its use.

EX-19 accident investigation

NEDU performed an archetypal computer-controlled rebreather investigation in 1993. The EX-19 (Figures 24–25) was built by the U.S. Navy in Panama City, FL, and tested at NEDU, where a near-fatality occurred in its test pool (Figure 10). The incident was the first known respiratory arrest in a computer-controlled rebreather. Fortunately, the test diver was revived by CPR.

Figure 24. The EX-19 at Morrison Springs, FL.

Figure 25. The EX-19.

Post accident UBA condition

Immediately after the accident, 45 ml of water was removed from the canister housing, and traces of water were noted around the O_2 sensors. The unit would not maintain the target PO_2 of 0.75 atmospheres absolute (ATA), and PO_2 readings for two of three sensors were high (0.9–1.0 ATA). One sensor read low PO_2 (0.4 ATA).

Hypothesized accident scenario

The investigation's conclusion hypothesized that condensed moisture had covered O_2 sensor surfaces and caused them to become insensitive to O_2 levels in the breathing loop. Water trapped O_2 on the sensor surface and initially caused normal sensor readings in spite of decreasing breathing bag levels of O_2. Because of the unchanging sensor readings, oxygen was not added as the diver consumed it. As the sensor's electrochemical process slowly consumed O_2 adjacent to the wetted sensor face, the unit could have been commanded to continuously add O_2. But that did not happen: perhaps due to diver motion–induced changes in UBA orientation, the offending water moved; the lock-out condition was not static. Voting and alarm logic algorithms reset the software triggers before alarms could occur. Without alarms, the diver went into respiratory arrest from severe hypoxia.

The investigation observations leading to those conclusions summarily follow:

Initial laboratory testing results

NEDU attempted to reproduce the dive events in its unmanned laboratory. After two to three hours with the rebreather in a prone (horizontal, face down) position, O_2 sensors began "locking out", meaning a sensor quit responding because water droplets were shielding it from ambient O_2. Up to 285 ml of water were generated in the canisters from condensation and water produced in the CO_2 absorption reaction. Only 45 ml of water was needed to transiently cover sensors. Alarms were not always generated; as the number of locked-out sensors varied, alarms were reset per the alarm algorithm which was designed to minimize false alarms by resetting if the sensor state varied within one minute. During this first laboratory test, the rig eventually began continuously adding O_2.

Oxygen control algorithm testing

To discover the root cause of this accident, NEDU performed exploratory tests concentrating on critical steps in the O_2 control system. As in most modern CCRs, three redundant sensors assessed PO_2. An onboard computer monitored sensors and performed actions based on sensor voting logic rules designed to control PO_2 within narrow constraints, despite changing dive conditions and partial sensor failures.

The UBA's O_2 control algorithm was tested through computer simulation, with the rebreather response being examined in the face of random sensor failures. The tested O_2 sensor modes included complete failure of the sensor (0 voltage output), simulated sensor lockout, or a combination of these modes.

Testing revealed that loss of O_2 control could occur with two of three sensors locking out, *e.g.* with one sensor functioning normally. (So in this case, "triple redundancy" is really a misnomer.) The simulation showed that loss of O_2 control can result in either a hypoxic or a hyperoxic O_2 level in the breathing loop. Statistically, a hyperoxic state potentially resulting in seizures was found to be more likely than a hypoxic state. Furthermore, based on the simulation used to test the voting logic rules, a low diver workload was more likely than high workloads to produce hypoxic events. Thus, the hardworking diver in our test pool was unlucky to experience a hypoxic failure mode. On the other hand, he was quite lucky to be stricken with resuscitative medical help standing by.

EX-19 computerized alarm bench testing

Further bench testing used a computer to generate varying sensor voltage states while the alarm status of the rebreather was monitored. The number of actual alarms generated by the rebreather software and electronics were compared to the number that the alarm logic rules *should* have generated. The test computer produced random and transient sensor voltage dropouts (Figure 26).

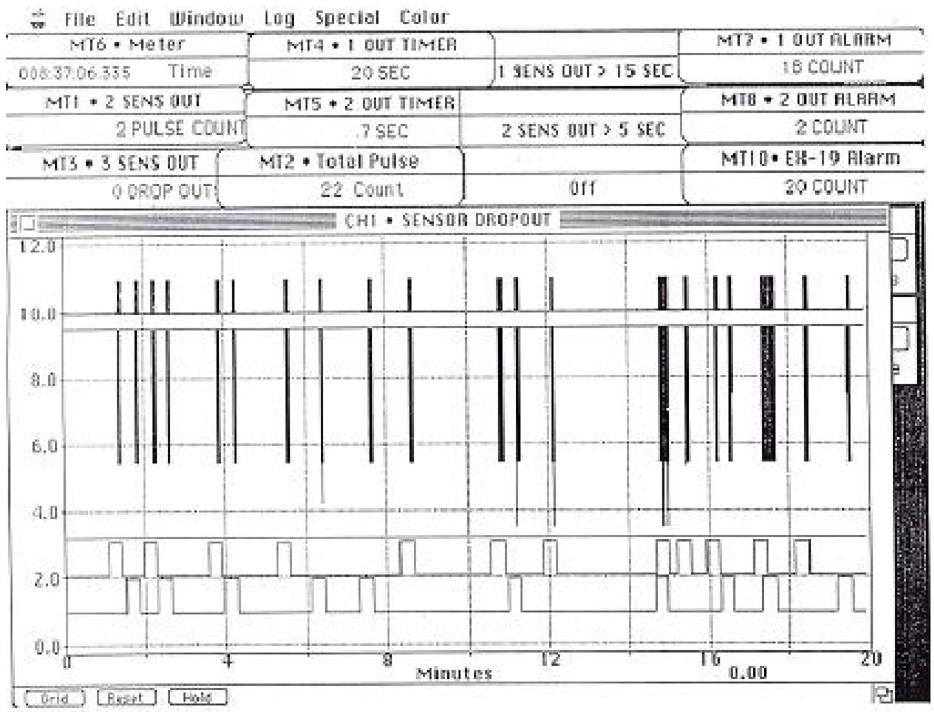

Figure A2. Macintosh/UBA Alarm Tracking Chart.

Figure 26. Plot of random presentations of error stimuli (bottom traces) and the respective alarms (spikes in the top traces).

Testing of the alarm algorithm demonstrated 2,076 alarms out of 4,179 simulated sensor failures, a 50% error rate due to software-controlled resets. After the UBAs were reprogrammed by the Navy, the failure rate for the alarm logic improved markedly: 4,374 alarms were generated by 5,007 simulated failures (13% error rate). Careful review of the stimulus timings made the remaining errors explainable.

Lessons learned

NEDU's experience with evaluating commercial computer-controlled rebreathers leads us to the following conclusions:

- Because of the perceived proprietary nature of O_2 control and alarm algorithms, manufacturers are reluctant to divulge those algorithms.

- Investigators must develop a trusting relationship with manufacturers, so that concerns about releasing sensitive algorithm information are alleviated. As a last recourse, investigators should be prepared to identify such algorithms through reverse engineering.

- For the good of all divers, no obstacles should impede efforts to determine the cause of a rebreather fatality. In fact, withholding information in a fatality investigation should be illegal, just as it is during NTSB investigations.

Recommendations for improving accident documentation

At a minimum, sensors and data loggers for O_2 should be installed in all computer-controlled closed-circuit rebreathers. Better yet, solenoid valve and alarm activations should be logged. In other words, the industry needs dive data recorders in all computer-controlled closed-circuit rebreathers, recorders analogous to those required for logging flight data (Figure 27).

Figure 27. The data recorder recovered from an airliner crash in South America.

Investigation team requirements

In the best of all worlds, an investigation team should have access to both a manned and an unmanned test facility, access to experts in all diving equipment (scuba, rebreathers, helmets), and the ability to conduct *and interpret* gas analyses — sometimes from minuscule amounts of remaining gas. At a minimum, such a team needs the ability to download and interpret dive computer/recorder data. Some investigations may require the simulation of UBA-human interactions for "re-enactment" purposes. An investigation team should also have diving medical expertise available to review medical examiner reports for consistency with known or discovered facts regarding the accident. Last, it should have in-depth knowledge of police investigative procedures, particularly of the procedures and documentation for maintaining "chain of custody" (2).

Do rebreather investigations have a future?

Considering the resources and timeframes required for NEDU to conduct diving equipment evaluations on a limited set of accident cases, and the unfunded costs associated with those investigations, it is difficult to imagine a resolution to an ever-increasing need for rebreather investigations. Almost certainly, no independent federal agency similar to the NTSB will ever be responsible for investigating diving accidents, simply because diving accidents lack national attention: the public at large is not being placed in jeopardy.

It is also unlikely that diving equipment manufacturers would welcome federal agency oversight and regulations comparable to those engendered by the FAA and NTSB. Diving might become exorbitantly expensive. For instance, if a $5 part available for purchase in an automotive store were to be used in an aircraft, it would become a $50–$500 part because of FAA required documentation that it meets airworthiness standards.

The U.S. Coast Guard initiates diving accident investigations and in some cases conducts hearings into those accidents; however, with its enhanced role in Homeland Security, the Coast Guard is unlikely to welcome any efforts to diversify its mission. The cost/benefit ratio would appear to be too great.

NEDU cannot increase its number of investigations to respond to an ever-increasing rebreather accident rate. That is not its primary mission. However, NEDU will attempt to educate the diving public about interesting findings from its investigations, whenever that education can be conveyed without incurring legal liabilities. That is why this presentation has discussed only Navy rebreather accidents.

NEDU encourages Divers Alert Network (DAN) to continue its lead in fostering diver education and applauds it for establishing this workshop. For the future, as Dick Vann of DAN has suggested, the resolution may ultimately depend on rebreather users funding a team of dedicated, professional accident investigators. The cost of conducting worthwhile investigations has yet to be determined, and therefore the amount of funding needed to support it is unknown. I suggest that obtaining those estimates should be a priority as we, rebreather users and the industry, decide the next steps in investigating rebreather accidents.

References

1. U.S. Navy Diving Manual, Vol. 1 Rev.6, Naval Sea Systems Command, Washington D.C., 2008.

2. NAVXDIVINGU Instruction 5102.1A, Procedures for Evaluating Diving Equipment Involved in a Diving Related Mishap, 28 Apr 03.

3. U.S. Navy Unmanned Test Methods and Performance Goals for Underwater Breathing Apparatus, NEDU Tech Man 01-94, Navy Experimental Diving Unit, June 1994.

4. Clarke JR. Contrasts between Semi-closed Circuit Underwater Breathing Apparatus of the ‘70s and the ‘90s. Proceedings of Ocean Community Conference ’98, Marine Technology Society, Washington, D.C. November 1998: 976-982, 1998.

5. Clarke JR. Underwater Breathing Apparatus. In: The Lung at Depth, ed. CEG Lundgren and J Miller. In series, Lung Biology In Health and Disease, ed. Claude Enfant. New York, Marcel Dekker. p.429-527, 1999.

6. Nuckols ML, Clarke JR, Marr WJ. Assessment of oxygen levels in alternative designs of semi-closed underwater breathing apparatus. International Journal of Life Support & Biosphere Science. Vol 6, (1999), p 239-249.

7. Nuckols ML, Clarke JR, Grupe C. Maintaining safe oxygen levels in semi-closed underwater breathing apparatus. International Journal of Life Support & Biosphere Science. 5:87-95, 1998.

8. Hancock TM. Application of Independent Verification & Validation analysis techniques by software development organization. Space, 2005, American Institute of Aeronautics and Astronautics, 2005-6656,

9. Systems Engineering Fundamentals, Defense Acquisition University Press, Fort Belvoir, VA, 2001.

MANUFACTURERS PANEL DISCUSSION

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Divex
Aberdeen, UK

Jarrod Jablonski
Halcyon, GUE, Extreme Exposure
High Springs, Florida, USA

Gene Melton
Neptune Rebreathers
St. Augustine, Florida, USA

Pete Nawrocky
DiveRite
Pompano Beach, Florida, USA

Martin Parker
Ambient Pressure Diving
Helston, Cornwall, UK

Peter Readey
Steam Machines
Lebanon

Leon Scamahorn
InnerSpace Systems Corp
Centralia, Washington, USA

Bill Stone
Stone Aerospace
Del Valle, Texas, USA

GAVIN ANTHONY: As I said at the beginning, this is where we deviate from the conventional format of conference presentations. The way the panel is going to work is, we have a fantastic group of manufacturers here who are prepared to participate. Questions have been sent in. Questions have been identified in what the UK would call "a starter for ten" for the panel discussion. I've put these in a nominal running order. The panel members have them, and I've asked individual members on the panel if they would give a lead response to that question. Now, what I'm not looking for is the panel member just to answer the question and we move on to the next question. They should present a view, and then we see if there are other views from the rest of the panel. At some stage during the discussion I want to leave the formal set of questions that we've got and to give you in the audience a chance to ask the manufacturers questions. Now, I'll give you some warning, but then when it comes to that point, if anyone has a question they'd like to ask, if they can make their way to a microphone. Now, to kick off, I must admit I had only met two or three of the people on the panel at the start of the conference. What I'm going to do is ask each of the panel members to introduce themselves, what their background is, and the systems that they manufacture.

PETE NAWROCKY: I'm the national field manager for Dive Rite. I'm also the Northeastern representative. I'm an active CCR instructor and technical diver just like a lot of you folks. I see a lot of friends out here, I'm here enjoying a very informative conference and I have learned a lot in the last day and a half.

MARTIN PARKER: I represent Ambient Pressure Diving from the UK. We manufacture the Inspiration Rebreathers. Started diving in 1974. I was introduced to rebreathers at the same time I was getting involved in electronics in diving during the 1990s. It was this guy next to me, Peter, who introduced me to rebreathers. Since then the reason for building the rebreather was to satisfy my requirement to go trimix diving. It's now been 10 years that Inspiration has been on the market.

PETER READEY: I took Martin for his first rebreather dive. I wonder if that was a good thing? I've been working on rebreathers for nearly 20 years. I've done work for Draeger. I worked for Oceanic many years ago. I'm happy to give you any information that you ask me for.

BILL STONE. Probably my infamous claim to fame is that I would never tell anybody before this, that my second dive was a cave dive. My first dive was in a pool the night before I did my first cave dive; that was in 1976. I never got certified in diving until three years later, and only a few years after that was I really formally chasing cave diving. So I was lucky. I think that it's interesting to see here today where everything has evolved to. We were mainly focused on deep cave explorations and running through underwater tunnels and places like this; it forced us into building and designing our own SCUBA gear.

So we started off building composite equipment in the early 1980s, and ultimately the picture that somebody showed the other day here, with a diver with ten tanks wrapped around them, that actually looked like us in 1984. So we knew a lot about that and we were forced as a result of that to go into closed-circuit design. So in 1984 we started a company called Cis Lunar, and built a prototype rebreather over the next couple of years. Eventually the Mark V was commercially produced in the mid to late 1990s. Then there was a hiatus for various reasons, largely due to the dot-com crash. Two years ago we established a joint venture with Poseidon to design the Mark VI, which just appeared a few months ago. I'll be answering questions within that context today.

ALEX DEAS: I'm involved with two different activities, one of them is the development of commercial dive equipment. So, first of all, commercial diving, the other area is sports diving, a long passion. I started in 1979, and finished extreme sports diving about 1999. We can go down to 100 meters now, but it was extreme at the time. I have a long history of diving, and commercial diving with rebreathers as a primary system, not a secondary.

PAUL HAYNES: I would like to personally thank all the speakers yesterday and today, very informative. It's a pleasure to be here. I started diving back in 1990 using closed-circuit rebreathers. After that my passion for sport diving kicked off. Since 1998 I've been working for a company called Divex, which is the world's largest manufacturer for professional military diving equipment. I appreciate there are many people that haven't come across Divex. We can build you a saturation system in 24 months. My job in the company is primarily to look after the defense business. My other roles would be development, chief instructor trainer for the company and the company diving officer. I perform all of those roles for naval divers and the equipment we supply to them. I'm also a passionate technical diver myself. First class diver and instructor trainer. I'm fortunate to dive with a group of divers in Scotland who are dedicated to wreck exploration. We find six or seven virgin wrecks each year. You must go up there because there's so many stories to tell. I will be back here as well this afternoon. I'm now responsible for developing the BSAC pool of technical instructors.

GENE MELTON: I represent Neptune Rebreathers. Back in the 1970s, I worked for the Harbor Branch Foundation at Fort Pierce, as a submersible pilot and lockout diver. We used the Bio Marine CCR 1000. I also have a passion for cave diving. As part of that, I wanted to use rebreathers to continue that endeavor. However, the problem was no decompression capability. I started development of a dive computer and then got into the rebreather business. That was in 1999 and currently we have the Neptune Rebreather as a kit. This works for me in the exploration role of something that I can take to a remote site and have some survivability for what I do.

JARROD JABLONSKI: I'm the CEO of Halcyon Manufacturing and president of Global Underwater Explorers (GUE). As a consequence of the expeditions for GUE, I got into rebreathers and started dabbling with them in the mid-1990s. In the late-1990s we started using them in expeditions, most notably for long range cave expeditions, and then expanded out into a range of ocean environments as well. As a consequence of GUE, we're also involved in the training of rebreathers as well as a range of mission-specific rebreather utilizations.

LEON SCAMAHORN: I represent Interspace Systems Corporation. I'm a 12½-year Army Special Forces veteran. I've been diving rebreathers since 1986 and have a considerable amount of experience. I got out of the military and started teaching for Bio Marine. I was a primary instructor until they went out of business. I was convinced to start my own company and work on my own apparatus. So that's what I did. So myself and my business partner have been in business since 1999 building the Megalodon CCR, which has been very popular, especially throughout Europe. Very robust apparatus, very modular. It's used for deeper diving, for challenging dives, and so it's a fine piece of equipment. I'm a former private investigator, so that gives me a good eye on observation and a pretty good ear, and I take good notes.

GAVIN ANTHONY: The first question. There are two basic principles for rebreathers; semi-closed and closed-circuit, and there are obviously disadvantages and advantages between them. As Jarrod is involved in semi-closed, I've asked him to lead on this and to give us an initial comment.

JARROD JABLONSKI: Probably overly simplified for this group of pretty high capacity. But when I think of the two systems, I think it's easier to start with closed-circuit systems, where we're dealing with really just a static volume of gas, breathing in and out into that loop as a result. We're going to have a consumption, or a metabolized O_2, and production of CO_2 and we have to manage both of those by eliminating the CO_2 and adding O_2. That can be done in a few different ways, which is obviously part of the main points of contention. We might bleed gas in with a fixed flow. We might manually add the oxygen. We might electronically control the addition of the oxygen or some combination thereof. With a semi-closed system we've really just got gas that is being encouraged to be removed from that loop. As a consequence of that removed gas we have to add gas to make up the additional volume. This can be done, again, through a variety of mechanisms. Perhaps through a fixed orifice flow, or my preference would be in a respiratory coupled capacity where you're attaching the amount of gas added to the loop as a consequence of the diver's breathing. This tends to give you a little tighter control over the oxygen. Obviously, from a theoretical point of view, I think that the gas consumption logistics are favourable on a closed-circuit system because you really, for the most part, are only adding what you've consumed in the form of oxygen. Notwithstanding the vertical changes in depth, which require you to add a diluent to make up for the lost loop volume. The other big advantage in the CCR side is the reduction or elimination of bubbling. On the other side, I think the presentations this morning help us to understand the significant degree of complications that can also result. From my perspective, I look at this a little bit mission-specific, so I don't have a sort of theoretical opposition to the closed-circuit paradigm. I just try to evaluate whether the logistics of the mission warrant, what I perceive to be, the additional risk of the system that you might be utilizing. So by-in-large I've found that a semi-closed system, for my own use, has had a more favorable risk versus benefit relationship; recognizing that it does have some limitations, but over a relatively constrained set of parameters, for example: if you're operating within a fairly fixed depth range and you have easy access to supply gases, you can sort of mitigate any of the oxygen variation problems fairly easily. Gas consumption from my perspective has rarely been a real problem. I would very easily and immediately change that when looking at some of the stuff Bill Stone is doing; long distance dry cave expeditions where it's very difficult to get additional gas. Or, of course, there are examples as well in aquatic expeditions. So for us we continually evaluate those circumstances and remain open to CCR application wherever it would be practically more useful, but generally tend to focus more on a semi-closed capacity, or some hybridized version of the two, whichever seems to be most useful. I tend to gravitate lastly to the simplest of the systems. I find that diving in general has a lot of moving pieces, and expeditions by default have even more moving pieces. There's a whole lot of variables that are difficult to control. So I like to control as many variables as possible, but through standardized systems, and then as much as possible through the simplification of the equipment system that I'm using. So whether it's CCR or SCR, I prefer to use as simple a system as possible, and in general I've found that that's historically for us been a semi-closed capacity.

GAVIN ANTHONY: Just being provocative. If semi-closed is simpler, do you think they're safer?

JARROD JABLONSKI: You know, I'd have to say that very generally speaking, I think that when things are simpler, there are fewer unknown variables and so they're generally safer. With a lot of caveats, however, because there are circumstances in which having a significantly reduced gas consumption could be safer. But in general, I think if you look at the average dive, then the simpler the better. In expeditions I think there are plenty of reasons to use more complex systems. But there is an attendant risk to the increased complexity of any system. That is within and outside of rebreathers.

GAVIN ANTHONY: Would anyone else like to comment?

LEON SCAMAHORN: The simplest thing can be done wrong. That's a fact. That's all I'll say.

JARROD JABLONSKI: I wouldn't disagree with that. It's harder to do simple things wrong.
PETER READEY: One of the things we found using semi-closed systems, was when teaching scientists; this may come as a big shock to you, that they weren't always the most attentive in terms of keeping an eye on their rig. I was fortunate to get a Drager, which was actually a semi-closed rig, and later on that type of device was taken on by another company, which is a constant ratio system; it very nearly gives you a constant PO_2. That's something that doesn't exist in the recreational arena and it may be something that Jarrod may look at in the future. I don't know if the audience is familiar with that type of system, but nobody really did too much with those two companies.

GAVIN ANTHONY: Just to state that that type of system is used by the Canadian Navy. It does work and it's out there. To move on to the next question, because it's very much linked with my last provocative one. How should a failure analysis of a rebreather be conducted? This is not an incident investigation. It's when you're designing it. Then when the most likely failure points are identified, what are the appropriate actions regarding design? Now, Alex Deas challenged me earlier on EN 61508, and if I could ask him to lead.

ALEX DEAS: EN 61508 really covers the electronics, electrical and software, which is an all-encompassing standard, once you start with it. Now, there it lays down requirements for carrying out an assessment, it lays out what you should do with the answers. Things which are highly recommended are likely to be certified. The next step is identifying the hazards. Now, you can really go from top down to the bottom up. The top down is bringing all the knowledge one has about accidents and incidents in the past as well as going through a rigorous system through each part of the rebreather. What happens if this fails? How can it fail? One does the same thing from the bottom up. We've published a few of these on the website so you can see, for example, just a simple thing like a breathing hose. You put it before the oil companies in Norway, and you expect it to run the same way as you're designing a nuclear submarine. That is the standard. So that's the standard we set for our clients. Then one goes through all the possible factors in identifying key words, for example, how to change the temperature, pressure, mechanical, torsion, manufacturing defects, every type of defect. Then applying key words to that, for example, temperature under and over. So something as simple as a breathing hose what happens when it's under temperature, very cold and stretched or is very hot and pulled. Those that do not meet the requirement, you have to deal with them. You have to design them out, and that's the standard we've set and that's the standard used in most industries, aviation, submarines. Its the way one does things, It's expensive. You've got 15 people for several days. So you have to start learning things through other industries and apply them to rebreathers.

GAVIN ANTHONY: I think those of us who have been involved in military systems have experience of this, the military goes through the various techniques, but one of the things it comes down to that is the fact that it's not a black and white answer. The UK military actually has a system of scaling from A to D, the scale identifies when you have to do something to make a system safer and when you don't.

ALEX DEAS: Take an example, say with breathing hoses, there are minimum safety levels. Below that you have to do something. The question is, of what is the plausible pull a diver can apply? If he jumps off something and catches his hose, then his full weight will be applied. So what we did with the different oil companies and dive service companies, we concluded that 100 kg is what can be applied with a hose under plausible conditions. The frequency that that load can occur is more greater than the SIL which you're trying to achieve. If they do a billion hours of diving, then some divers in that time will catch hoses. Therefore, we don't have an option. It's now no longer gray. It's black and white. We have to redesign the hoses to achieve that. It comes down to black and white, and it's fully traceable back to both the standards and the cause.

GAVIN ANTHONY: Any other comment?

MARTIN PARKER: Sorry, just going over the hose standard. I agree the EN 14143 standard is very low. It comes down to, you can't dictate standards in Europe. You can't dictate standards in the British standards side of it. You go along and make recommendations. We certainly tested 70 kg and I'm quite happy with 100 kg, but it is a low standard. When people sort of worry about the EN 14143 and think it's a difficult standard to reach, it's pretty easy to reach. I think, Gavin, you probably have a better idea of why we settled on 25 kg.

GAVIN ANTHONY: I don't think we necessarily need to get into it at this stage. It's the principle of testing. What I want to draw on here are things are not necessarily black or white.

LEON SCAMAHORN: In critical analysis you've got severity, occurrence and detection, and each one has a table. That table has a list and can go from 1 to 10. Those numbers can be specified by a whole bunch of things. It could be based on historical analysis of similar products. It could be using similar products or manufacturers that have basically similar products, maybe not the same products. But you assign it a number, and that number determines what's acceptable to you, or your customers or your customers' requirements. If that number is too close to that, to the acceptable number, or you're not satisfied with that such as severity, occurrence or detection, if severity is high but occurrence is low, but you have low detection and the number on that one severity table is very high, you have to do something about that and design that out of there. You know, personally, I think toxic cocktails should be a thing of the past. The way you do that is you design the apparatus to have water traps or a water expulsion system. I don't believe divers should ever have a toxic cocktail. You have to look at reasonable doctrines also. You apply doctrines like, what is truly real world, what is plausible, what has happened. You brainstorm on what could possibly happen. But you've got to be real about it, and look at what has happened. I tell you, when you think you've thought of everything, somebody finds a way, to do something wrong with that. They get really creative. It's amazing what people do.

PETER READEY: Many of the issues that you see on various types of units, I guess you could liken it to the object of the operation is to get around the racetrack, and we've got a Model T Ford with an air bag, a comfy chair and a radio. There are some really good tools that you can use to look for condensing areas. John Clarke made a good point on the Mark 19. Some of the failure points could be discovered if you use tools in the design, before it goes through real world testing. In the old days, it was pretty tough and very expensive, because you had to build it in the garden shed. You built your prototype, go and test it, see if it would or wouldn't work. It cost a lot of people money to go to the Navy. There's companies like Solid Works that now have some excellent tools that don't cost a fortune. What you can do, particularly a CFD, or you can do a log test. Bill has just used this on the Poseidon. We used it on the Prism. That gets you a long way toward where you need to be to building a good, solid piece of life support.

GENE MELTON: For those who are interested, NASA produces a document for failure analysis. It's free. You can Google it. The booklet will take you completely through the failure analysis of any piece of hardware you want to do. Obviously, NASA has a concern, and we witnessed a lot of them over time. So they developed a good process for how to evaluate your hardware. As the owner of a piece of hardware, you can perform your own analysis and decide whether you need to take particular control or care with different items within it. It may be available on your Kennedy Space Center, standard KSC something, just Google NASA and failure analysis and you'll find it.

BILL STONE: We can probably belabor this topic for the rest of the day. Two points. One is that Peter recommended certain types of analyses. I think what his comments were largely directed to was performance analysis, not necessarily failure analysis; these are two very distinct features that they refer to in the European union. Coming out of NASA type analyses, there's really two separate things you need to think about when you're doing failure analysis, and that is they are environmentally or situationally dependent. Almost everybody in this room is a technical diver. There is an entirely different class, which greatly outnumbers us by a factor of 100 to 1, of people who use diving equipment to go out there and have fun, as opposed to directed mission type things which technical divers are good at. For a group that does nothing but recreational diving, your failure mode analysis may be reduced to the aspects you have to design into the rig in the event that a failure is detected; then you have to ensure that the detection is positive and the action is trained. When you're talking about a technical diving system, that's a whole different level. It's the difference between what we refer to as a system failure versus a mission failure. When you're talking about recreational, you really don't think about mission failure, because you don't have a mission. All you have to do is say, hey, it's not working, get the heck out. If you're talking about technical diving, and you do have a specific mission. You've paid transport time, possibly to some remote location and you've got all the helium that you've paid for. So the question is how can you have the best possibility of completing the job that you set out to do. This is where things get complex. I spent 25 years thinking on these topics, not just because of personal survival, but because of the fact that we have paid, on many occasions millions of dollars, to try to get where we want to go. This forces you to think, all right, if that goes wrong, how do I create backup such that I'm not in an abort situation. NASA actually has a phrase for this that came out of the 1960s. It was fail-operational, fail- operational, fail-safe. The fail-safe is abort. That means they're switching to a bail-out. The big question is how can you do analyses ahead of time that will get you to where you're reliable in those first two stages. This is a topic that we could spend at least a day explaining. I just wanted to say it's more complex than you think.

GAVIN ANTHONY: I'll take that as a lead to move on to the next question. Should a recreational rebreather be tested by a third party? Also, the available test protocols, are they actually appropriate for recreational rebreathers? If I could ask Pete.

PETE NAWROCKY: Well, everything we put out to the general public has to be tested and definitely by a third party. Dive Rite, when we developed the Optima, we looked in terms of U.S. Navy standards by the plain and simple fact we weren't planning on selling anything overseas. Also, the Optima is using extended cartridges made by Micropore, which they've done all the testing on. We're using Juergensen Marine electronics, who already have a proven track record. Dive Rite basically put a kit together and built the Optima that way. For what we're doing we feel we have the appropriate test parameters. But there's always room for improvement on everything out there. This is a growing segment of the industry, so anything we develop in the way of testing parameters should be built in so we have some growth, so we can improve on our product and bring out better technologies for the consumer.

GAVIN ANTHONY: Anyone else?

MARTIN PARKER: In Europe, of course, it's a legal requirement. We have to satisfy the PPE directive. So it's a legal requirement for us to comply, we cannot manufacture in Europe unless we have third-party testing. We've seen the importance of unmanned testing and manned testing for the scientists. If you go down the CE marking route, you'll

invariably be pushed toward EN 14143; at the very least take out of that what you can. Even if you're not going down the approval route, there's a lot of useful stuff. We don't have any choice. We have to have third-party testing.
GAVIN ANTHONY: Would you want to expand on your statement as almost a definition of third party. I didn't identify it fully this morning. However, the Notified Body in Europe is an overseeing body. They don't necessarily do the tests. The tests could be done in-house.

MARTIN PARKER: Yeah, absolutely. The easiest way is to take it to somebody like Gavin's Test House at QinetiQ, and they will do the whole thing; even then they're not a notified body. So you get the test house to do the tests and the notified body, to witness the testing and issue the certification; based on the testing conducted at the test house. Three years ago we installed our own machine so we were able to do a lot of our own testing. It doesn't have to be particularly onerous. If you are going to make rebreathers, you need to test equipment, and you can do an awful lot of the testing in-house and have the Notified Body simply fly over and witness it. There are notified bodies in the USA as well. The ongoing requirements of assessing the CE products is something that you tie into ISO 9000. So the ISO 9000 inspector comes every six months as opposed to every nine months to review.

ALEX DEAS: But there's detail involved in testing everything, this is then checked by the notified body to make sure that they get the same results, in the same circumstances, and that the results are calibrated and traceable in much greater detail, and they're all done in-house. But a notified body comes in to check the results and the methods. I was asked to reproduce that in random tests.

GAVIN ANTHONY: That was a very European in-house discussion. Anyone else have any comments?

LEON SCAMAHORN: In the U.S. there's really no standard like the EN 14143 requirement, and there's also no requirement for having a quality management system in place such as ISO 9000 1 and 2000, which I think every U.S. company who is going to build a bebreather should have. You have ANSI 100 and various other systems for aviation, and car manufacturers have them. I think that training agencies should be ISO, and I think rebreather manufacturers should be. Only in Europe is it a requirement to be ISO 9000, there's no such thing as being 50 % ISO. Either you are or you're not. That means you have to be audited by a third party.

PAUL HAYNES: As I mentioned, we supply almost exclusively to the military and particularly in the UK; the rebreathers we supply are subject to independent testing. On behalf of the UK, at the end of the day this is life-support equipment and there should be a standard against which this is tested, a minimum standard. So I believe happenstance is a good thing. Perhaps there are certain aspects of EN 14143 which could be looked at. At the end of the day it is a standard, so when this equipment goes on the market, at least from a users perspective, it's been tested to some form of standard and we should have a confidence in diving.

GAVIN ANTHONY: If we work on the basis that equipment has been tested and there are data available on it, should the manufacturers publish on the test results? For example, aspects that we've discussed, work of breathing, oxygen level and carbon dioxide canister endurance.

PETER READEY: Yes, I think we should. To carry on from what Paul just said, I think we need a minimum acceptable standard that's an International standard. So when we say the rig is good for three hours at a certain depth, then we understand which rig or the collection of rigs will meet that standard. I think an important aspect, and I notice you talked about this previously, is it looks like the U.S. Navy and the Royal Navy (RN) are beginning to come together on their testing standards.

But I think, yes, it helps the public and would be good for the customer, because then he could pick and choose a system to meet whatever requirements he has. Right now it's pretty much all over the place. People will say the rig is good for a number of hours and it's only surface runs. You have other people who have done deep diving and they'll give you a number. So, yes, I do think it's important. Once you've got your test data, it should be published to a standard that's Internationally recognized.

MARTIN PARKER: There is some information you don't want to reveal. Carbon dioxide canister duration, that goes without saying, you've got to publish figures for that. We've just done so much CO_2 testing; it's unbelievable. We're going cross-eyed trying to keep up with it all. If you start doing tests in warmer water and at slower flow rates, you can get some fantastic durations out of the rig. But if you're going to quote those times, the divers will take those as gospel and what they'll start to do, instead of using it for one dive, which is actually a test, they'll start using it for multiple dives. So you've got to be very careful as to which tests you actually publish and which results you put out there. You really don't want to be misleading the public. Oxygen setpoint tracking, that goes without saying, you've got to publish the accuracy of your controller. You just cannot do anything else. We don't publish the exact accuracy we get. Anyway, if you're planning on running at a PO_2 of 1.30 bar then for decompression you say 1.25 bar and for CNS you assume 1.35 bar. Work of breathing. Does it meet the standard? I think that's the way you need to answer the question. Is it easy to breathe or not. Some regulator manufacturers will publish their test data, but it's a tight test to prove. It doesn't seem that every single regulator you're going to

buy is going to meet the standard. Some manufacturers will actually publish a certificate for every single regulator they produce. To do that on a rebreather would be a big involvement. We won't be publishing work of rebreathers in the near future.
PAUL HAYNES: Besides the mandatory information that you're obliged to provide your customer, if the standard is good enough, then why should there be a need to publish information such as work of breathing. Possibly if a manufacturing uses it as a marketing tool, because mine is better than his. If you have a good enough standard, if it meets the standard, it's good enough to breathe from.

GAVIN ANTHONY: Let's get into slightly more hardware and configuration control. This one I know to be a point of debate over the years. If you're going to use CCR rather than SCR, should rebreathers have an automatic diluent addition valve (ADV) as standard, or would a valve be more of a liability than an asset in some circumstances?

MARTIN PARKER: The answer is yes and yes. People that start off with an ADV go through a lot of diluent at the start. They hear the regulator kicking in and think that's normal. Certainly by starting them off on a manual feed, they learn the basics much more quickly. There was a death, I won't say which year, the diver had a slider valve fitted to the ADV, and it was closed. The diver, instead of pressing the manual button, went onto open-circuit. The diver had a kit configuration problem as well with a wing. It only inflated one-third of the size because of the additions that were made to the rig. The diver grabbed hold of the down line. The whole thing collapsed around the diver who ended up sinking down to a great depth and tragically ran out of open-circuit gas. The whole thing started off by 1) not being used to using manual add, and, 2) having the slider valve fitted. Then the pre-dive inspection wasn't good enough so it was actually closed and not open. Other things on the downside of an ADV is that if it starts to leak and dribble into the rig, it reduces the PO_2. You then start to lose gas from both sources. The same thing occurs if you've got a leak in the loop, or it might be a leak from your mask. An oblivious diver might not appreciate the importance of this. So the ADV adds gas and reduces the PO_2. The set then adds oxygen. So you lose gas from both sources and you see yourself going down this spiral, just because you've got a leak on the loop. It's actually learning to dive without an ADV that is quite a valuable resource. I certainly appreciate having used it manually. Having said that, every unit we sell in the States has an ADV. That is 95 percent of all units we sell anywhere. Personally I dive with one. The safety feature of not getting a negative pressure on the lungs as a diver descends is a great, great safety feature. And, yes, I think they should have one.

GAVIN ANTHONY: To put the question in the inverse, do any of the manufacturers on the panel think that you shouldn't have one?

PETE NAWROCKY: If you're looking at real-life situations with an ADV, it really depends on what the type of diving that you're doing. If you've got both hands free and you can manually do your adds, you'll have no problems at all. Most of you who know me, know I carry a camera probably 95 % of the time I'm in the water. So swimming into a cave or swimming down into a ship wreck having that ADV makes it easier for me in a heavy current, makes it easier for me to get into a cave, because I know I'm always going to have breathing gas. This because I have one hand full and possibly the other hand is going to be busy too. I happen to like having the slide on it, because once I reach depth I turn it off and now I do my manual adds if I need any gas. If I do have a leakage problem, I can reach back and turn it off. That's just my personal way of diving.

PAUL HAYNES: If you apply a safety study to any rig, human error analysis, the result of that will demand you have an ADV, because the risk of not having one is unacceptable.

ALEX DEAS: I concur with that. But I suggest that with the shut-off valve, the same study would indicate people haven't shut it or have them half open. So I think the question is whether one has that the shut-off valve.

PETER READEY: We used to use a diaphragm, and we went to a valve not too dissimilar to the Biomarine 155, it was a Schrader. One thing that was found by John Clarke and his crew, there were certain orientations we did not advocated putting the slide valve on. It was a quick disconnect, but a high flow valve into the Schrader. One of the reasons we put it on is, because whether you're sponge collecting or commercial diving it was pretty much mandatory you had a valve to add the gas. There was no way you could pull up heavy bags of stuff and start pressing buttons on your lungs. That's one of the key things when you're training people, about 70 % of you will blow gas out of your mask. Makes no difference on semi-closed-circuit. So that's one of the areas that we have to focus quite heavily on training.

LEON SCAMAHORN: OK. Automatic demand problem, an advocate for that for a long time. We have two systems that we designed, the first one we had was basically a second stage that was plumbed into the breathing loop. It was a Super Pro G250. It was a nice kit. Worked really well in all orientations of a diver, but it had limitations. You could dial up the sensitivity to it and you could deliver fairly well in a high flow, but it was big and bulky. Customers wanted something smaller, so then we went to a piston-style system that was more mechanically operated. Where there was the collapse of the counterlung, that would physically activate the system. I would personally prefer it; it's much smaller. The flows are higher. What is important about an automatic demand valve is, if you're diving down quickly, and all of a sudden the diver experiences a negative lung load and feels like he's trying to draw air out of a pop bottle, you understand that there's absolutely some value added to that automatic demand valve, and you're glad to have it. It should also be ambidextrous on the body. You should be able to reach it with the left and right hand. Your buddy should be able to reach it. If you had any of the three H’s [Editorial note: Hypoxia, Hyperoxia or Hypercapnia] and you didn't know which one it was, and neither does your buddy, the one standard thing that should be taught in training is that your buddy can flush you in all orientations, and flush the loop of any toxic gas that might be in there. Hopefully then recover the stricken diver. ADV are good for that, they're very good for that. Does anybody dive a drysuit without an inflator valve? Think about that with your lungs now.

GAVIN ANTHONY: That looks to me like a consensus, which is a nice outcome [Editorial note: See consensus statement on ADV]. Another design and configuration question. For electronic CCR should they turn on the electronics automatically to reduce the risk of hypoxia?

PAUL HAYNES: Should they turn on? Well, assuming that the rig is designed and built in accordance with good engineering practice and to a standard, probably a safety case study will reveal that the man is the weakest link in chain. So it's hard to justify not incorporating into a life-support system a feature that mitigates human error. There does come a point when the user has to take responsibility for the correct testing of his rig. If that means turning it on, doing a pre-breathe before jumping in the water, I don't think it's unreasonable to expect a manufacturer to expect that of the user. That said, hypoxia is a recurring problem whenever you do a safety study of a rig. So as rebreathers become more mainstream and they drift toward the less disciplined side of the market, again, it becomes harder to justify not incorporating a feature that offsets human error, which was believed to be the cause in a number of fatalities. I just throw that up for thought. By incorporating that feature does it foster or nurture a lazy state of mind? If you think it's going to turn on when you jump in the water, and design the breather to account for that kind of person, they get in the habit of just jumping in the water because the unit turns on and because that's what it always does. If it doesn't turn on and he's not paying attention to his alarms or lack of alarms, then you're back at the same point. So I don't have an answer because, fortunately, as a manufacturer of defence equipment we're not faced with that issue. We have diving procedures to make sure that, before the man gets in the water he's prepared and good to go. So I don't have an answer, but I can see there's two sides to it.

ALEX DEAS: There are two different questions here. First, can the unit we breathe from can allow the diver to become hypoxic? Second, do you allow the user to put it on, dive in the water, and it operate normally? It's two different issues. The first question is dealt with by looking at the number of accidents that appear to be caused by people just jumping in the water. You apply the procedures; it's an obvious hazard and frequency is going to be extremely high. The second issue is how do you deal with it. So there's a user issue here. What the decision is in terms of how you handle this problem, the main thing is just to keep them alive.

PETER READEY: We have an analogue secondary, which is live 24/7, I guess you could argue technically that it's on if you are not getting an automatic function. We have had one issue where someone didn't turn the system on. It's been a very rare occurrence. Also, because we're using an analogue display as our backup, secondary display, we try very hard to impress upon them that once you're on loop, the rig is on. It's a good question for debate. And I don't think we made the decision on that yet. But the customers will probably make the decision for us.

PAUL HAYNES: Perhaps from the audience here, how many rebreather divers are out there?

GAVIN ANTHONY: How many people in the audience dive rebreathers? Can we do it the other way around. How many don't dive rebreathers? I can see, in what would be a British union vote to strike, that it looks about 50/50.

PAUL HAYNES: So of those rebreather divers, could you put your hands up if you would not want an automatic turn-on. Now, of you people, could you please come forward and perhaps explain why you would not want it.

CHAUNCEY CHAPMAN: It sounds like a very good idea. But to make it work you've got to have a valve on the tank that the system can turn on. By not having that full functionality, what you provide the operator with is a false sense of security.

BRUCE PARTRIDGE: I make computers that automatically turn on right now. I think that is really an overrated feature. I think I can safely argue the other side of it, because I do have it available, so this is not a marketing issue. If you won't look at your display, you cannot be kept alive. You can put systems in, you know, rocket ship systems. If the user will not look at his display, certainly as technical divers we are now, you can't keep them alive. Does my automatic turn-on ever function? No. I would quit diving if I ever had it function once. You need to pre-breathe your unit. You need to make sure that your oxygen is turned on. Unless you're taking care of all those things before you get in the water, you should not be diving rebreathers.

JOHN CHATTERTON: First, I'd like to thank all of the panel members. You guys make the tools for us, the end users, to achieve our goals, achieve our dreams, all that kind of stuff. Obviously, you guys don't do it for the money. At the same time, you will never make the foolproof rebreather. You will never wire it up so that somebody can unwire it and kill themselves. I would rather see the emphasis on training rather than on devices that are going to, somehow, some way give us some sort of blanket of protection; really no matter what you do, you can't supply us with. We've got to turn the valves on.

SPEAKER: I think one of the big things you have to consider, if you make everything so automatic, it encourages divers not to think. I know a lot of people who virtually don't even track their PO_2 because they're waiting for the unit to do all the work for them. If you're taught that the unit is a manual piece of equipment, then have backup features, like it will activate the solenoid if you get down to below 0.2 bar or so, in that ballpark, that's a good feature. But it still shouldn't be saying, oh, it's automatic. As we said earlier, Bruce said, you've got to learn to turn your valves on. Divers have died because they went in the water with valves off or with wrong gas. So you've got to teach the pre-dive check, and encourage boat owners to watch it.

LEON SCAMAHORN: Don't forget to make sure there's gas in the tank, and it's the right, proper gas in the tank.

JEFF BOZANIC: It looks like an audience debate now, rather than a manufacturers debate. I'm going to take the opposite path from this. I agree with everything that's been said. We need to train our people better. We've got a training committee panel meeting this afternoon. That being said, I also believe there's at least some functionality that, if you have electronic controls and if you have the ability to provide alarms to the user, at an absolute bare bone minimum, I believe those alarms ought to turn off and on, and function. I'm stating that based on fact if you look at the accidents, and Alex Deas, Ian Martin, myself and others have been working on putting together databases, in addition to the DAN database. You look at those incidents, and there are numerous incidents where people jumped into the water without their units turned on. The unit did nothing to tell them that, and they expired because of that. Should they have been there? No. Should they have jumped in the water with their unit turned off? Obviously, not. Was it an obvious pilot error? Yes. But in those instances we can utilize design features to help protect idiots from themselves. We're never going to be able to stop that 100 %, but we didn't end up driving automobiles that go 90 miles an hour by ignoring the mistakes that people make on their own. We didn't develop open-circuit diving gear to the point where we've got a large enough market to allow all of us to go diving, by ignoring the stupid mistakes that open water divers make on their own. We have to take those things into consideration. Design and training need to go hand in hand in terms of development, if we're going to grow this beyond a really narrow special niche that meet our needs in the military, or our needs in the commercial sector, or our needs in the technical diving sector.

SPEAKER: I have the advantage of owning a training facility that thousands of divers come through every year. Several of the panel members rebreather training has been there. Jarrod has been there. What's that other fellow down on the end, Pete's been there. But the thing I've seen, and what bothers me the most being a training agency director as well, is the fact that there's a lot of very well experienced, qualified divers with a proper mental

attitude, the equipment is good, but there's a lot of rebreather divers dying worldwide, some friends of mine, some instructor trainers from around the world. I want to ask the panel a question here. Do you feel like we have lack of training in the industry?
LEON SCAMAHORN: Yes.

SPEAKER: Where is it? I see a lot of good training going on in our place. Jarrod there, with his video, I watch and I said, wow, those guys really work their butts off to teach these things right. I went through a closed-circuit course with Leon back in the 1990s or something. I don't think the training is the problem. How does the audience feel about that? Is training a problem or is it the mental attitude or the complacency or the fact that we still do certify idiots?

MARTIN PARKER: There's no simple answer to that. If you look at every incident, better training would have helped, better diligence by the diver, better equipment configuration would have helped. You're looking at a really broad spectrum and I think the work of DAN collecting the data is going to start to focus on issues that we all need to look at, whether it be training or equipment design. The biggest cause of open-circuit deaths is running out of air. How many manufacturers have active warnings to advise the diver you're running out of air? Not very many. It's up to the diver to turn his gas on and monitor his own gas supply. With rebreathers, we've taken the stance that the diver should switch the set on initially. The set has to do pre-dive checks. It has to check the sensors, it has to check connections to all the devices. If the diver gets used to jumping in and the whole thing switching on and working, there will come a day when the batteries are dead and the guy jumps in and there is not even a red light to show him there’s a problem, he's going to carry on breathing. That's the problem with rebreathers. We're going to try to cover some of that with training and through design and through education. But there's no one answer that cures the problem.

MARK CANEY: I'm Mark Caney from PADI. I think we've heard a lot here about technical diving. I'm very aware this is a technical diving conference and currently CCR are really in the realm of technical diving. I imagine some of the gentlemen at the table there wouldn't be too upset if there was an opportunity to sell hundreds of thousands of these things to recreational divers. Once you start going more mainstream, you broaden the number of people taking part in this big experiment, and there's more likely mistakes being made. People make mistakes and maybe there's one authority who wasn't invited to the table here, Mr. Murphy, because people will make mistakes. It is possible to jump in with the thing turned off, some people will do it and the more people who buy these units and go in with them, the more will go in with them turned off. So my view will be, if you can engineer a problem out, please do it. You don't have to make the thing work, but you should at least try to warn the person if they make that stupid mistake, because for sure they will make stupid mistakes. I absolutely agree training is a good thing. If you can have a backup for training, put it in. I have a dive computer I use for regular open-circuit diving. It has a little alarm feature which warns me if I go too high on my oxygen, if I have been too long and I'm approaching my limit for decompression. I think that's quite a good thing. I know I should look at my device. I shouldn't need it. But I'm not going to switch that off. That's quite a nice thing to have. The more backups we have to good training the better.

GAVIN ANTHONY: So the logic there is if you can engineer out these problems, do so.

ALEX DEAS: But that's one of the fundamental problems. Many lessons learned in helicopters and other things, is you don't have people going around the power station, saying, if the needle is here, it means the power station is blowing up. That does not happen. With a life-support piece of equipment you need clear enunciation. Quite frankly, that means a field display is needed. We also believe voice annunciation is needed. The user has a hand set. Also flashing you in the face and telling him, bail-out, bail-out, system is off. If he's ignoring it, the system is still trying to keep him alive. So most users would not go and do dives of that nature. They know the system is telling them to bail out. They have a system that's keeping them alive but their decompression obligation is high, but you've stopped the person from dying that just jumped in. These are very experienced divers dying. Some people dived with jumping in with units turned off.

BILL STONE: We have all of that stuff and have had all of that stuff since forever when. You can defeat it. You can always defeat it. I've watched people do that, who had head-up displays flashing in their eyes, who had audible alarms beeping that people could hear 100 feet away and they walked into the water. There is a certain amount of discipline that is required to use these things. Would you jump in the water with an open-circuit gear with the tank turned off? What's needed here, clearly are two things. There are situations where having this automated turn-on situation is good, and how you implement that is depending on what the industry thinks is a reasonable thing. If you can turn it on and maintain minimum PO_2, yeah, you should. Can you make it totally automated? No. Right now nobody can get around the issue: Are you going to turn your oxygen tank on? If you don't turn your oxygen tank on, you don't have access to oxygen. No electronic equipment can do that unless you put in something that is a huge valve to turn on the oxygen tank. So really what it boils down to is two things. Should you have one? Sure, it's an easy software to implement. Is that the only solution? No. What you really have to do is implement a training protocol that can be understood by everybody, that's basically it, we have many pilots in this room. You don't turn an engine on to a plane and take off on the runway before you go through a pre-flight checklist. People think it's so simple you don't need that. Somewhere in there, there's the thing that says check, have you turned the tank on before you dive in the water? You have to have checklists for rebreathers, whether it's technical or recreational. You have to instil discipline in the people who are going to use them. The bigger question here is to ask, are there people who should not be using this equipment? How do you identify them?

GAVIN ANTHONY: Would anyone from the audience like to come back?

SPEAKER: Just very quickly, you're quite right, and that's why we don't have a rebreather course at this point in time. It might well change, but your point is valid, and it is possible to make mistakes. We have to get to the stage where we can be confident people aren't going to make mistakes. Whether that's through screening out the people or changing the machines.

BILL STONE: I think that's part of the safety process of training. If you want more information on that, go talk to NASA about astronaut training.

PAUL HAYNES: Just very briefly, I come back to the point about the training. Yes, there's some superb training going on and there's no doubt about that. It's very hard to enforce standards unless there is an accident that's reported. In terms of training, my opinion is probably somewhat conditioned by my military background, I believe five days for a CCR diver is too short.

GENE MELTON: A brief for the pilots out there. The number one cause of accidents is pilot error, and of pilot error the major cause is fuel mismanagement. Now, how many hours are required for training, if there have been millions of pilots trained over the years and the same mistakes are still being made? The training has done everything it can do to minimize this happening. The alternative, rather than have the pilot switch the fuel tank, is to have it switch it on its own; they haven't figured out how to do that in aircraft yet! But the accidents are still happening. I could go on and on and on with these type of things. You can't legislate against stupidity. I'm sorry.

JARROD JABLONSKI: They're waiting for us to address a lot of the automatic aspects. I have a predictable response to most of them. I think for me, the more complex the unit, then the more difficult it is to make a lot of the nuance kinds of decisions that you hear everyone debating about. When you look at open-circuit, it has an obvious failure mode. If you forget to turn on the tank and you jump in the water, if you don't breathe, you quickly come to the surface. Whereas, with a rebreather there's a range of problems. You can continue a dive with a variety of various units out there and get yourself into quite a lot of problems. The problem from my perspective, with a lot of these various warning systems is that we quickly become reliant and desensitised to a lot of these things. One of the most common things I see in CCR, both in cave and ocean, is people swimming by me with red lights flashing on their mouthpieces. So from the outside they're intentionally doing this; I understand there's a lot of practical reasons for that as well. The point is that people will often defeat these mechanisms or ignore them entirely. The more of those kinds of systems that you end up creating, the more the practicality of the desensitizing results. You have to very carefully and judiciously choose what kinds of things you really want to build into systems. I think a lot of them are mission-specific. So there are bail-out rebreather applications; given the nature of a mission-specific bail-out rebreather, a lot of things that we consider nuanced and common sense for the more recreational or common user might be impractical or inconvenient or the size limitations might really make it impossible in any given type of unit. The more recreational rebreathers become, obviously, I recognize the more problematic leaving out some of these things becomes. That's why I'm not in favour of the recreational mode of rebreather use. When I say recreational, I mean pretty distinctly recreational. There are people who are doing non-aggressive dives that aren't necessarily recreational. But the average open water user is trying to work out which way to get the regulator turned on a yoke style regulator. Nonetheless, people are making a lot of very simple mistakes. You have to dive regularly, and probably all of these individuals would unanimously say if you're going to use your rebreather, you've got to use it a lot. You've got to become familiar. You've got to understand how the unit operates, the more complex, the more frequent. Users in general don't dive often enough. When people ask me about rebreathers and ask about buying our unit, I tell them generally no. You've already made the decision when you come to me, from my perspective, if you need my help in making that determination, you're not ready for any rebreather. I prefer the more technical or very avid diver range, and for those people I think we need in general less of these various controls.

PETER READEY: One of the biggest problems I've seen is unfortunately most of you come from an open-circuit background, and you have a mindset, whether you know it or not. I'm breathing therefore I'm OK. It happens real quick when you don't get gas on open-circuit, it's pretty immediate. Nothing focuses your mind like the thought you're going to die; whereas, on semi-closed or closed-circuit, a lot of time we spend on students is trying to get them to the look at the display. The hardest thing is to get them to look at the display when they get in the water. They breathe, they say everything is fine, normal. You're in the red zone. I don't know how you can fix that, other than to get them to use the system a great deal or extend the training to some considerable period of time. That's a different question.

BRUCE PARTRIDGE: I have a couple points. First, on the specific issue of the automatic turn-on. First, it's very difficult, if not impossible, to engineer a system that will automatically turn on in all cases. As you get to very pure water it gets very hard to turn on with it. If it does turn on with that, it won't turn on in the boat. Also people defeat them; this is real life. Turning on by breathing also has failure modes. If you're at altitude or you're in a plane, you have to take the sensors out, so now it doesn't work. You've got to put the sensors back in for the thing to turn on automatically. Yes, you've changed the failure mode, but you haven't eliminated it. Going from there to a philosophical view, I agree wholeheartedly with Jarrod about simplicity. I find that many systems are way too complex for people. There's a philosophy that Gordon Smith put me onto, and I believe we can all benefit from it, and that is John Adams work on risk. We don't react to risk, we react to perceived risk. We always need to keep that in mind when we're designing these systems. You can read more about it in the book.

GRANT GRAVES: I think there's two functions here. On the design issue, it's got to be unit-specific. If the unit is able to function and give diver information when it's off, then it's a different equation than if you have no information and you cannot fly on that unit without power. If you have an auto on and somebody doesn't want the auto on, somebody will take the battery out. The other problem is with technical and recreational diving you cannot system the diver out of the situation. They are free swimming. They're un-tethered. It's not for everybody. We can set parameters for safety and set up a training system, the question is even the best diver will be a weenie one day. We can't ‘weenie out’ the factors in diving. You have to use the right divers, train the mindset. No matter what you engineer in, you're still only as good as that end user.

GAVIN ANTHONY: I'm conscious of balancing between the panel having a say and the audience having a say. Another question.

ERIC MACHUM: PADI instructor and DAN representative. In the 1950s they came up with a rather unique sort of thing, called a seatbelt, and there were people that argued that that should not be in a car. If we take out the seatbelt, is that going to change the way people drive and reduce accidents? It's a good safety feature. It doesn't change the driver from speeding and causing accidents and killing people. We wouldn't see all the new companies making rebreathers, if they weren't looking for the recreational market. The more people that are getting involved in this, the more safety features that are there the better. The divers that have died have all been instructors or commercial divers; they've forgotten the things that they teach their students. They didn't follow through with what they were supposed to be doing, and it's very sad. We all fail. And the more safety features that are there the better, I think, as far as I'm concerned as a recreational diver.

JARROD JABLONSKI: I just want to address the seatbelt concept. I've read some interesting statistics that actually indicate people wearing seatbelts tended to drive faster and more recklessly and get into worse accidents. I'm not trying to say that seatbelts aren't valid, or they shouldn't be included in cars, nonetheless, other caveats start to come into play. How do people respond to their perceived level of risk as a result of a safety belt?

ERIC MACHUM: I don't wear a seatbelt. I drive a motorcycle!

ALEX DEAS: There is a simple solution, comparable to the problem that on open-circuit you can't breathe. We've been advocating auto shut-off valves for a number of years. When the unit is off, you cannot breathe through it. It's simply a valve that incorporates in the mouthpiece. That gives you the same feeling as you do on open-circuit. I spend a lot of time in Russia. In Russia they kill a lot of people. I've seen dead people on the roads every two weeks in Russia. I've never seen one in Scotland. You see the whole family spread out all in this position. The people just don't think about it. In the west we used to say no to valves, I can tell you, safety valves save people. Safety features in rebreathers will save people, and simple features like auto shut-off valves, they can prevent a lot of accidents.

PAUL BURNHART: I think if you make something more idiot-proof, they just improve the idiots for you. Two things. We treat training as a one-time event. One of the problems is probably more related to the fact that we don't promote ongoing training and proficiency practice. It doesn't help if the last boom drill you did was three years ago in your initial training. As a pilot I go every year to simulator training. So the focus has to be on ongoing, recurring training, not just initial training. To ask the panel, when we certify an aviation instrument as a level A, the FAA is less concerned with whether or not it fails, but whether or not the pilot knows absolutely that it failed. Do you feel you do a better job in providing absolute indications that something is seriously wrong, as opposed to having six or seven different minor alarms that get ignored? That's what happens in the cockpit. You have a whole bunch of ground proximity alerts. You turn the thing off because it's a waste, and you lose the critical thing. So are we providing too many alarm systems, too many notifications without an absolute indication that something has failed or there is a problem?

PAUL HAYNES: Interesting that there's been no reason given, and probably because people haven't had time to think about it. There's been no operational reason given to this point why they should not have automatic turn on. If the diver can't turn it on, the diver shouldn't be diving with rebreathers. When you come back to people that engineer safety analysis and that is identified as a human error, you are obliged to design that out.

GAVIN ANTHONY: If I was to try and summarize what happened there, I'd probably be a fool. It looks to me like the general consensus today is, if you can engineer out some safety aspects, you should try to do so. But, and a piece of paper was handed to me just now, and I'm actually going to use it. “Nothing is foolproof. The fools are too clever.” I think that's it. You can't solve everything just by engineering it out. You've still got to take a brain under water. Moving on to the next question. We've heard about maximum depth from a physiological point of view over the last couple of days. What equipment factors determine the maximum recommended dive depth of a rebreather? Is there a specific depth for your own equipment?

LEON SCAMAHORN: I'm going to start from the bottom up. I'm going to start with a test facility that's going to be doing the audit on your equipment. You need to have a facility that can test to the depth that your customers intend going to. They also have to know, not only the time but duration for the scrubber and everything. I've experienced various tests. In fact, I'm doing a study on test labs, and they are different. They may share the same machine, but it's the people running them that are different. So there needs to be standards in that regard. Then you look at regulatory requirements. You look at regulatory requirements for testing. You may decide to design to, or to live up to that standard. Or you're going to request a variance. Customers requirements are pretty important. A lot of customers want to beat on their chest and say that their apparatus can go the deepest, the longest, and all of this. It's a marketing fact. So you want to design to customers' requirements whatever that may be, either for military application, maybe some sort of cave penetration, some exotic thing, or to recreational limitations. So you've got to design to that. Carbon dioxide, of course, we've heard a lot about carbon dioxide. Just carbon dioxide in the human body by itself, you can have that from build-up in the apparatus or from the diver themselves. The diver may be out of shape. Hydrostatic lung loading, all these things incorporate design in the apparatus. Probably the biggest thing is how do you keep everything pressure proof and dry. From the simplest cave light, canister light for cave diving, we see implosions and accidents and things like that, where guys are losing their lights to flooding. Flooding is a problem. Saltwater and electronics, they're incompatible. You've got to protect that at all costs, so the diver doesn't lose their ability to monitor what they're breathing. That leads down to the displays, the actual information that the diver has to physically look at, so he can make a determination if he's breathing too much or too little and he's within that tight realm of physiological requirements for oxygen; not only to stay awake or from doing the kickin' chicken, but to make sure they're not going to get bent like a pretzel. Then you look at the time. There's the time that a diver is in the water. I've got guys that spend 11 to 15 hours in the water. You get a lot of moisture build-up in the system. Of course, sensors have an issue with that regard, so does absorbent. You also get tired of listening to a raspy sound in your exhalation hose, and so you have to have an adequate water trap or the ability to dry out the system to keep your sensors dryer, or you design that in from gas flow characteristics and minimizing humidity in certain parts of the loop. So time is another critical thing. Of course, water traps because you have a build-up of moisture in the system from the carbon dioxide absorbent producing water along with the heat, you have to have adequate water traps to minimize the collection of water that's going to build up over that period of time, and have some sort of effect on the apparatus. I've got customers that dive typically to 500 feet. They take it like it's a casual dive to them. They go to a warm-water environment. They jump in the water, minimum bail-out. They are a manufacturing nightmare, but they're good customers. They're good divers. But they treat it like a dive to somebody diving to a recreational depth of 60-130 feet. I do have personal discussions with these people and I do shake my finger at them because I have that ability. I have an open-door policy as a CEO, any customer can talk to me about anything, and that's important. So customer perception, pretty important. But 742 feet is what my apparatus has been down to on several occasions, and I get reports from guys that want to go past 1,000 feet on the apparatus. So that makes me have to consider design, and breathing simulator test, to see what can happen. I had to give one guy a larger scrubber canister, because he insisted that he was going to take the canister that comes standard with my apparatus that he had dived, to 660 feet; then he said, well, now that it can do this and I tell everybody, why should that justify them buying a more expensive radial canister. Can you understand what I'm getting at here? OK, so I, at my cost, over-nighted to France a larger canister because I just knew he could have been a fatality, because he was diving the wrong canister for that type of dive. But that's the things that manufacturers have to face.

ALEX DEAS: Limits are set for rebreathers and I think the limit, is work of breathing. Every Rebreather, work of breathing is limited. Now, what happens is that people take them too deep and they breathe faster. Breathing faster causes higher work of breathing, higher carbon dioxide tension. It's a one-way trip. Dan Warkander has done some outstanding work in establishing what are these standards. They've done the work, and we have to abide by those. I know a lot of technical rebreathers divers like going deep, because you don't have to carry so much gas to go deep; there's news. The news is that is not a safe practice. The more people that do this,the more accidents there's going to be. So you can either argue with Dan Warkander over his figures and produce your own. Or you can label yourself, I'm a looney doing this, and sooner or later I'll die.

PETER READEY: Now I can answer the question I should have answered earlier. We have a different approach on building systems. Way back when, last century in the Diving Diseases Research Centre in England, we did quite a lot of testing on systems in the hope it would keep us alive. After that we found some theoretical programmes, I worked on the principle, I didn't want to use customers, myself or the customers who did scientific work as crash test dummies. So I tried to get as much of the data as possible to look at a system that we could use safely to 300 feet. That was the idea. Once we got all of the data in terms of how we built it, how strong it would be, and looked at some of the flow characteristics, what's the minimum size of hoses and make sure we had no hole size too small, only then do we get an estimate from the U.S. government or go to DCIEM [Editorial note: now DRDC Toronto]. We had this great idea for a scrubber, and all the numbers in its program were superb until we checked it in the water. In the tropics, not a problem, two and a half hours. When we put it in cold water and tested, we didn't even get 50 minutes out of it. So we had to redo that. Fortunately, we got the numbers close enough, and increased some of the hole sizes to get the breathing resistance down in some areas; then we actually got the Navy to get interested. Even then there's still some idiosyncrasies. So before we wanted to sell a system to the public, we felt a better way to do it was to get as much of the theoretical testing done. There's a lot of programs. They're not hundred thousand dollar programs anymore. They're a lot less expensive than spending out on testing. I'm sorry to perhaps kill some of the work for you guys, but we used to spend a lot of time and money on test facilities to find out whether we were on the right page. I think now, with technology, it's much easier to predict what your system is going to do at the 400-, 500-, 600-foot mark, and then back it up with independent data. If you've got a customer that is going to 600 feet, you know that your system is capable of it. You should be able to tell him what your unit is capable of. I rest my case.

BILL STONE: I don't believe we got to a direct answer to the last question. I think probably the closest answer was this one right here by Paul, and that was that you can design these things to do whatever you want. The question is, are people going to physically manufacture these things because they do have to have a consideration of staying in business? If I sold one rebreather, that would go to 600 meters and that's the only thing I sold this year, did I really make a good business choice? But ultimately, the answer is, is it going to operate reliably from a work of breathing standpoint. Peter said you can simulate and analyze most of this before you produce it. So just a minor follow-up.

GAVIN ANTHONY: The next question is about bail-out. What are the relevant issues regarding equipment and procedures for bail-out gas systems?

BILL STONE: This would fall into two categories. One would be from a technical diving standpoint, the other from a recreational standpoint. The latter one would be the easiest to answer. If you're talking about a recreational rebreather, by definition, we're talking about a decompression device, so 40 metres with decompression. Within that regime, you can make a fairly accurate calculation on what the diluent bail-out should be, to get a semi-stable person to the surface. If you have a totally panicked diver, your respiration rate goes up. So within that context you can design an on-board diluent system to act as an open-circuit bail-out directly within the integrated rig. When you start going to more complicated technical diving, that is a mission management or physics calculation that you have to make on your own. People like Jarrod could probably give you an entire-day lecture on how they go about calculating bail-out extremes. So it's not a question of whether or not to have one. You absolutely have to have a bail-out extreme. The question is, how do you go about setting those things up? It's really a personal calculation. If you're concerned about redundancy, then you have to figure out do you have split systems or, whether you have single systems with you. Most of the people that I've seen doing deep diving with rebreathers will typically have twin large-capacity open-circuit bail-out things and then a string of either vertical or horizontally deployed stages for getting yourself back up. Should open-circuit bail-out be standard equipment on all rebreathers? No! It's a diluent gas and oxygen supply gas for a closed-circuit system. When you're talking about bail-out, for integrated recreational rebreathers, yes, you should be sizing the diluent bottle for a very specified condition. The problem with technical diving is you're entering into a very highly variable situation, so you have to do a custom design for your bail-out system. Should there be minimum standards? Again, this is a custom thing that is dive dependent that is defined by the people who are setting up the mission for a technical dive. What I would set up for a deep cave recovery bail-out, would be totally different from what Jarrod would set up for an abort. So I don't know that we can converge here on a single set of procedures. If somebody believes that they can do that better, then I'm quite happy to listen.

LEON SCAMAHORN: We saw yesterday in the movie, that a three-liter cylinder just wasn't enough; the guy ran out. I've never advocated on-board bail-out on any rebreather, because it just was not enough. If that three-liter bottle was just enough, maybe it was just enough for one tiny dive or shallow dive. If that guy had put two dives on that rig, he definitely would have run out of gas a heck of a lot sooner. Nobody recharges those cylinders between dives, unless you replace the cylinder. Generally rebreather divers dive with what they've got left in their cylinders because they have that capacity to do so. The bail-out is the one tank you know for sure that's good, it should be fully charged, never used, class A regulator, analysed gas. But a bail-out bottle, which is truly intended to do that, should not violate gas sharing principles with another open-circuit diver. That means it should have a long enough hose, independent gas supply that you can hand it off, or hand off as a second stage for somebody else to breathe on. To have a tiny, little thing on the side of your rebreather that only you can breathe on to me is a violation of gas sharing principles that any basic open water diver is taught not to violate.

PAUL HAYNES: Just to pick up on that. In terms of a standard for bail-out, that's pretty hard to define. In terms of a basic unit, I wholeheartedly agree that a bail-out should be a completely and totally independent system. It shouldn't be inflating the BC or your dry suit. It should be a stand-alone system. So it's not just a recreational issue here. Bail-out is bail-out. It's an independent system. It doesn't fit your suit, it doesn't fit the BC, and it also can support a buddy diver.

JARROD JABLONSKI: A particularly problematic aspect from my perspective is this issue of bail-out. I think it dovetails with Hal's question earlier that I set aside on the training issue. These are not easy decisions to make. I think from a training perspective as a preamble we have a lot of things that we need to do. We need to carefully evaluate the entry qualifications. We need to stop treating it, as if it's inevitable that rebreathers will be used by the very basic, recreational, open water diver. That's a decision that we as manufacturers and consumers and training organizations have to make on one side or the other. It's only inevitable in so far as we make that choice. I think we'll need to tie that with a rigorous evaluation criteria of the people we do choose to certify, and along with that I'll come to the issue of bail-out. I think, clearly we're all going to have pretty reasonable differences of opinion. It wouldn't be hard to say that we can take a baseline conceptual experience of a rebreather failure, and try to decide whether we're going to plan for that, which is what we do and what I believe needs to be done in a bail-out scenario. So I plan for the rebreather to fail completely. It hasn't ever happened, it probably will one day. We've done everything we can to design out the potential for a complete failure. After ten years or more, I can say that that is something we haven't been unfortunate enough to have to deal with, but we plan on every dive as if the rebreather would be completely useless to us, and then we still have to get home from there. As a general caveat roughly twice the open-circuit gas that you would need is sufficient to allow a buffer for extreme degrees of duress, and to also allow you to help a dive buddy who has had some type of a problem with their system. That's generally what we plan around to great success. We've done a wide range of trials on it. We've had a lot of long series of dives that range up to 30 hours of total underwater time. We're planning for significant immersions and a wide range of failures. But I think this is one area that the industry really needs to come to some kind of consensus. Even if we've filtered well, qualified individuals carefully and evaluated them rigorously, in the end if it doesn't incorporate the opportunity for those individuals to have a problem, to go to an open-circuit and carefully decide the most rational course of action, I think we're seeing very capable, very intelligent people dying on rebreathers unnecessarily. That should be a cause of concern for those of us who care about diving rebreathers, and those of us who make them because it's incredibly unfortunate when those sorts of things occurs. While it won't be trivial, I think we can work to at least a moderate level of consensus.

PETER READEY: To date open-circuit is really the limiting factor; on open-circuit it is typically the amount of gas you can take with you. Closed-circuit now brings out a whole new dilemma, because if you're using a system, a technical system, the limiting factor is your physiology, not the system that you're using. The only way I can see, on some of our technical guys, is that we should be looking at the bail-out system being another rebreather, because you can't take enough gas with you to get yourself back to square one.

JARROD JABLONSKI: I think a bail-out rebreather can, and will inevitably be incorporated, but isn't all that relevant for the bulk of the diving community? The bulk of the diving community needs to be able to switch to open-circuit. Our dives are inevitably incorporated. Our biggest drives incorporate at least two rebreathers. So I agree in that capacity, but still ample open-circuit bail-out is necessary in the transition between units for all of the most extremely capable people, which I don't think really is important to be part of public dialogue.

PETER READEY: I'll agree with you. I'm not talking about a bail-out rebreather is the same size as we're using. There is a place for a small, compact unit. We have customers who have been diving to some very serious depths, and they have another rebreather they call affectionately the ‘line queen’, to get back from where they're working to the line.

That's not really appropriate for recreational diving, but I think if you're using a recreational set, and if you go beyond the no-decompression to decompression diving, even a semi-closed system that would be a lot smaller would suffice; but that's the future.

GAVIN ANTHONY: I'm going to close now. From my perspective, it's been a very useful and very informative discussion. It has involved the panel members and the audience as well, which is encouraging. I would certainly like to thank all the gentlemen on my right for agreeing to participate and for giving their views.

TRAINING WORKSHOP: CHAIRMAN'S SUMMARY

Petar J. Denoble, M.D.
Divers Alert Network
Durham, NC

This workshop is divided into three parts. The first is presentations on diving fatalities and expedition planning. The second is a panel discussion with eight diving instructors. The third is answers to written questions submitted by the instructors.

Technical diving involves complex equipment and procedures which allow divers to extend their penetration into the underwater world with consequent exposure to numerous challenges. The knowledge and skills to master this environment require dedication and systematic training which most divers obtain through training agency programs followed by extensive experience. Divers and the diving community need to monitor safety in real time, intervene preventively, and stay up to date with safety measures, but accidents will happen despite these efforts. This workshop reviewed planning procedures, accident statistics, and training issues pertaining to technical diving safety.

John Chatterton and Richie Kohler presented their risk assessment plan for the 2006 expedition to the wreck of the *Britannic* at 400 feet below the surface. All dives were conducted with closed circuit rebreathers by untethered divers in a busy seaway. Risks considered included equipment malfunction, DCI (DCS and AGE), oxygen toxicity, gas supply issues, entrapment or entanglement, disorientation, panic, thermal stress, and diver adrift. To decrease the chances of problems, fit, well-trained, and experienced divers were selected who had to be not only skillful and self-reliant, but capable of cooperative teamwork. A tight-knit organization is essential to mitigate possible adverse outcomes. "No matter how much you want something not to fail or need it not to fail, it probably will fail."

Petar Denoble presented statistics on diving deaths for cave diving, rebreather diving, and recreational diving. Cave fatalities have declined steadily since the mid-1970s, while rebreather fatalities, although rare, have risen since 1998. Reductions in cave-diving deaths appeared related to increased emphasis on cave diving training and restricted access to caves for untrained divers. The increase in rebreather deaths may reflect the growing popularity of this equipment. Many rebreather deaths were associated with either operator error or equipment failure leading to an unsafe gas and loss of consciousness. Sequential analysis revealed the most common triggers, disabling agents, and disabling injuries were: (a) insufficient gas, emergency ascent, and asphyxia for open circuit; (b) becoming lost, insufficient gas, and asphyxia for cave diving; and (c) procedural or equipment trouble, insufficient gas, and loss of consciousness for rebreathers. Once a sequence of adverse events began, there seemed to be a twilight zone between consciousness and unconsciousness during which a diver is incapable of self-help but might be safely rescued.

A panel discussion among training agency representatives and independent experts addressed previously suggested questions. (Some panelists submitted written answers, which appear at the end of this workshop.) Most agreed that formal courses are stepping stones to perfecting skills and achieving self-reliance but cannot produce competent technical divers by themselves. Defining technical diving was a challenge. Some panelists did not distinguish between technical and recreational diving, others contrasted recreational to occupational, and some contrasted recreational and technical rebreather divers. There were similar discussions concerning prerequisites for technical training and the progression of training. Everyone agreed that using rebreather checklists before diving might avert some fatal errors, but how to ensure that checklists would be used was not clear. There was extensive debate of how to achieve diver compliance with procedures taught in training. The issues of buddy diving and buddy breathing elicited spirited discussion. The importance of role models and the diving culture itself were emphasized as key re-enforcers of safety practices.

Audience questions reflected differing views as well. Why, some asked, were training courses briefer today than in the past even though equipment and procedures are more complex? The responsibility of individual divers was frequently emphasized. Differences in attitudes toward diving among three generations of divers were discussed, and the challenges of instructor quality control were pointed out.

The workshop reached no firm conclusions, but Karl Shreeves of PADI summed up a general feeling: "For our culture to grow, our subcultures need to communicate by expressing our opinions as we have done this weekend. DAN can give us that venue."

RISK ASSESSMENT ANALYSIS: EXPEDITION *BRITANNIC* 2006

John Chatterton
Last Breath Productions LLC
Harpswell, Maine

Richie Kohler
Laughing Swordfish Productions LLC
Brick, New Jersey

RICHIE KOHLER: In 2006, John and I lead The History Channel *Britannic* Dive Expedition. Each of us came to this expedition with years of offshore diving and charter experience. But this was my first Britannic dive, and I was an expedition leader. John had a lot more experience so we divided the responsibilities, and I chose to be the dive safety officer or the DSO.

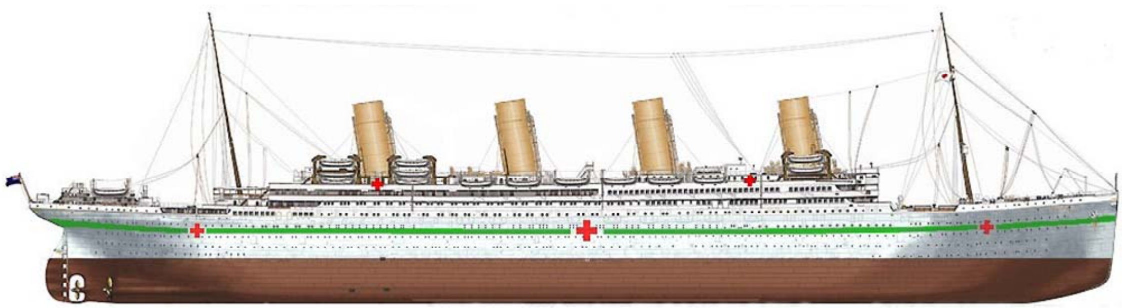

Figure 1. Model of HSS *Britannic*.

JOHN CHATTERTON: My job was the dive operations officer, and between us, we put together an extensive, written dive plan. I wish we could say that we pulled this whole thing together ourselves, but we didn't. In 1994, a British group Starfish Enterprise went to the *Lusitania*. They had a dive plan built over many expeditions. There was also the 1998 expedition to the *Britannic* on which I was a member. So we really had a document to which many people had contributed.

RICHIE KOHLER: The risk starts with the people we brought to the expedition. We chose 12 bottom divers who had to meet exacting criteria. They had to be closed-circuit rebreather divers as our permit would only allow rebreather divers on the wreck. They had to have wreck diving experience up to at least 300 fsw. And John and I had to know them personally or have been diving with them because on an expedition dive, you need to trust your co-workers.

For example, if somebody was taking over-the-counter or prescription drugs, it might not be the drugs that caused a problem as much as why the drugs were needed in the first place. Every one of the team members had extraordinary responsibility to the team. In other words, if I'm not ready to make the dive, I have an obligation to say so. That helped maintain team integrity and minimized the chance of injury.

Organization. The dive marshall (DM, aka diving supervisor) is the "go to guy" running the daily dive operation topside, liaising with the captain and support crew, tracking all diver's times and assigning tasks to support divers as required by schedule or emergency. In short the DM has the final word on everything that pertains to the dive. Mirrored after military and commercial operations, our dive plan command structure was designed to control all activity on the back deck so as to ensure that all aspects of the dive operation were monitored and a clear and concise emergency protocol was available if needed, all with a nod to the limits of the team resources.

After a long day of diving on the wreck, bottom divers would take the following day "off," that is not doing a repeat deep dive, but work topside to assist in operations for the next team of divers. A detailed schedule was drafted in which the most important of the jobs without fail was the support divers, whose single most important task was to provide gas (or back up CCR) to bottom divers in the event of a major unit failure. Layered support provided the ability to handle multiple situations so that no matter what issue or combination of problems arose, the decompression phase was uninterrupted and as stress free as possible. Besides their assigned jobs for the normal or planned dive, emergency scenarios such as diver adrift, gas loss, electronics failure, loop flood and even an unconscious diver were discussed and prepared for with a planned reaction and assignments. Everyone clearly knew what was expected of him or her in case of a problem. Long runtimes clock out the OTUs and a CNS oxygen toxicity seizure during the long decompression phase was a very real possibility. Support divers were in the water with the dive team during the entire hang, diligently monitoring them, ready to lend assistance and help a convulsing diver to the surface. The number of support divers, (deep, intermediate and shallow), was determined by the gas needs of the bottom divers, the environmental conditions, and the size of the dive platform. Having more support divers in the water was not as important as having support divers in the water when needed.

When we were convinced we had good people, we began to study the risks – real or imagined – as listed in Table 1. First, the risks are identified, then prioritized. Which will be life-threatening, which will just be annoying? Next came the primary responses for the man in the water, his buddy, the deep support divers, intermediate support divers, shallow support divers, and top side.

After the primary responses comes the backup plan. Murphy loves divers and loves complicated plans into which he can throw a wrench. Now you layer your support from intermediate, to bottom, to surface – because several emergencies may occur at once. Finally, in case everything goes belly up such as if someone blows to the surface, you need an evacuation plan that will not strand divers still in the water.

Table 1. Managing risk in expedition diving.

Identify	Back-up plan
Prioritize	Primary response
Evacuation	Layered support

JOHN CHATTERTON: I was diving a rebreather during my previous expedition on *Britannic* in 1998. It was early in my rebreather career, and I was at a critical move on a wreck penetration when I noticed my handset was blank and stayed blank no matter how many times I looked. Somehow, I got back to shore and called the rebreather manufacturer who is not here today. I explained that my handset was bad and was told, “No problem, we’ll FedEx you a new one, what’s the address.” I ran down to the hotel and learned that FedEx doesn’t deliver to the Island of Kea. But all that was needed was to write on the package, “Deliver it to the port of Kea and give it to somebody coming to the hotel.” When I said, “Fine, what’s the address?” I was told, “Triangle, backwards E, happy face...” The point being, we would need backups, and we would need to bring them with us.

Table 2. Identified risks.

Equipment malfunction	DCI (DCS and AGE)
Oxygen toxicity	Support team
Entrapment or entanglement	Gas supply
Communications	Panic
Lost or disoriented	Diver adrift
Hypo/hyperthermia	

Equipment malfunction. If it's in the water with you, be prepared for it to fail at the worst possible moment. No matter how much you want something not to fail or need it not to fail, it probably will fail. Whatever we needed as a team, as an expedition, we needed to bring it with us. We did pick up a few items in Greece, but everything from local providers let us down – compressors, booster pumps, cylinders, everything. An expedition has to be prepared not just with what is needed but also what is needed for backup.

Figure 2. Evan Kovacz and Carrie Kohler analyzing gas (Richie Kohler).

Decompression illness (DCI). DCI (decompression sickness, DCS or arterial gas embolism, AGE) was a real concern for which we definitely wanted to be prepared. How would we manage it? Our first approach was avoidance by having experienced team members who would ascend the shot-line according to controlled decompression. In preparation for trouble, however, we had information sheets on every diver in case someone came to the surface unconscious. This printed information was in the hands of the DM, and ready to send along with an injured diver. We contacted the chamber in Athens so they would know when we were diving. If we had an injury, it could be very slight or a major event. For minor injury, we could transport by boat to the chamber. For a major injury, such as a blow-up from 400 fsw, we needed healthcare professionals involved, not our fellow wreck divers. For this, there was a helicopter on standby so an injured diver could be picked up at Kea and transported to Athens.

Figure 3. Helipad at island of Kea (PJD). Figure 4. The medical center at Kea (PJD).

Oxygen toxicity. Oxygen toxicity was a real risk on our very long dives. We used air breaks and for divers who were comfortable with them, full face masks. We did not push divers who were not comfortable with full face masks into using them. A full face mask not only gave us safety in case of oxygen toxicity but also allowed us to use underwater communications which was very helpful for bottom divers, and support divers as well.

Figure 5. John Chatterton donning the full facemask (PJD).

RICHIE KOHLER:

Support team. The buddy team helps if you are in trouble or panic. If everything went bad, we had topside support to get an injured diver back on the boat and evacuated quickly so that other divers didn't break decompression. We maintained a support team on the boat including a kitted-up rebreather deep support diver and two open-circuit intermediate or shallow support divers. We also had a RHIB (Rigid Hull Inflatable Boat), which maintained a position above decompressing divers to render immediate surface assistance to support divers. The support divers had full face masks for communications between the vessel, divers on the wreck, and divers at the decompression station.

Entrapment or entanglement. We planned to go into the *Britannic* where no one had been before. We hoped we knew what to expect, but we really didn't know. Outside the wreck is also a problem because of fishing nets, fishing lines, and previous expedition lines which were strung all over. Diving in experienced buddy teams is the best way to manage the risk. If you're entangled at 400 feet, tell your buddy, resolve the problem, and move along.

Gas supply. Closed-circuit rebreathers have finite amounts of gas. Our greatest worry wasn't depletion of diluent gas, it was the high pressure loss of oxygen, and somebody on each team would carry a large amount of oxygen. Although we were using different rebreathers (Megalodons, Inspirations, Ouroboros), everybody had low pressure fittings and whips that could connect to anyone else's bottles. It was a little bit more complicated, but you were more confident about your next breath. Open circuit bailout was also available, and we did toy with the idea of having a bailout rebreather much like the military but having three types of rebreathers was too complex. Figure 6 shows the open-circuit bailout gas one person would need to ascend after a 50-minute dive at 400 feet.

Figure 5. Gas supplies for open circuit bail-out (Richie Kohler).

Communications. Communications are particularly important in emergencies and are the best way to manage risk. Figure 6 shows Evan Kovacs is using the OTS communication system which worked pretty well until the boat captain ran over the transducer, but we even had a backup for that. OTS is engineering a new armored cable for the transducer so that it will still work when the captain runs it over.

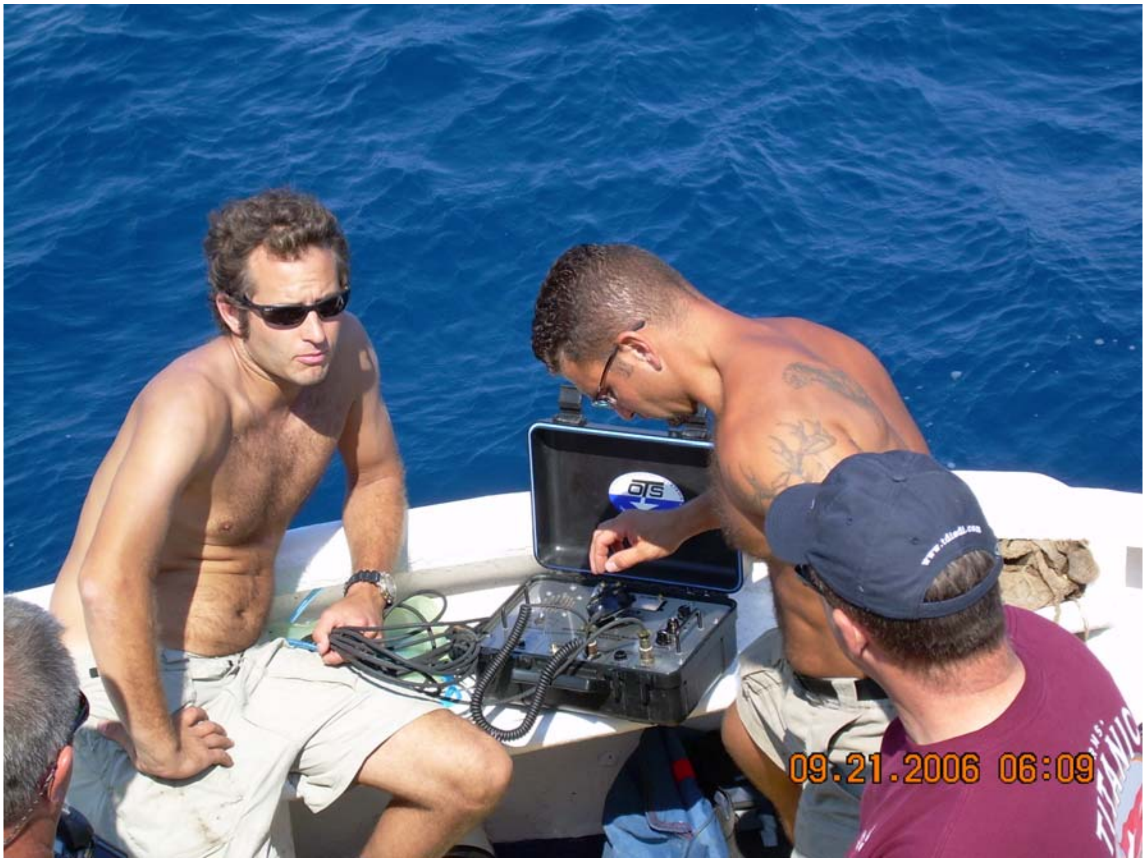

Figure 6. Evan Kovacz, left, and Frankie Pellegrino, right, operating a communication station (PJD).

JOHN CHATTERTON:

Panic. Panic causes irrational behavior. A panicked diver is not acting in his or her best interest. Panic is also extraordinarily contagious. If one diver panics within a team, there's a reasonable chance another diver will panic. The best way to deal with it is by bringing it up, discussing the hazards, reviewing the plans, and talking about past performances. This was essential.

Lost or disoriented. This is certainly a possibility on a ship wreck that's almost 1,000 feet long, stands off the sea bed about 90 feet and has cavernous penetrations. The first thing is for everybody in the water or topside to understand that somebody is missing. Next, start appropriate steps to locate the missing individual. The lost diver should attempt to communicate with the surface by electronic communication or SMB.

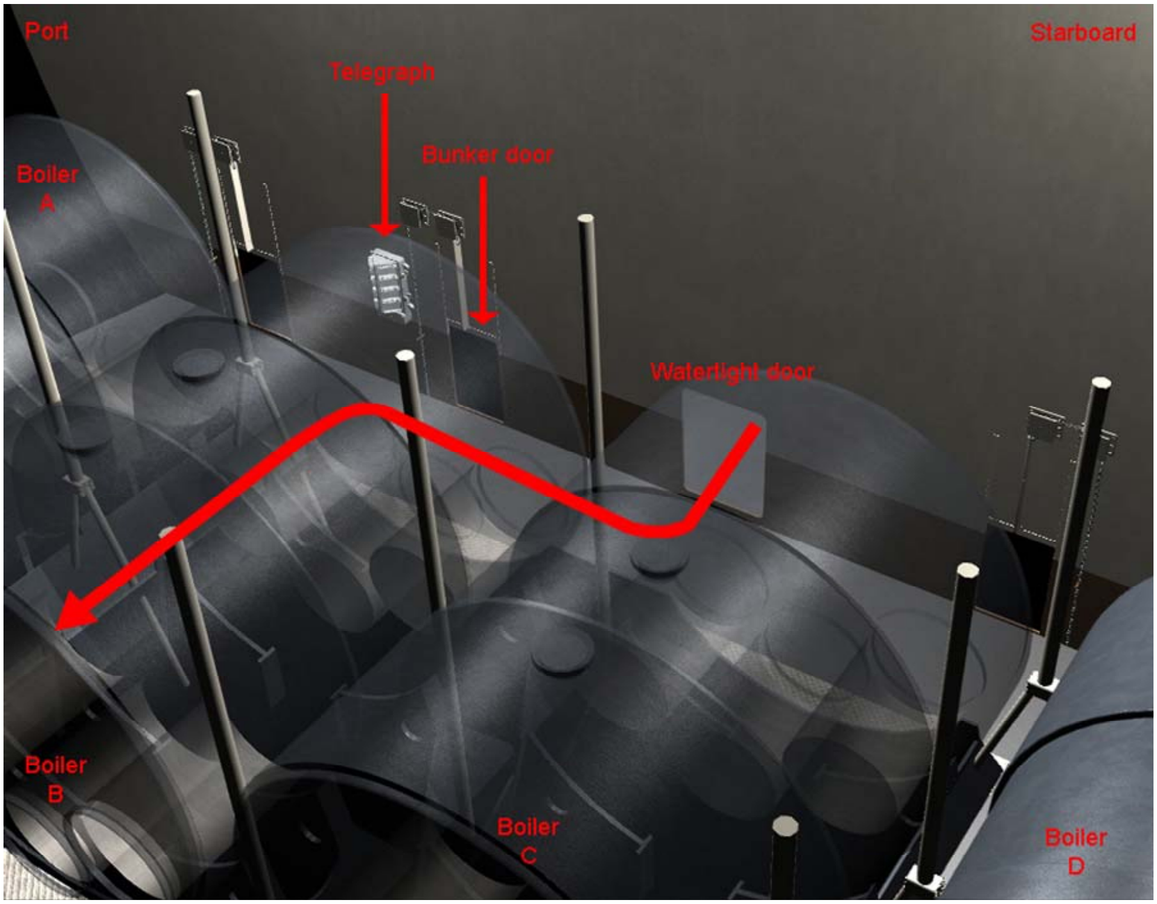

Figure 7. Boiler room (Parks Stevenson).

Figure 7 shows the Boiler Room Number 6 where Richie and I were going. If we were lost there, sending up an SMB wouldn't be much help. We had lights, but for secure voice communications, we used a 70 watt military system which allowed us to talk right through the boilers. (The buddy phone was 5 watts, and the commercial system was 10 watts.)

Diver adrift. When I dived the *Lusitania* in 1994, divers became lost and surfaced away from the boat. Our system for signaling the surface was a red SMB for everything is okay, but I'm adrift so come help me. A yellow SMB meant emergency.

On our main dive vessel is shown in Fig. 8 and was a RHIB. It carried pre-made lines with gas for the appropriate depths that could be thrown out of the boat adjacent to an SMB so that the divers would almost immediately have what they needed. The biggest danger was that the tanks would hit the diver below. We would follow deployment of gas by sending a support diver down to make sure everybody was okay.

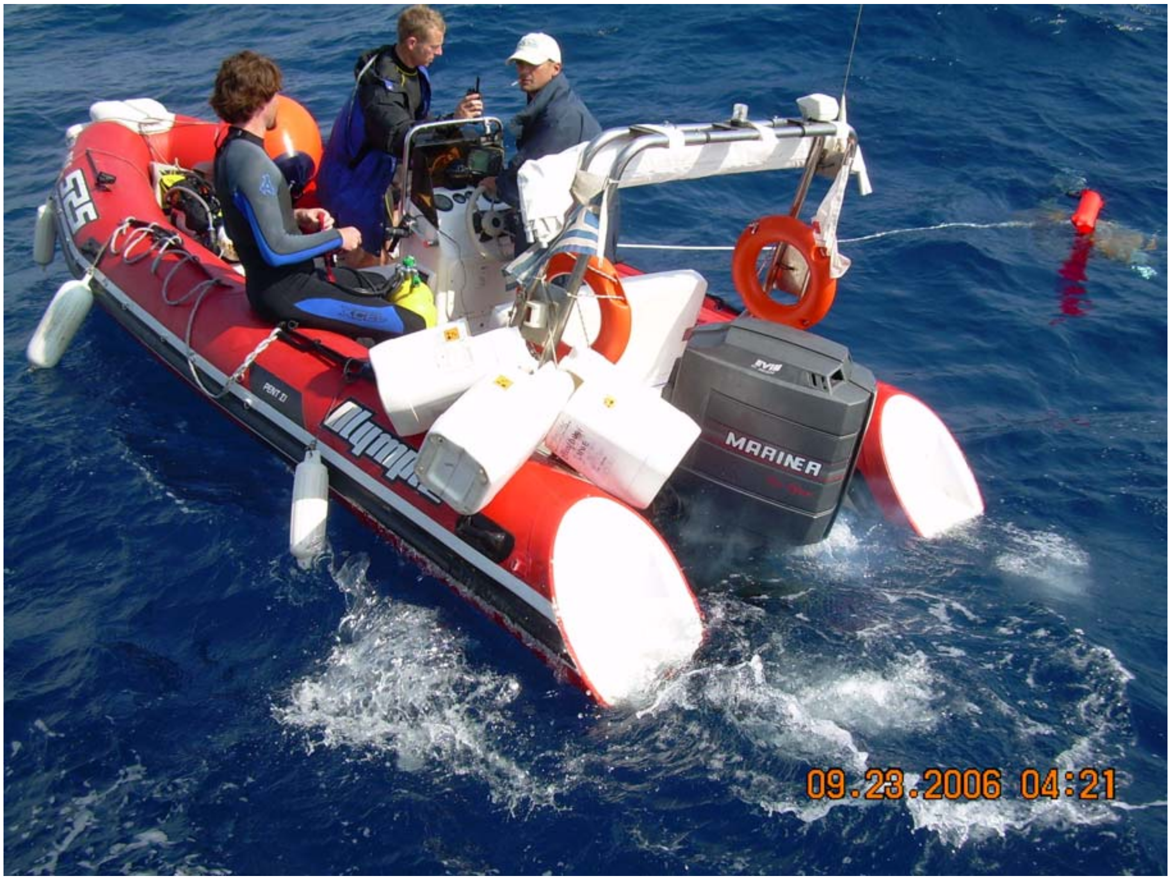

Figure 8. Surface attendants in the RHIB with buoys, lines and reserve gas for decompression (PJD).

RICHIE KOHLER: The next thing to consider was that John would be eaten by a large whale. Hazardous marine life must be part of the risk analysis. If you are going to be in "sharky" water, you need a crew to help fend off sharks for six or seven hours. In the Aegean, the second most hazardous forms of marine life were jellyfish and extremely sharp oyster-like growths on the wreck. Easily, the most dangerous life form in the water was the divers.

Hypothermia and hyperthermia. The water temperature was 78°F at the surface, 70-72 on the bottom, but a lot colder inside the wreck. With in-water runtimes exceeding seven hours in some cases, hypothermia was a real concern. Everybody wore drysuits, but even thin underwear made you incredibly hot while waiting in the 85°F weather for your turn to dive. Thus, external cooling with occasional drenchings and fluid replacement were essential to avoid dehydration.

Illness and injury. You must expect and plan for illness and minor injury. Half of our 12 bottom divers were stricken with a stomach virus which knocked them out of the rotation. This almost shut us down because of lack of healthy support. If you fell and banged your knee, the dive marshal would have taken you out of the rotation.

JOHN CHATTERTON: There was tremendous diversity within our group. We had divers from Canada, Italy, the UK, and the United States but no unanimous consensus as to what gases or decompression tables to use. Rather than try and get everybody onto the same page, we decided to let the divers make their own choices based on their prior successful experience in deep diving operations. This made things more complex for us as expedition leaders, but the divers were very confident in their procedures, equipment, and dive tables. Confidence, you know, is a big element.

To that end the majority of the team used redundant decompression computers, each with their own algorithms and conservancy settings, except for two of the team who chose to use lineal dive tables of their own creation. But everyone on in the team carried the same emergency open circuit bailout tables and each team of bottom divers carried gases defined in the OC bailout plan. No matter how aggressive or conservative an individual's dive plan may have been, the emergency plan and bailout gasses were the same.

Dive computer are powerful tools, but the commercially available units were not made for the sort of dives we planned. Simply put, they made us hang longer than we thought necessary. Decompression times that were longer than necessary would put us at unnecessary risk from exposure.

Over the years of diving these computers, we slowly gained empirical knowledge in manipulating the computer input in order to have the computer give us results that kept us DCS-free. We would manipulate the gases, their concentrations, and the gradient factors, to give us decompression times that more accurately reflect our individual decompression philosophies. In essence, this was the only way we could use dive computers on these dives. It worked for us.

RICHIE KOHLER: We identified 13 expedition risk factors, and during two weeks of diving operations on *Britannic*, we lost dive days due to weather, illness, equipment failure (compressors, etc.) but didn't have DCS or lost divers. Some of this was luck, but our luck was certainly influenced by a formal dive plan built on the experience of previous expeditions with layers of defense against the likely risks.

Rebreather diving is complex and is becoming more common and to greater depths. Complexity, particularly on deep dives, requires operational planning, not the informality usually associated with recreational diving. Proper support is essential, and as you have heard over the last two days, this support is often lacking in technical diving. As rebreather diving grows in popularity, tragic accidents will become more common if planning and preparedness are not improved.

JOHN CHATTERTON: Richie glossed over the two fatalities we had: two Sony Z1U high definition cameras. One of them was lost topside when a life jacket to which it was attached was thrown across the deck. The other one flooded on a dive. All in all, we got off cheap.

And with that, I would like to introduce Dr. Petar Denoble who brought back a boatload of data for DAN with the goal of understanding what technical divers like you and us do when we are underwater. This information can have a big impact not only on technical diving safety but also on the safety all diving communities. We encourage you to collect data on your own dives and send it to DAN. Contact Petar for details.

COMMON CAUSES OF FATALITIES IN TECHNICAL DIVING

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Introduction

Scuba diving is an activity with an inherent potential for harm. Technical diving magnifies this potential through extreme environmental conditions and complex technology including air dives with long mandatory decompression stops, multiple gas mixes, and open, semi-closed, or closed circuit breathing apparatus. Problematic diving incidents that do no harm would provide valuable lessons about how to avoid injuries, but we have no such information at present. Accordingly, we used the DAN fatality database to investigate the nature and potential causes associated with diving mishaps.

Background

Data on the number of scuba injury deaths in the U.S. was collected by McAniff from 1970-1989 and published in a series of reports (1,2). Divers Alert Network (DAN) assumed the task of diving fatality surveillance and reporting in 1989 (3). Figure 1 shows the annual estimates of diving deaths among United State and Canadian residents since 1970.

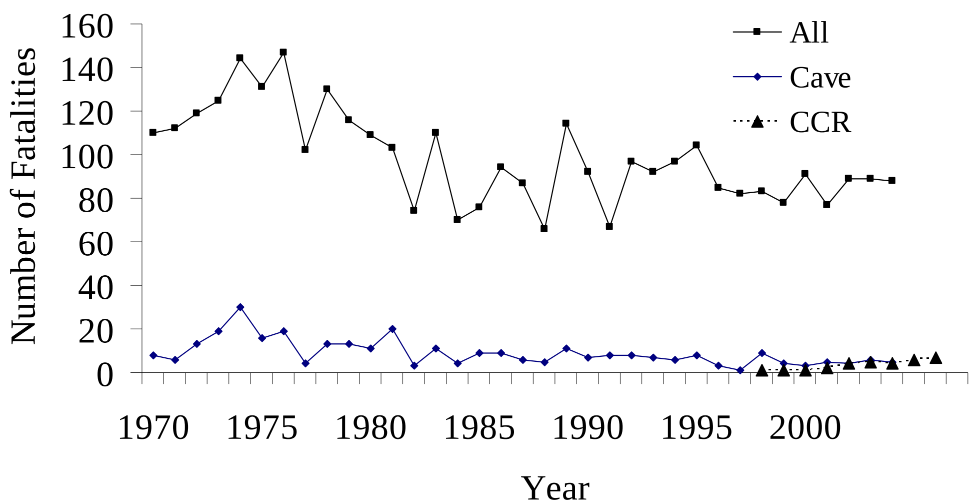

Figure 1. Annual count of scuba injury deaths in the U.S. and Canada.

The annual count of diving injury deaths reached a peak of 150 in 1976 and has gradually decreased until stabilizing over the past decade at 85 (77–91 range). Similarly, cave diving fatalities peaked in 1974 with 30 cases per year and declined thereafter. U.S. and Canadian rebreather deaths have increased gradually since 1998 when data was first available.

U.S. and Canadian cave and rebreather diving fatalities are shown in Fig. 2 as a percentage of all U.S. and Canadian fatalities shown in Fig. 1. In the mid-1970s, cave fatalities were 20% of all fatalities, but since the introduction of formal cave diving training and improved control of access to caves, cave diving fatalities have decreased steadily as a percentage of all U.S. and Canadian fatalities to about 5% in recent years. On the other hand, U.S. and Canadian rebreather fatalities have increased from 1 to 6% between 1998 and 2006 of all fatalities in USA and Canada, probably owing to the increased popularity of rebreathers.

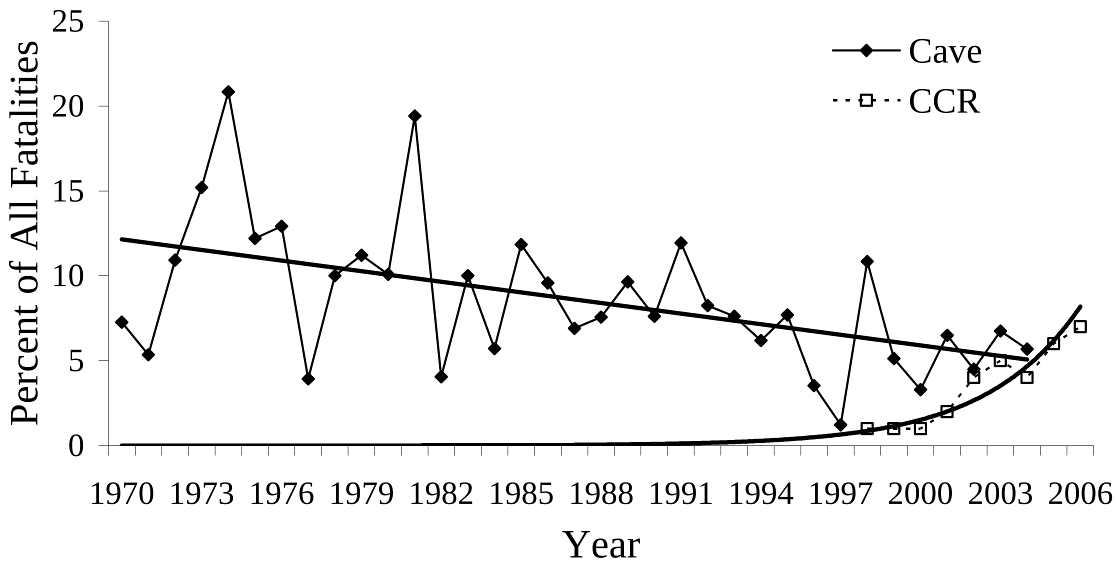

Figure 2. Cave and rebreather diving fatalities in the United States and Canada as a percentage of all U.S. and Canadian recreational diving fatalities known to DAN.

Methods

Data

Our data represented diving fatalities from three groups with distinctive hazards: cave divers, closed-circuit rebreather divers (CCR), and open-circuit, open-water scuba divers ("recreational divers"). The recreational dataset includes fatalities of U.S. and Canadian recreational divers from 1992 through 2003 (3). Cave diving fatalities are described by

Buzzacott (4). Initial rebreather data were provided by Steam Machines, Inc. (personal communication, Sharon Readey), and worldwide rebreather fatalities are now actively sought by the DAN surveillance system.

Root cause and sequential analysis

Each case was reviewed for root causes and sequential events when sufficient detail was available (5). A root cause is a specific event that could be reasonably identified, was potentially causative, and for which a guideline might be proposed to reduce recurrences (6). Fatalities often had multiple root causes or contributing factors, and had one or more not occurred, the chain of events might have been broken and the fatal outcome avoided.

The sequential analysis attempted to identify: (a) the trigger or earliest adverse event (root cause); (b) the disabling agent immediately preceding and causally related to the disabling injury; (c) the disabling injury which incapacitated the diver; and (d) the cause of death as specified by the medical examiner. For example, a diver might become entangled (trigger), drop his weight belt (adverse event), make a buoyant ascent (disabling agent), incur an arterial gas embolism (AGE, the disabling injury), and drown (cause of death). To identify the most common triggers that could be targeted for intervention, we used the Pareto principle, which posits that most fatalities have only a few causes (7). The most common triggers and the sequential patterns were compared for open-water, cave, and rebreather fatalities.

Results

The fatality data are summarized in Table 1. There were 964 recreational, 424 cave, and 83 rebreather fatalities. Decedents in cave accidents were younger than decedents in the other two datasets. Females were under-represented in cave and rebreather fatalities in comparison to recreational.

Table 1. Available diving fatality data.

Dive mode	N	Period	Mean age	% males
Recreational	964	1992-2003	43	81
Cave **	424	1962-2006	24	95
Rebreather***	83	1998-2006	45	97.5

** Early years include McAniff data. *** CCR includes worldwide data.

Figure 3 shows the three most common triggers for the three classes of fatalities. The most common trigger for recreational fatalities was insufficient gas. In cave diving, it was getting lost and in rebreathers, it was equipment related (either failure or operator error). Insufficient gas was also a common trigger in rebreather and cave fatalities. Running out of gas may seem paradoxical in rebreather diving, but the diluent and oxygen supplies in rebreathers are small and leaks can be more dangerous than with open-circuit scuba.

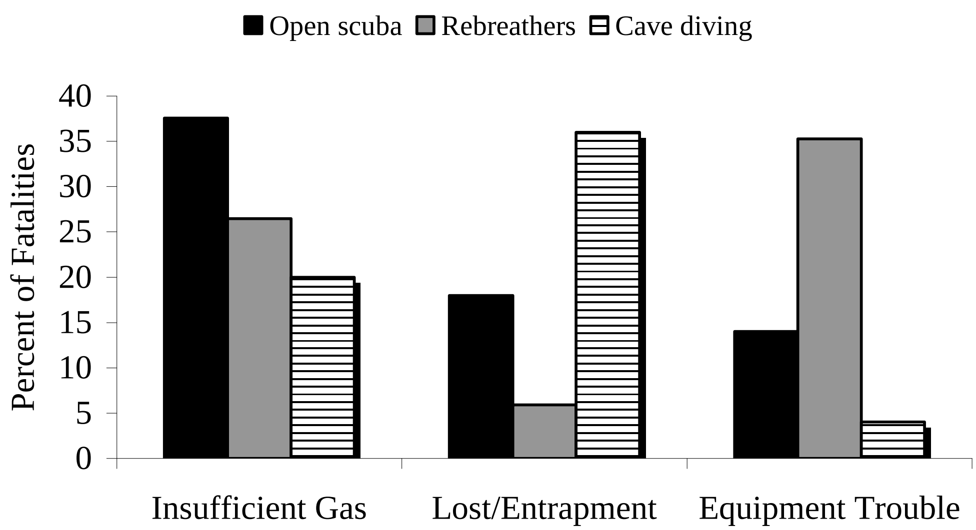

Figure 3. Most common triggers.

The most common disabling agents are shown in Figure 4. The most common disabling agent in cave diving was insufficient breathing gas after getting lost. In recreational and rebreather diving, insufficient gas and the emergency ascent were equally common. Breathing an inappropriate gas for the depth (frequently hypoxia or oxygen toxicity) and equipment problems were common in rebreather diving but unusual in open circuit and cave diving.

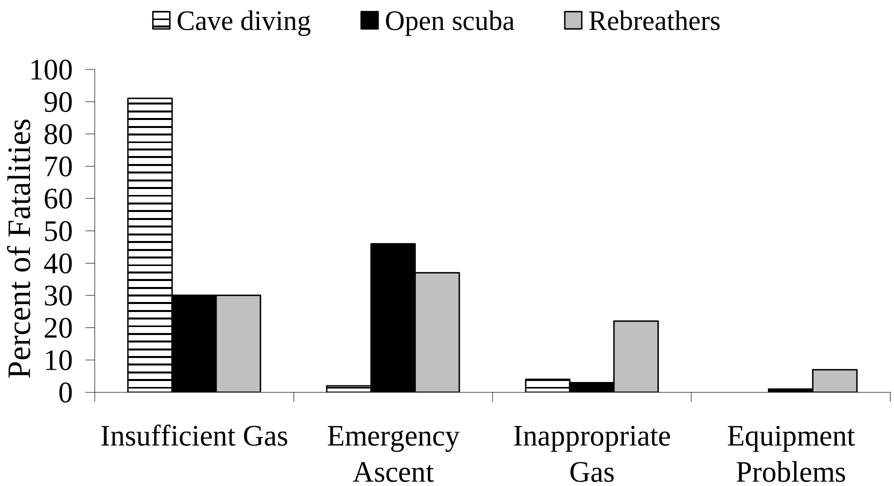

Figure 4. Most common disabling agents.

The most common disabling injuries are shown in Figure 5. For recreational deaths, the three most common injuries were asphyxia, AGE and cardiac incidents, each responsible for nearly one third of the fatalities. For cave diving, asphyxia was the injury in more than 90% of the deaths. For rebreathers, loss of consciousness (due to hypoxia, hyperoxic seizure, hypercarbia, or undetermined causes) was the most common disabling injury. When hypoxia occurred, it was frequently the consequence of a rapid ascent due to an emergency or unknown cause.

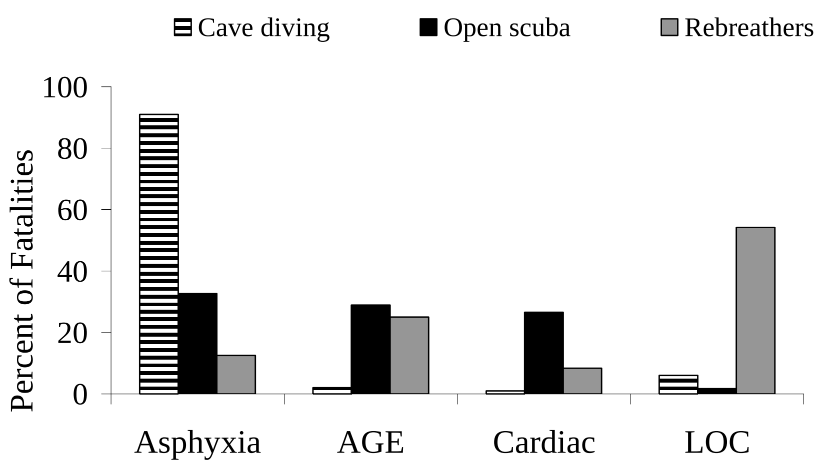

Figure 5. Most common disabling injuries.

Operator error or procedural problems were the leading triggers in rebreather deaths. Twenty-six cases included errors such as omission of the pre-dive check, not turning on the electronics (3 cases) or oxygen cylinder valve (2 cases), or using the wrong gas. Three cases involved solo test dives after major rebreather modifications. In three cases, the divers were aware of rebreather malfunctions before diving but dived nonetheless. Eight cases involved inadequate maintenance.

The following cases are typical of rebreather dives that resulted in death.

Case 1. Hypoxia. A young, experienced male instructor speared a 50 lb grouper and became separated from his buddy at 180 fsw. The buddy saw him sink to the bottom, unconscious, without the mouthpiece in his mouth. The buddy lifted victim to the surface rapidly where CPR was performed to no effect. The electronic record of decedent's dive profile indicated ascent from 190 to 50 ft at 12 minutes into the dive followed by descent to the bottom. Eight minutes elapsed from sinking until reaching the surface. Post-dive equipment inspection revealed the mouthpiece was closed, the oxygen tank was empty, and the diluent tank valve was closed. The bailout tank contained 38% O_2 but had no regulator. Errors made by the diver included beginning the dive with a depleted oxygen supply, apparently closing the diluent gas supply, and not having a functional bail-out system. Using a pre-dive check list and having a proper buddy check before diving might have been helpful, but it was unclear why the diver closed the diluent valve. Had he used his diluent supply in open-circuit mode, he may have been able to reach the surface safely. It was also unclear whether he knew he was out of oxygen, but he may have been distracted while chasing fish.

Case 2. Hypoxia. This diver was very experienced in rebreather use. His buddy saw him having convulsions 35-40 min into the dive at 147 fsw. The buddy tried to put the back-up regulator into victim's mouth, but his teeth were clenched. The buddy made an emergency ascent with the victim and developed severe DCS. Equipment inspection revealed that decedent's oxygen tank was empty. The convulsions may have been due to hypoxia.

Case 3. Faulty equipment. The diver was a middle age male with two years experience in rebreather diving. Witnesses reported that before diving, his electronics unit was beeping which he "cleared" by hitting it on the boat railing. At 125 msw, while exploring a wreck, he was witnessed to switch to his bail-out gas supply. Shortly after he was seen shaking as in a convulsion but did not take his buddy's backup demand regulator. As the buddy had a significant decompression obligation, he inflated the victim's buoyancy compensator and sent him to the surface alone. The victim was unconscious on the surface and remained so. The cause of death was determined as drowning. The diver had ignored a warning signal before diving and may have damaged the electronics by hitting it. He apparently became aware of a problem at depth and switched to his bail-out gas but not soon enough to avoid convulsions from what was probably oxygen toxicity.

Case 4. Rebreather electronics not turned on. A diver planed a solo dive to 50 fsw. He prebreathed his rebreather for 20 minutes and turned it off to suit up. He had bought a new suit, and this dive may have been a buoyancy check. The diver forgot to turn on the electronics before entering the water and neglected to check his displays. He lost consciousness due to hypoxia shortly after immersion. The electronic switches were off when victim was found.

Discussion

Diving risk cannot be completely eliminated, and complex systems have the greatest risks. For best reliability, the diver, the equipment, the environment and the operating procedures should be designed to work together in as much as possible. Of course, this is more difficult for complex equipment such as a rebreather when compared to open-circuit. Accordingly, human procedural errors seemed more common for rebreather diving than for cave diving where insufficient gas was the primary trigger or recreational diving where insufficient gas and entrapment were the primary triggers (Fig. 4).

Loss of consciousness was the leading disabling injury with rebreathers with hypoxia being the most frequently suspected cause, especially when approaching the surface. Hypoxia is insidious and difficult to recognize and correct. Most victims of suspected hypoxia did not use their bail-out systems, and when bail-out was attempted, time was insufficient before unconsciousness. Carbon dioxide-related problems were suspected in only three cases although this may be underestimated since CO_2 cannot be monitored in the breathing loop.

The inability of a diver to recognize when the breathing gas is unsafe (due to hypoxia, hyperoxia or hypercarbia) makes self-rescue unlikely. Unfortunately, a buddy often does not recognize this condition until the mouthpiece is dropped, and the diver is incapacitated. Moreover, helping an unconscious diver underwater is difficult for even the best prepared buddies. Thus, preventing loss of consciousness during rebreather diving should be a primary objective for equipment design, procedural planning, and diver training. The use of full-face masks may be of particular value for improving rebreather safety.

References

1. McAniff J. U.S. underwater diving fatality statistics, 1970. Kingston, RI: National Underwater Accident Data Center 1970.

2. McAniff J. U.S. underwater diving fatality statistics, 1988: with a preliminary assessment of 1989 fatalities. Kingston, RI: National Underwater Accident Data Center 1989.

3. Vann R, Freiberger J, Caruso J, Denoble P, Pollock N, Uguccioni D, et al. DAN's Annual Diving Report: 2006 Edition (Based on 2004 Data). Durham, NC: Divers Alert Network; 2006. Report No.: ISBN 0-9673066-3-9.

4. Buzzacott P, Zeigler E, Denoble P, Vann R. American Cave Diving Fatalities 1969-2007. *International Journal of Aquatic Research and Education*. 2009; 3:162-177.

5. Denoble PJ, Caruso JL, Dear GdL, Pieper CF, Vann RD. Common causes of open-circuit recreational diving fatalities. *Undersea Hyperbar Med*. 2008; 35(6):393-406.

6. Rooney J, Vanden Heuvel L. Root cause analysis for beginners. *Quality Progress*. 2004;July:45-53.

7. Busino G. Pareto, Vilfredo. *The New Palgrave, A Dictionary of Economics*. Vol. 3; 1987:799-804.

TRAINING PANEL DISCUSSION

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PETAR DENOBLE: The purpose of the Training Panel is to discuss questions panel members and others developed in the months before the conference. A full list of questions and written answers submitted in advance appears at the end of this discussion. All training agencies were invited to participate. A few could not. We begin with brief introductions.

STEVEN BARSKY: My background is in commercial and recreational diving. Like Kirby Morgan, I do consulting in both fields for companies. I have created a lot of training materials for various training agencies and have a publishing video company on the side.

JEFF BOZANIC: I'm a semi-employed beach bum. I've been involved in diving instruction for a long time as an independent instructor. I have worked with a number of the agencies in the past and currently. I served on National Association of Underwater Instructors (NAUI) technical advisory committee for many years. I've worked with IANTD on its board of advisors and with Technical Diving Instructors (TDI) on its rebreather advisory board. My ultimate goal is to improve the safety among all recreational and scientific divers. I've also worked with the American Academy of Underwater Sciences (AAUS). And I've written a little bit here and there.

SEAN HARRISON: I have been involved in the industry in various facets, starting with retail and three liveaboard operations around the world. I am now with TDI, responsible for quality management and membership services.

TOM MOUNT: I am with International Association of Nitrox and Technical Divers (IANTD). I started diving 1957 courtesy of the Navy, before all the people on this panel were born. When I got out of the Navy, my first dive was a cave dive. I had read an article about it by Bill Roy and Eugene Clark. One of their warnings was: "Be sure you wear enough weight that you don't get stuck in the roof of the cave." I followed the advice for one dive and one dive only. My next big adventure was deep diving, in which I joined the likes of Hal Watts. I think we were some of the crazies at the time, and we are still crazy. I was lucky enough to be involved with the development of formal cave training, deep training, and rebreathers. I was in right place at the right time. I dive as much today as I did when I was younger. Just as serious, just as far out, actually more so because of better tools. My whole goal is to make dive training as safe as humanly possible.

KARL SHREEVES: I've been with PADI (Professional Association of Diving instructors) for about 20 years. I started diving in 1970, which was before I was born, just for the record. I got into tech diving in 1991 on Rob Farb's *Monitor* expeditions, and took up cave diving in the early '90s. I also dived with the Cambrian foundation, and I'm on its safety board.

PAUL HAYNES: I'm the rebreather and open circuit instructor trainer for the British Sub-Aqua Club (BSAC). I sit on the National Council of BSAC as their technical development officer.

DAVE PENCE: I'm the Diving Safety Officer for the University of Hawaii. I started diving in the 1970s, a little bit after Tom. But after coming to school in North Carolina at N.C. State, I started working as an assistant instructor, and that combined with my science lead me into dive training specifically for scientists. When I took over the scientific diving program at the University of Hawaii, I inherited a graduate student by the name of Pyle and that necessitated my rapid education in advanced diving techniques. Probably because I was one of the first lemmings off the cliffs in the scientific world, some of the other diving officers seemed to look to me for advice for better or worse. But my advice has come as much from the other people sitting in this room as well as at this table.

JARROD JABLONSKI: I'm here primarily in my capacity as president and director of training for Global Underwater Explorers (GUE). GUE is a nonprofit organization I started in 1998. I've trained and been on the advisory panel and on the training committee panels for many of the different major and not so major organizations. I always felt a strong responsibility to try to promote vibrant and passionate interest in the sport that I love at the same time as trying to promote a realistic and safe standard by which we all try to pursue the activity, which is the reason for the formation of GUE.

Question #1. Training objectives

JEFF BOZANIC: The first major objective of any training program has to be to keep our students alive. The second objective would probably be to keep our students alive. And the third objective would be to keep our students alive. If you look at the accidents that have been going on, between 80 and 95 percent of them, depending on how you want to interpret the root cause of any given incident, can be attributed to pilot error. To me it says that there is a lot of room for improvement in our training programs. The reality is that training for rebreathers is no different than training for open circuit on major objectives. We are trying to instill the knowledge and develop skills students need to dive safely. In addition, we want students to develop the proper attitude so when they leave the training program they continue to dive in a reasonably safe manner. I think most of the people at this table agree about basic objectives, but the devil is in the details and how we go about achieving these objectives is kind of where we're at.

TOM MOUNT: I think there would be one more objective you should add. One of the things training agencies need to do is to make trainees aware that it's their responsibility to remain true to the foundations we train them on. You cannot make an expert in one week and, unfortunately, many of the divers after one week or two week courses think they are experts. It's important for a trainee to realize that formal training is only a foundation and they need to keep up building their skills and maintaining proficiency. Personal training is what works. Teaching students the importance of discipline is the most difficult part of training.

JARROD JABLONSKI: I think our first and foremost responsibility is to evaluate the suitability of the candidate to pursue whatever type of training is involved. On the recreational level probably most people can pursue recreational diving activity. But there are some who are not qualified for a variety of reasons. As diving becomes more complicated, there are more people who are not suited to that sort of diving. Still, most people are capable. I see that as one of our primary responsibilities. It sounds easy. It's, in fact, one of the least favorite parts of my job when I have to tell someone he is not qualified. Second, we maintain a responsibility to provide a core understanding of various aspects that are relevant to that particular kind of training whatever it is. I would second or echo Tom's comments about telling students that this training is a precursor to their developing proper experience. The instructor's job is to provide students with an understanding of all the major areas that can go wrong and to give them a basic platform so they can practice safely. However, the mantle has to be passed at some point. Ultimately, we have the responsibility to evaluate their core competency to pursue the activity that we're "certifying" them or qualifying them to pursue. This includes establishing a realistic minimum standard that involves problem resolution and stress management. An example in recreational diving is being able to clear a mask while being neutral in the water. In a technical diving, it means being able to solve basic problems while under some moderate level of stress.

TOM MOUNT: I would like to add a little bit to what Jarrod said. I think one of the problems we see today is that some instructors teach students to do skills static. Students need to learn to do things in the diving environment while moving. Keep the emergency as part of the dive. Don't start concentrating on emergencies. Most people when they get in an emergency, they leave the dive mode and go into the emergency mode and then they usually create two or three more emergencies.

Question #2. Concerns about training

PETAR DENOBLE: What are the major issues concerning technical diving training? What's the difference between technical and recreational diving?

JARROD JABLONSKI: From my perspective, cave and technical dive training really opened a very new world for me. I was an avid ocean diver and wreck diver. Not as much in the technical realm initially. When I eventually got into technical diving, I quickly saw that I knew almost nothing. Then as I started teaching cave divers, I followed the established norm as I had been trained, and people performed wonderfully. I was really impressed with how quickly I was able to get people comfortable. When I started to apply some limited level of stress, I was fascinated by how quickly the best of my students began to just sort of degrade, sometimes to the point where I would just stop it and say, hold on. What Tom is mentioning is the insight that I gained from that. I teach this a lot. When we have a problem, the biggest challenge is to not make the circumstances worse by attempting an inadequate resolution. This can be experienced in any type of diving but in technical diving this is experienced to a greater degree. There are more things that can go wrong. Teams will often only partially resolve problem or not resolve it at all, but they won't stop. They'll just kind of continue along in a stressed state trying to exit or surface inadequately. It ultimately begins to spiral and multiple problems start to move along, which is one of the reasons I was interested in data presented by Petar. That's been my personal experience in fatality review and recoveries and training students. It taught me a lot about how to train our divers. But I would say generally that would be the biggest issue that's different.

Question #3. Recreational vs. technical diving

TOM MOUNT: I don't differentiate between technical and recreational diving.

PETAR DENOBLE: Let's discuss this or at least the difference between recreational and rebreather divers. I have heard the phrases "divers with a mission" or "expedition divers." So now it's expedition or recreation or sport divers. How do we distinguish between these groups?

TOM MOUNT: Technical diving requires more complex skills, use of more complex equipment, in more threatening environments. You have to make people aware of that. It gets more important as you get more advanced. You must train someone from the level they're at and make sure learning is achieved. We talk about training, we train people and they perform in training, but they didn't learn it. In real situations, they don't perform the learned response. There's a huge difference between learning and training. Regardless whether you do mountain climbing, cave diving, or whatever, one of the biggest things for survival is what you learned. In technical diving, you must learn that any piece of equipment and any human component can fail. You have to accept that the sport is risky and you can die.

JEFF BOZANIC: Rebreathers will be different in six months from where they are now. When the buoyancy compensator (BC) was introduced, it was considered to be technical diving equipment because it came from the cave diving community. When dive computers were introduced, we had all kinds of specialized courses for them, specialized procedures and workshops on how to use them, and they were considered to be technical diving equipment. Now there are agencies that require every entry-level divers to have them. Nitrox used to be considered technical but no longer so by most people's definitions. Rebreathers are becoming closer to that transitional state. Rebreathers have been considered technical in large part because they have been used for diving deep, extending cave penetrations and the like. I personally don't believe that rebreathers are more technical than open circuit dive gear and certainly not more than open circuit dive gear was in 1960 before lots of development took place. I argue that rebreathers are, or will be in the very near future, a piece of gear that is recreational in nature as long as used within the recreational dive limits, i.e., no stop diving and free surface overhead, depth less than 130 feet or 40 meters, and carrying sufficient bailouts that provides open circuit capability to get safely to the surface.

PAUL HAYNES: I think 10-15 years ago the term technical diving was quite clear. The demarcation was quite obvious: divers breathing a gas other than air, usually going deeper and requiring mandatory decompression stops. These days it just has that machismo sort of feel about it, which certainly can attract the wrong type of diver, and perhaps now it's time for the term technical diving to just fade away. There are different facets to diving. I'm an open circuit scuba diver. I'm also a closed circuit but not mixed gas diver. I'm a full cave penetration diver. It's just the type of diving that you do. We probably couldn't come up with a clear definition at this point.

DAVID PENCE: My biggest complaint is trying to compare recreational versus technical. The opposite of recreational is occupational. One of the problems over the last 20 years with the improvements in the reliability and capability of standard single tank, no-deco diving, is that there's been a reduction in the technical level of those divers. As one who deals primarily with occupational divers who are almost always mission-driven whether they're counting fish in 20 feet of water or doing a 300-foot geology study, every one of those dives is technical in nature and should be approached with the same mentality. So if you want to separate it, don't call it recreational versus technical. Call it technical versus less technical. We should require a higher standard of performance and knowledge and ability among divers. That would help us deal with attitude problems among a certain segment of technical divers.

SEAN HARRISON: I think all we've been discussing is recreational diving under which there are the subsets, sport and technical. We also have commercial and scientific applications. Those are the three categories: recreational, commercial, and scientific.

KARL SHREEVES: Part of what makes this discussion difficult is we're muddying terminology that happens to have the same labels. Rebreather diving (as Jeff was alluding) may be no-stop shallow dives, but with respect to the discipline and training, perhaps it's still a technical dive. It's hard to discuss these things intelligently. We have to define what we're talking about or whoever reads these proceedings won't get anything from them.

JARROD JABLONSKI: I agree that it's a matter of degree, so it's all technical. But as gear junkies, we often forget that people who don't love to play with gear find open-circuit gear very technical. I joked about turning a regulator around the wrong way, but that is evidence that even open circuit is technically demanding for some people. So I think all diving is technical. Ultimately, the type, quantity and application of the equipment we use makes it more or less technical. For my purposes, I distinguish between recreational and technical in so far as we apply stress management and problem resolution more aggressively for technical diving. In the recreational world, we work with people more on fundamental skills with less emphasis on stress management. I consider all rebreathers to be technical because the level of complexity requires additional problem resolution skills, which need more aggressive training.

Question #4. Prerequisites for technical diving training

PETAR DENOBLE: Let's rephrase the question. When you say recreational, I immediately think of open-circuit air diving. If we have candidates for a basic open-circuit air diving course that fulfill the requirements for entry-level training, could they also be trained for closed circuit? What are the prerequisites for technical diving training?

TOM MOUNT: I agree with Jeff. I think there are open-water, recreational rebreather divers. We have them, we trained them. I voted against the program when we developed standards, and I have been amazed. I know several people who took recreational rebreather training and returned for a full technical rebreather diving course. They were the best rebreather students I had because they had buoyancy control down. The only emergency procedures they were taught in recreational rebreather course was to shut the unit down and to go to the surface. They turned out to be the most skillful divers I know. There are advantages in teaching people right off the bat to avoid needing to adjust the attitudes of experienced open-circuit divers. Open- circuit habits may get in the way of learning rebreather skills.

JARROD JABLONSKI: However, if they don't have those open-circuit habits, when they go to bailout, they don't have any appreciation for the time the gas will last. They end up in these extreme dives because gas is not an issue with a rebreather. By diving open circuit, at least for a short period of time, they learn that gas is very much an issue.

TOM MOUNT: JJ, I beg to differ with you. When I voted against immediate rebreather training, I was wrong based on seeing how well it can work. These were some of my best students.

JARROD JABLONSKI: Sure they're great students.

PETAR DENOBLE: I know that training can do wonders, but how do we achieve that? What are the minimum competencies for closed circuit?

SPEAKER FROM THE FLOOR: Excuse me one second. Does the panel know this is strictly a rebreather panel discussion? That's what it says. Everybody is arguing over open water.

JEFF BOZANIC: As panelists, we were submitted questions that were about technical diving in general. This particular question is about rebreathers, but we were asked to consider open-circuit technical training as well. If we're sometimes blurring the issue, it's because we're really doing two sets of things.

PETAR DENOBLE: Open circuit and closed circuit are polar opposites, but we would like to address both types of diving.

PAUL HAYNES: Having dealt with most militaries worldwide, almost all have gone through the process of evaluating training requirements. At some stage, they decided to forget open circuit and train from the start with closed circuit, but everybody goes back to open-circuit training so they can grasp the fundamentals of being underwater as a human being. Is it right or wrong, I don't know, but that's the process that is repeated worldwide by the militaries. Whether it's applicable to the recreational market, I don't know.

JEFF BOZANIC: The question is should recreational divers be able to participate in closed circuit training initially. I have no problem with that. I've trained people that have never been on open circuit at all. Jarrod commented about needing to have initial open-circuit training to learn about bailout. That's part of the training regimen you go through if you're going to learn to dive on a closed circuit to begin with. The way you structure a course for someone who is already open circuit certified is different from the way you structure a course for someone who is not. It's the responsibility of the agencies or instructor to tailor the course for the people who are being taught. It's no different than any other course that we teach.

PETAR DENOBLE: Regarding training, what's the difference between open circuit trimix diving and rebreather diving? Can you start entry level training with heliox?

TOM MOUNT: I wouldn't, but I know people who would argue about that. Divers should learn to dive on air first. For trimix, divers need a couple hundred hours under their belt first.

KARL SHREEVES: If there's anything that the accident data shows, it is that one needs a lot of recreational or no-stop experience before making a technical decompression dive with a rebreather. I doubt that anyone at the table would disagree. I would say from my gut, not from data, that if you're an experienced open-circuit diver, you probably need more because you're actually overcoming old habits and old ways of thinking. Rebreathers are more cerebral, if you will, than open circuit, and that becomes innate to the way you behave underwater. You need reprogramming before you go into the more extreme environments.

JARROD JABLONSKI: I don't really understand the value. I appreciate your point, Jeff, I have a lot of respect for your effort. We just have a difference of opinion.

JEFF BOZANIC: That's never happened before.

JARROD JABLONSKI: That's what makes the world go around. I guess I've never understood the motivation. What is the value to it? For example, if you're not an active diver, it's hard to imagine you're going to invest the kind of money and training time and effort associated with a rebreather. If you're an active diver, why wouldn't you want to be able to dive open circuit? It doesn't seem to me it's all that practical to sort out your understanding of the environment until you've had some level of experience. I don't see how novices can come in and make an educated choice about choosing a rebreather when they know really nothing about scuba diving in general. So what is the value to going down that road?

JEFF BOZANIC: We tend to emphasize our own prejudices when we make decisions for other people. One of the people who came to me specifically wanted to do underwater photography and specifically wanted to get photographs of critters that photographers on open circuit couldn't get. He had already ruled out open circuit and wanted to go straight to closed circuit to meet his objectives. It's not my job to tell all of you why you want to dive a particular piece of equipment. It's your job to tell me this is what you want to do, and I will help you do it.

JARROD JABLONSKI: Good. That was very subtle, the prejudice part. Of course I disagree. But it was artfully done.

TOM MOUNT: I think we have three different levels. You've got the open water, recreational rebreather diver that starts in open water. Not many are going to do that for the simple fact that a rebreather dive course right off the bat costs $10,000. What you do see is people who are nitrox divers with minimal experience, but they want to do photography and don't want to do decompression. You do a minimal course. They already have open circuit, and they don't want to go into more advanced forms.

PETAR DENOBLE: What are the prerequisites for technical diving not just rebreathers?

JARROD JABLONSKI: Let's address both these issues at the same time. Where we disagree is that I have a responsibility, obligation ultimately, to help my students make decisions. Sometimes that can appear prejudicial and domineering, but it fulfills an obligation I feel I have. My students have lots choices. They don't have to come to me or GUE. They can go a lot of places, and I fully support that. I wouldn't try to monkey with Jeff's ability to teach this guy who wants to shoot pictures as their first effort. For me, I think removing barriers is not always good. If you want to learn how to fly, you don't start with jets in the class. There's a progressive process. More complicated activities require more steps to learn. That's useful in many ways because it gives the diver, the instructor, and the agency means to evaluate an individual over time. That's valuable for everybody and offers a lot of protection. We've created a whole class structure for cave training to prevent people from getting into advanced forms for which they aren't ready, comfortable, or psychologically prepared. I don't want them to waste time and money and energy getting into things they're ultimately not ready for. That's just my perspective. I really do respect other people's perspectives, but I feel I have a responsibility to people who come to me to let them know this ahead of time.

Question #5. Progression of training – training levels

PETAR DENOBLE: Let's discuss levels of training. How do we progress from one level to the next? What are the minimum skills for entry-level certification, and how do we move on to become mission or expedition divers?

KARL SHREEVES: This will be a little waffle-like, but it's the heart of the problem from an instruction design point. Before I can tell you what your entry and exit levels need to be, you have to tell me what you want to be able to do. You build from there. If someone off the street who's never been diving says, "I want to dive the *Britannic*. Train me." You can design a program to do that which will be very long and comprehensive with periodic checks to stop you if you are not mastering the techniques. I imagine most people at this table are involved with groups who can design most anything. This is a difficult question to answer without knowing the minimum required capabilities. Well, the minimum capabilities are nothing. So we must ask what is the population I will draw from? Do I want to draw from existing recreation divers? That's one set of skills. Do I want to draw from entry-level tech divers? That's another set of skills.

DAVE PENCE. As an end user of training materials at a university, I spent time looking at the training progressions from a lot of agencies. They're all converging over time into a series of fairly fundamental levels. Students come in as accomplished, basic, open-water scuba divers with dive rescue and nitrox, and you build progressively on their skills, knowledge, and attitudes. Most of the agencies are converging to a common paradigm.

PETAR DENOBLE: Are you saying there are no issues, and there is a common practice? I am glad to learn about that.

DAVID PENCE: There are differences in implementation those progressions at this table, but ultimately they come down to a progression from nitrox to technical nitrox with staged decompression. But it's a logical progression based on physiological and technical complexities. Ultimately, the diver or the end user determines where to stop in order to meet their objectives.

JARROD JABLONSKI: I agree in general that the standards are similar, and I think that ultimately the criteria are where people will differ: how capably should trainee be able to perform certain set of skills? From my perspective, there are roughly three levels of training in a given category that seem to be useful: beginner, intermediate, and advanced. What we would reasonably tweak would be the performance level expected for each category. So roughly, we have three evaluation criteria.

Question #6. Use of checklists

PETAR DENOBLE: Without using checklists, are divers prone to error? Should we train to improve compliance with checklists?

PAUL HAYNES: Nobody forces the requirement for checklists during training, and after certification, I'm not sure there is much that can be done. A diving club is different. Diving clubs are structured and organized with a dive manager who is usually one of the more experienced divers in the club and is responsible for diving safety. In commercial diving, he's equivalent to a diving supervisor, on site and taking notes. Checklists are not in place at the moment for rebreather divers in diving clubs but could be introduced as part of the dive manager's responsibility prior to allowing a diver in the water. Aside from a diving club, I'm not sure how you would do it.

KARL SHREEVES: I've studied checklists, and we were talking about them at lunch. Effective education is the issue. We're trying to train somebody to make the choice we think is right. When we design instruction, I can test if you know how to use a checklist. I can watch you do it, and you will do it for me. When you leave my course and you don't do it, why did you choose not to? We see this frequently. You can't get out of high school in the U.S. without knowing why you shouldn't smoke and yet some people choose to smoke. You can't perfectly train affective education, but we know at least two things that are good at influencing affective decisions, role models and culture. Many of you have seen the deceptively easy way to dive video. We chose Lamar Hires as a role model, as someone most divers might want to emulate him. Actually, Tom Cruise was our first choice. It sounds funny until you look at the demographics of people who are dying in caves because they weren't certified. They were males in their 20s. Tom Cruise would've been a good spokesperson for that video in the mid-1990s. Culture also creates social pressure which makes it unacceptable not to do the desired behavior. I mentioned I dive with the Cambrian Foundation. We are a scientific organization, but our driving force is cultural. Before we dive, we use checklists for both open circuit and closed circuit. There's tremendous social pressure to do that. Scientific diving might require checklists, but no one else would think of it. All of us in this room respond to both culture and role models. Hopefully, we are role models, too. Some of you may think that's scary, but we are role models. People see what we do. So we need to be practicing what we want other people to do. We also need those around us to become part of the culture. John Chatterton and Richie Kohler described their teams, and I can tell that this is a culture, a discipline. Well, that spreads, and we can all be part of it. There is a separate problem concerning checklists called involuntarily automaticity which is where you learn to do something by rote. If you do something often enough, it becomes automatic. With a checklist, you can check everything off but not actually be doing it. Federal aviation authorities have investigated accidents where they can hear the crew doing the checklist on the black-box recording, but the check wasn't properly done and caused the accident. How do you create checklists that break out of that? One suggestion is to have computerized checklists that shuffle the order of the checks, so you have to read the list every time because it's never in the same order.

DAVID PENCE: I'm here representing the American Academy of Underwater Sciences. Doug Kessling, other dive officers and I developed a set of standards for technical diving over the last 10 years. We take entry-level divers and certify them as basic scientific divers, equivalent to lead divers or divemasters in the recreational world. This qualifies them for assignment as team supervisors and project managers. I think that's really where you want to enter technical training. That's where your role models are as well. Ultimately, the instructors from all agencies are the role models, and the students will emulate them which puts a burden on the training agencies to maintain quality at the instructor level. As an end user looking at technical and recreational instructors in Hawaii, the quality fluctuates over time. The only way I have been able to ensure quality control has been to train within the university program. AAUS organizations are more like the University of Sunderland Sub Aqua Club (BSAC) in that the divers must be formally approved. When the university does any technical diving, a representative of the university is typically on-site as a dive officer, so it's much more a command structure.

PETAR DENOBLE: That's not feasible in recreational diving.

TOM MOUNT: The problem in recreational diving is once they get out on their own, there's no way to hold them to a standard. Divers and their buddies go diving themselves. Checklists are ideal but lots of people don't look at them. Bill Stone's solution many years ago was to have the checklist in the rebreather display. You couldn't get the rebreather up unless you completed the checklist. That was good, but people even messed that up. So I don't know how we can absolutely protect the diver from him or herself. We can standardize, teach, holler, and yell, but peer pressure may be the best solution.

Question #7. Solo vs. buddy diving

PETAR DENOBLE: Ideally, each diver should be self reliant, but what is the approach of the training agencies regarding solo versus buddy diving? And what about buddy-breathing?

SEAN HARRISON: We do have a solo program, but we don't believe it belongs in the technical end of diving. All technical divers are self-reliant divers. Our position is if you are on a rebreather, you should not be alone. If you are in any type of an overhead environment, you should not be alone. We do not encourage solo diving in a technical realm. That's not a good practice. The second part of the question concerns the value of buddy breathing for technical diving. Buddy breathing is a skill that's not necessary if the bailouts are removable and could be handed to somebody else. Personally, I believe the buddy breathing skill is not as necessary for technical diving.

TOM MOUNT: I believe you should train people to be self-sufficient divers at any level, but I don't think we should encourage anyone to dive solo. I've met divers who do dive solo at times. I think a self-sufficiency program is very important. If you and I go diving together, we'd be great buddies. But if we get separated, I need to be confident in myself and not freak out because I don't have a buddy.

JEFF BOZANIC: So far I'm hearing that people say we shouldn't tell people to go solo diving when the reality is we all recognize that they will. It's kind of like open-circuit diving where we said always dive with a buddy, never go by yourself. The first thing you see is your instructor take the dive float down and set it by himself when he just said, no, don't go solo diving; it's dangerous. We're dancing around the issue. I dive by myself. I technical dive by myself. I don't advocate it's the best way to dive. When you dive by yourself, you're missing what is arguably the most important piece of diving equipment that we can carry, somebody else's brain because mine is sometimes out. But recognizing that people are going to do it anyway is an important part of setting reasonable risk levels for an activity that is going to occur. And it is, we can't make it go away by putting our heads in the sand. I don't think we ought to be advocating solo diving at the training level for technical diving because you are still reliant on a buddy, and nowhere is that more evident than with rebreather diving where problems can come on you and you have no or little awareness. You need a buddy to help you until you learn how to monitor what's going on reasonably well. And if you don't monitor, you can't tell if something is happening. For us to state that we're just going to tell people not to go solo diving and expect that to solve the issue is wearing blinders. We need to recognize that solo diving will occur and possibly set parameters under which it might be done at an acceptable level of risk. It comes to personal choice and what levels of risk any individual is willing to accept for him or herself.

TOM MOUNT: I don't think we should say, here's your certification, go ahead and dive solo. I dive solo, too, at times. People say, I used to dive solo in open circuit, but I wouldn't on a rebreather. If I were going to dive solo, I would rely on my skills on a rebreather to dive solo before I would on my open-circuit skills.

KARL SHREEVES: I'll only side mount solo basically for the same reason. Where I am half the time, nobody could help me anyway.

JEFF BOZANIC: I'm hearing that three of the people on this panel admit to diving by themselves, so at this point it would be really silly for us to say, just don't do it, because we all know it doesn't work.

DAVID PENCE: I want to say within the U.S. scientific diving community, it's actually in federal regulations that we must have two similarly equipped and trained divers in contact at all times, who are able to offer immediate aid.

PETAR DENOBLE: How many fatalities did scientific divers have in the U.S. in the last five years? I didn't see any.

DAVID PENCE: We had two. One of them was, I believe, on full commercial gear, but it was independent of equipment. But my point is that if you have a diver who is on closed circuit, if their buddy is not familiar with the specific equipment and doesn't know how to assist with problems that might occur, the diver is close to solo. So in addition to training the rebreather diver, there is a great need to ensure that buddies have the effective knowledge and skills to assist. Otherwise, they are essentially diving solo. If a rebreather diver is diving in a mixed-equipment team, all members must be conversant with the methods for assisting a rebreather diver. In many cases the methods are the same, such as you're going to try to get an unconscious diver to the surface as quickly as possible.

JARROD JABLONSKI: Guess I would say, Jeff, despite my prejudiced view, I agree with you in some part.

JEFF BOZANIC: Make that four now.

JARROD JABLONSKI: People are going to dive solo, there's no question about it. From my perspective, it doesn't seem like we need to do a lot of training. If people think there's something useful to talk about or to create some guidelines for it, I suppose that's OK. From my perspective, it's more useful to learn how to dive effectively in a team. If you start working in teams from day one and you teach an effective team management and buddy awareness strategy, those divers become much more capable and more aware so they're less likely, in my experience, to have a separation problem. Indoctrination with that philosophy from the very beginning is key. Gas and logistics management are more difficult for a team because they have to account for another diver. So I have to conserve my own gas. Even in a recreational dive shallower than 100 feet, I have to have a fair bit of gas available to help my out-of-air dive buddy to reach the surface. If that buddy is gone, and I suddenly am solo diving, my gas management is less critical. I don't think that's necessarily safer, but if you've buddy is well trained, you've already taken care of the problem. You've taught somebody who can task load, who can manage. I don't see the point of creating special training. In the end people are going to solo dive. Okay, they're adults. If you want to do that, it's fine. For my part, I don't solo dive anymore because I enjoy the social aspect. It's not that I haven't, but in the end I enjoy diving with teams and with dive buddies more.

PETAR DENOBLE: We'll now take questions for the training panel from the audience.

JOHN CHATTERTON: When I first got certified, it was a YMCA course. It took 16 weeks, and I think the first four weeks in the pool we didn't even see a scuba tank. Then it was just a scuba tank and a regulator. The divers that got cranked out were pretty good. Now, with technical diving, with rebreathers, with trimix, nitrox, technical nitrox, deep air, it certainly seems like students don't have to make the same investment in time. It seems like we're training a much more complex dive system in a far shorter time period. Is that reasonable?

JARROD JABLONSKI: No, I don't think it's reasonable at all. Dive training has become a commodity with no minimum standard. Here's the cost of your card. If you can get one cheaper, obviously, you're going to go there. A real performance standard is needed where you demonstrate good mask clearing and buoyancy control skills while neutral and moving in the water, not while plastered at the bottom by a weight. Lack of those two skills has degraded the quality of our training in general. It doesn't matter what we write on pieces of paper, it matters what it looks like in the water. Dive training has become perilously short. People get certified in a day, day and a half, and they're diving. As an industry, we have lowered the age, shortened training, and reduced standards even more because our audience is shrinking. We're moving rapidly in the wrong direction, and people are having bad experiences. They're not comfortable in the water. They don't have a basic level of proficiency, and they leave diving. The sport continues to shrink, and we respond in the wrong way by continuing to shorten training and reduce standards. It's unsustainable.

JEFF BOZANIC: I have to agree with JJ. Classes are getting too short, and too segmented. I don't believe people are getting enough experience in most of their training programs to be as comfortable as they need. To turn that around, we need to have longer programs with more dives.

PAUL HAYNES: I'm not going to disagree. I just want to reinforce what has been said. Fifty years ago, the skills of someone coming out of a YMCA were very good. There was more snorkeling and more swimming, and you got the skills down. It took months to get trained. Unfortunately, agencies had to respond to the marketplace, which is a detriment to training, and the end product is less skilled. We have to respond to the marketplace;

otherwise a club would probably die. That's unfortunate, but it's the process we've had to go through.

STEVE JOHNSON, Yorkshire, United Kingdom. I have an issue about how much supervision and follow-up is done for instructors by the agencies. Training can be variable. As a consumer of training, I don't see very much supervision by the agencies or the manufacturers. I wonder if people on the panel could comment on that, please.

TOM MOUNT: We do QA (quality assurance) review boards and send QA forms to everybody, but it's hard to supervise when someone has a complaint but won't say so. And it's hard to say to an instructor, I heard that you did this. Quite often we can't find evidence where somebody was instructed wrong.

PAUL HAYNES: We just introduced a QA process. We're very concerned with the quality of technical instructors, as all the other agencies are. The students send off a separate form which is very descriptive (have you done this, have you done that?), and the instructor sends his report. When both records come together, the student is certified. The QA process monitors training continually and gives constant feedback on basically every technical course.

KARL SHREEVES: That's a lot like PADI programs where we randomly survey divers who send their forms directly to PADI. We don't count on the instructor to send the QA form. If we find a problem, we follow up. If we've had an instructor who has had some problems, we'll do remedial training, and all of his students will have a certain number of follow-up surveys as well. As Tom says, you do run into the issue that I don't want to rat on so and so. We've gotten pretty good at making people feel comfortable that they are not ratting. "You're helping us make this person a better instructor so we can make diving safer." That's kind of finesse. I'm sure my colleagues at this table do that on a regular basis. It's kept quiet often for legal reasons, so that's why it's not always visible.

SEAN HARRISON: Our process is identical. We have a global verification system for all our programs. So no certification is issued anywhere in the world without first going through the centralized database at headquarters. As Karl says, a lot of this stuff cannot be disclosed because some countries have privacy laws. But it's amazing how little feedback is negative. There's not a lot of bad instruction.

KARL SHREEVES: You may be surprised how much dialogue there is between the training organizations. Steve Mortell, my colleague who works in the training department, and Sean are on the phone all the time. When you have an individual who is a problem we share that information but, quietly. That way an instructor can't simply change agencies and continue doing something that's not safe.

SEAN HARRISON: What Karl is referring to is when we see instructors who start developing problems, and as they realize their agency is coming down on them, they immediately want to jump to another agency. We verify an instructor's credentials when he comes from another agency. This process is signed off on all of our membership agreements. There are so many choices out there, as many people have said, they will move around so we do monitor.

JARROD JABLONSKI: From my perspective, I agree, quality control is important. I was happy to hear that there is some additional hundred percent QC. We've done that since the beginning, and whether the students pass or fail, they have to get a QC form and can't be certified at any level without it. However, it's not as useful as other forms because a student doesn't know that something was wrong or missing unless it's pretty egregious. Because they're new, how will they pick up on the subtleties? Half the time they can't remember how many dives they did because they're focused on own performance. That's not the best way. From my perspective, recertification is better and should be mandatory. We require recertification for our students and for our instructors. It's much more elaborate for instructors, as you might imagine, because they can create an exponential kind of problem in the end of a day. It really is extremely difficult to keep people on the same page because things change over time. Our instructors have to teach with instructor trainers over three years to become re-qualified. This is to be sure that instructor is still is teaching a quality class and represent the organization well. It takes a lot of energy to do it.

TOM MOUNT: I would agree that instructors recertify periodically, but we tried to recertify divers when I was with the YMCA in the late '70s and were told by the lawyers that if you create a standard you can't enforce, you create 100 percent liability. It wasn't as bad then as today. You can't enforce recertification. For example, your student shows a card on a dive trip in Grand Cayman and says he's an open-water diver. They're going to let him dive even if the card is expired. It's your liability because you said he couldn't dive unless he had recertified.

JARROD JABLONSKI: I would accept the liability, if that's what it comes down to because I think it's an important process. To be clear about instructors, we all renew every year which is just filling out paperwork and verifying CPR qualification. But requalification means they have to teach in front of an instructor trainer who knows the program intimately. Is that what you mean or do you mean just renew?

TOM MOUNT: We renew and we have instructor updates. They don't go through the whole course. After QA reviews, they go to an instructor update. If they haven't been active, they have to come back and prove proficiency.

GEOFF SALINGER, Reston, Virginia. With driver's licenses and other important things in life you have to re-up. Why shouldn't continuing education be a requirement to keep your diving certification?

TOM MOUNT: Driver's licenses are issued and enforced by state agencies. You'll get arrested if you drive without one. We can't go out and arrest people. We have no policing authority. We can do it with instructors but not with divers.

JEFF BOZANIC: I agree with JJ and Tom. In the best of all possible worlds, we would have mandatory re-qualification for all divers at all levels. It shouldn't necessarily be a course. It could be something as simple as showing a logbook with a minimum number of dives, but it can't happen until the entire community gets together. The only civilian group that does this with any degree of effectiveness is AAUS.

DAVID PENCE: I just want to comment on that. Within each institutional AAUS member, divers are required to log at least 12 dives a year and at least one every six months to get their depth authorization. Even after 150 contact hours of training as a scientific diver and supervisor, they're only authorized to supervise dives to 10 meters. My university has 12 closed circuit rebreathers on hand and about 25 active rebreather divers who go in and out of certification. They'll have a period of active diving and then none for six months. It's definitely "use it or lose it," especially if they're back and forth between closed circuit and shallow open circuit. There needs to be a process by which those people requalify and refresh before you turn them loose again.

JARROD JABLONSKI: I agree. That's somewhat the system we use. The cards have an expiration date on them. Obviously, I can't control what a provider is going to do when they see the card, but I'm trying to indicate to, say, a boat operator, that this student was certified some time ago but has not necessarily maintained currency. They can ask for a logbook or call the organization. People will often say, I got certified five years ago and don't remember everything, but I'm comfortable. As an industry, we should recognize that those people are not comfortable and competent. It's been too long, and they may not have had enough proficiency when they left the sport.

PETAR DENOBLE: Should it be left to the individual diver to decide he's not competent? The more the diver is educated, the more objective he will be about himself.

JARROD JABLONSKI: They should have to requalify. For divers who stay at one level and dive actively are gaining experience. Most people don't do that over ten years. If they're active in the sport for a long period of time, they'll seek additional training. But we can monitor an average open water diver who dives occasionally by their dive frequency. Recertification should be mandatory. Lifetime cards don't make any sense.

KARL SHREEVES: Jeff brought up logbook review. It's frustrating for the recreational organizations because RSTC requires them. You complete a PADI course, you're going to start a logbook, but they don't get used because dive operators don't ask for them. As a community, if we were routinely asked for logbooks, we would have the documentation.

JARROD JABLONSKI: I didn't know it was an RSTC requirement. How many of you know that? OK, I'm just ignorant. Certification cards that expired would be another way. Dive operators would feel more uncomfortable with that.

PETAR DENOBLE: Have we come back to no difference between recreational air diving and technical diving? We argue for a requirement for recreational air divers, but how about for technical divers?

JEFF BOZANIC: The issue is not that we have something for air divers. The issue is we have nothing for everybody, and we need something for everybody. That's not going to happen without all the training agencies, the equipment manufacturers, the resort operators, and the liveaboard boat owners getting together. It's been tried in the past, but we've not been able to get the consensus to put it in place. We need to do so.

HEATHER ARMSTRONG: I have a comment regarding logbooks. I recently had a student seeking technical instruction who had eight lifetime dives and said, "I hope you're not one of those instructors who requires logged dives because any idiot can pencil-whip a logbook."

KARL SHREEVES: We've heard comments like that over the years, and it's a good point, but when you investigate the abuses, you get into the fixing something that ain't broke. I can't say that stuff like that never happens, but in our data it is rare. Few people are that insane, and a diver is taking on a huge amount of liability by outright misrepresentation. In theory, our master scuba diver certification can be done with five distinct specialties that don't involve diving, but it's never happened because people don't become divers to sit in a classroom. If they happen to take one of the specialties, it's because they have a real interest. People don't routinely falsify logbooks. Let's go back to what I was talking about earlier. What we do, we do as a culture, and we are all one culture. I know that makes you nervous looking at me, but we are. We have subcultures, which as Jeff points out, we see more easily, but our culture has values. Nothing we do will ever be perfect. I can tell some wonderful horror stories on myself about checklists, but I'm not going to. But if we take all these little things that we've been talking about and pull the links out of the chain that Petar has been talking about, will we stop all accidents? It's probably not going to happen, but we can stop a lot of them.

HAL WATTS: I've been up here so long waiting, I almost forgot what I want to ask. I want to talk about logbooks. I started diving in '62, started teaching in '63, and I loved every dive I ever made up to this past New Year's Eve. When I first opened a training facility to the public, I was going to require that everybody have a logbook to dive. If I had instituted that requirement, probably 90 percent of the instructors could not dive at 45 Fathom Grotto. Most of the instructors that come to that place do not have a logbook. I'm with PADI, IANTD, Winn Dixie, Publix, whatever it is. And it's interesting to see that when people come to us for referral dives, from IANTD, PADI, they bring a logbook. They buy that logbook because it's required, but the logbook has not been touched. The pool training isn't in there, the medical isn't in there, and the test isn't in there, nothing is there. So logbooks would be great if they were used. Another controversial subject is buddy breathing, the old-fashioned technique that I still teach and PSA requires their instructors to teach, where people pass a mouthpiece back and forth. My rationale is that if your octopus isn't working or it's in an octopocket and you can't get to it, time is of the essence, and your buddy is going to grab your regulator. The agencies should go back to the 1960s and teach buddy-breathing, but also say you should have an alternate air source because it's safer in an emergency.

TOM MOUNT: Hal, our standards require simulated buddy-breathing or during open water diving. The reason we simulate is many people think you can get communicable diseases.

HAL WATTS: You can do it kissing, too.

TOM MOUNT: But, Hal, you don't mind kissing them, it's worth the risk. We require the simulation for the reasons that people state. For example, I was on a wreck dive with a sales rep and his girlfriend. The guy comes to me just after we left the wreck, and he's out of air. I had an octopus which I gave him. Then the girlfriend runs out of air, too. I'm like, oh, shit, but I give her my regulator. And then I count – one, two, three, four, five – hey! She had no idea she was supposed to give it back, but she finally did. She learned to buddy breathe the first time on an ascent from 100 feet up. So, yeah, it should be done.

HAL WATTS: What did you learn from that? We've had people come to our place to take a course with no mouthpiece on octopus regulators, just metal or plastic. "Where is your mouthpiece," I said? "Oh, I don't need it," was the reply, "because I'm not going to be breathing through it." Running low or out of air is not an option, ladies and gentlemen. The industry still teaches this, right, and also teaches us to show the pressure gauge so out of air should not be an option. Too many people die running out of air, many more than due to decompression sickness or oxygen toxicity. So let's don't run out of air.

JARROD JABLONSKI: I want to support the logbook again even re-qualification is not a perfect system, very flawed and mostly broken. If you require a requalification through dive experience, that's the only thing that's going to motivate people to log their dives. Otherwise, they're just not going to do it. There are lots of systems that could be built – requalification through experience, through retraining, through evaluation, or through evaluating someone's training in another course. My argument is we should build something because somebody who hasn't dived for 20 years after certification does not know how to dive. No one in the industry would pretend that person is capable of diving. Starting with diving experience is a good place to begin.

TOM MOUNT: When I was trained at the YMCA, we started a policy that you had to have a logbook to dive. Probably 10 resorts in the world followed that, and others ignored it. Therefore, it failed. The only way it would work is if we get all resorts in all destinations to agree, but if someone comes with a $2,000 a week diving package, the logbook will be ignored.

JARROD JABLONSKI: We could expire the cards. You'd have to work this out through legal, but if you expired the cards, operators would have the choice to honor an expired card or to insist that the people be qualified. I think there are operators who would say no because the liability is not worth it.

BILL STONE: Having quietly observed these civilized deliberations among the eminent people here, I have come to the conclusion that there has not been enough controversy, so I will ask this question. If rebreathers became cost-competitive and of comparative operational complexity to open-circuit scuba, could the implementation of an introductory recreational rebreather training program be an opportunity to restore entry-level dive training to the standard of quality it once was and probably still should be? In other words, can we use a paradigm shift to get us back to the level of training we once had?

JARROD JABLONSKI: Sure wish that were the case, but I don't have any confidence. I think it's like giving politicians more money and expecting them to use it wisely. Nothing would warm my heart more than to see us realize that transition, but you've presented a utopian view.

TOM MOUNT: I think it could work, but it would only be for rebreather divers because you've still got people in other markets who won't change. But it would be good if we could start an open-water rebreather diver at the standards we used to have because the equipment is different, and the old standards are necessary to make him competent.

SEAN HARRISON: It certainly brings up an interesting point, but it would have to be well thought out. I don't believe it would fall within the definitions of ISO, and I'm fairly confident it doesn't fall within the definitions of RSTC training. I don't think these standards would allow entry-level rebreather training, but I do believe it is a good idea since the diver would start with a clean slate and no bad habits. However, regulations in place right now would probably make it a little difficult.

GREGG STANTON: Gregg Stanton, Florida State University retired. For the last three years, I've been approached by a number of people at our training facility who are not yet ready to take a class because they don't have enough information. They spend a day going over platforms, ideas, and applications and even get in the pool with a rig or two. What about training rebreather divers along the lines of the recreational pilot training program mentioned by several people? A ground school approach might give a person a better understanding of the options but not necessarily in the water. Classroom simulations might be cost effective. Then they can decide on the platform and finish with an instructor who is affiliated with training agencies and manufacturers. Would the panel comment on that?

STEVEN BARSKY: Gregg, I think your approach is not a bad idea. My wife and I used to dive with Draeger semi-closed circuit units. We approached them as maintenance-intensive tools. I don't think any rebreathers on the market today are less maintenance intensive. Those tools need to come way down in price, simplicity and maintenance because I'm not going to invest the time in pre-dive setup and the post-dive maintenance if I've got a film to make or photos to shoot for a book. It's just too labor intensive for most people.

MARTY McCAFFERTY: Who is better qualified or experienced: the diver who makes 15 dives a week on a live aboard or the diver who makes 2-3 dives one weekend every month?

SEAN HARRISON: I started as an active instructor for a retail shop doing a lot of open water training and then moved on to a dive boat for five years with 18 new passengers every week. We used to watch divers put together their equipment, and if we found one who couldn't figure how to put a regulator on a tank, the full staff was immediately dedicated to that one diver. This coaching was really a refresher course, and there's no doubt some people need a certain amount of retraining, but it's on a case by case basis.

The agency provides introductory training and that may be the only training a diver receives for the next 20 years as Jarrod said. The first line of defense after training is the resort or destination where the diving happens. From my perspective, the resorts should cooperate in coaching and refreshing.

JARROD JABLONSKI: Dive operators are a good line of defense, but we can't afford to shift the buck, and we should give them better support. There are very few, if any, instructors who teach insufficient classes maliciously. If you're a dive boat operator, it's a nightmare if someone gets hurt, but they don't feel they can make independent changes. I don't see how a resort could unilaterally decide to require logbooks if the guy down the road doesn't. It has to come from above and filter down.

KARL SHREEVES: Unless I'm mistaken, every agency represented here has refresher programs, so the support exists. But Petar keeps bringing us back to tech diving. You do have concern about the unqualified person, but people aren't suicidal for the most part. An individual should know if he or she has been out of the water for a year and has rusty skills, and the more complex skills, the more likely it is that a person will take a refresher. You also have instructional design issues with complicated capabilities. If Tom Mount didn't do at least one open-circuit cave dive for two years, for example, I imagine he could probably do a pretty competent dive without a heavy refresher because of recent experience. To be conservative, it would probably not be a big dive. Somebody who just fished a cave course and didn't dive for two years is in a completely different situation. The latency of experience complicates the competency question.

GRANT GRAVES: I would first like to thank DAN and everybody on the panel. At least we're talking again. I hear a lot about trying to regulate diver behavior, but I haven't heard about personal responsibility. Even the large agencies are small and don't have the resources to do everything we'd like. Wouldn't it be better to send a message about personal responsibility rather than debate what to do about bad divers? What can we do to send a message about bringing personal responsibility back to the divers?

JARROD JABLONSKI: We can increase the standard that we accept by increasing training time, expiring their cards, telling them what it takes to become a good diver and setting an example. We can't play a shell game that does a day and a half of training with no objective standard and gives them a card that lasts forever, and then say, "you should take some responsibility." They don't know anything which is why they're students and come to us for both recreational and technical training. They are not qualified to take responsibility until we teach them a reasonable level of proficiency.

GRANT GRAVES: I agree, but is there a way from the training agencies' perspective to send a clearer message about personal responsibility? It's not getting out there now.

JEFF BOZANIC: I'm going to bring this back to the technical diving because that's why we're here. What do we expect of our students when they enroll in a class? We should not treat them as robots. The idea of teaching somebody the "tao" of technical diving, for example, is unreasonable. We need to teach personal responsibility. They need enough information to make decisions for themselves, and their families, based on what they consider reasonable risk. Courses will have to be longer for that to happen with more dives and different gear configurations and procedures. Students must agree to adhere to standards such as the need for enough open circuit bailout gas to get to the surface after a rebreather failure or with open circuit, enough gas to get you and your partner to the surface after total equipment failure. We need to look at entry-level divers differently than technical divers. I think of my technical diving students more like graduate students in an academic setting and my non-technical students more like of undergraduates in how I present information and expect them to make decisions.

PETAR DENOBLE: Jeff, what do you mean about non-technical students?

JEFF BOZANIC: I try to teach open-circuit air students to think about the basic skills for which there is a high degree of consensus within our community. But that consensus doesn't necessarily exist at more advanced levels of training. Thus, we need to present multiple viewpoints to advanced students that will allow them to make decisions as to what works for them. It's my belief that not every configuration, procedure or technique will fit every person or mission they personally wish to achieve.

PETAR DENOBLE: Now I understand the distinction. But is entry-level technical diving at a higher level than entry-level open circuit air? When does the technical diving student become competent to make his own choices? What minimum skills are required to make a diver responsible for his own choices?

TOM MOUNT: That depends on the student's course level.

PETAR DENOBLE: Would you say that an entry-level technical student doesn't have to make choices?

TOM MOUNT: No. If you want an exact definition of qualifications, it depends on the level, and each level has its own standards and procedures. Our program has 15 checkpoints which must be passed with 80 percent or above for every dive in a course. Every diver is responsible for safety at a given course level. When he goes to another level, the agency takes responsibility again. Too many divers go through a course and take zero responsibility for their actions. If I get in trouble, it's still me that has to breathe, swim, and think for me. In survival situations all around the world, 15 percent of the population will do great in training but panic in a real situation. Fifteen percent are in a state of denial and may not react even though they know what to do. The other 85 percent hopefully will do well.

SEAN HARRISON: I think the question, "what is sport and what is technical diving," is probably agency-specific. We look at both programs. Using TDI as an example, we put nitrox into a technical category but only because it started there. I think the true foundation of technical diving is advanced nitrox and deco. In our curriculum, advanced nitrox and deco are the beginning of technical diving. It is not so clear to me when we talk about using rebreathers in the entry-level training.

TOM MOUNT: We use the same definition. Tech diving is a form of recreational diving involving more depth and more decompression.

KARL SHREEVES: Are you asking when a recreational diver is ready to move into technical diving? Or more broadly, when is a diver ready to go from no-stop to decompression and so on? We require rescue diving first for obvious reasons. At that point, we are pretty confident that people will be thinking outside of themselves. As Sean said, enriched air skills come first because there is no technical diving without nitrox. Then comes experience because cognitive scientists will tell you that experts who solve problems well do so not only because they have better problem-solving skills but also because they have a knowledge base to draw upon. Most everybody at this table follows that although they may draw that line in a different place.

JARROD JABLONSKI: Where do you draw the line? I've promoted a high degree of standardization, which ruffles some feathers. Part of my goal is to educate people who are new to the sport, don't have a lot of experience, and will have difficulty in making informed decisions. When I learn how to fly, golf, or bowl, I don't negotiate with my instructor. I expect he will teach me to the best of his ability and knowledge. Once I have the basic knowledge, I may make changes to my gear configuration and training. I imagine a lot of my students don't do everything I taught them, but it doesn't free me from the responsibility of trying to provide them my best knowledge. As an instructor with significant experience, I have an opinion about what is best and an obligation to say so. I tell them, after you leave the course, you're an adult, you can do as you please. I also argue that the recreational vs. technical issue is not very important. The fundamental skills necessary for both are similar such as holding buoyancy and buddy awareness, but running a reel and cave diving are not fundamental. If the early dive training was not adequate, the later training will be flawed or difficult, and that's a big problem.

STEVE MORTELL: There seems to be controversy between our desires as trainers to give the ultimate, the utopian course. But given that we are a recreational activity, how much do we drive the public and how much does the public drive us?

JARROD JABLONSKI: An excellent point and a real problem. The industry recognizes that there is a decline if not free-fall in the interest in scuba diving. From my perspective, there are a limited number of people in this day and age who will choose to scuba dive. A show that popularizes diving like John Chatterton and Richie Kohler are doing is exciting stuff that fuels the sport. We shouldn't make training easier or shorter to capture more people. I've just accepted that there will be a smaller number of people interested in diving. I'm going to do everything I can to ensure those people have a good experience, enjoy diving and tell their friends. That's the approach for me, but there will be a competitive battle for students.

SPEAKER: We've spent a lot of time talking about vacation divers who don't dive very often. The industry seems to be doing a great job because their accident rates are extremely small in comparison to other types of diving. When we go into more intensive diving, the accident rate seems to increase, and we talk about training versus currency. It seems the accidents we focus on tend to be in experienced, well-trained divers. Does that change when you go into rebreathers?

JEFF BOZANIC: You threw in rebreathers right at the end, but I'm going to talk about cave diving because we have more experience there. We just finished another analysis of cave diving fatalities which will be published within six months. We have about 650 fatalities in the database right now, most uncertified. These people died for the reasons most of us know – not using a line, not carrying enough lights, or not saving enough gas for exit. About 10 percent of the fatalities had some training in cave diving and usually went too deep or too far. We're now beginning to see a rise in the percentage of those who died and had had training. Vacationing cave divers, to use your terms, those who go cave diving once a year, are beginning to show up in the statistics perhaps because their skills have deteriorated. Another problem is that people exceed their training. For example, if they're certified at the full cave diver level, they're dying because they're taking scooters into caves and doing multistage dives before they have the training to do that. Twenty years ago, divers were like Tom and like me, diving zealots. All we did with our lives was dive. We would dive every weekend or more if we had the opportunity. The people who are learning to cave dive now don't necessarily do that. They may cave dive because of the wow factor in magazines and movies. They don't dive as often or maintain the skills like the older cave divers did. The other problem diving zealots, who haven't stopped being zealots, and are slightly older before. I'm in that category. We're seeing a higher incidence of heart attacks, poor physical conditioning and other issues impacting experienced divers that do not occur in a 20 year old because at 20, you don't have coronary artery disease. Unfortunately, at 50, 60, or 70, some of us might. Another issue beginning to show up is new technology for which we have not developed effective or appropriate safety procedures. People are pushing frontiers with rebreathers, for example, diving in caves to 600 feet or pushing very long distances. People on that cutting edge are at a much higher risk. With any developing technology, we need procedures to use it safely. Unfortunately, those procedures are often learned because people who came before us made mistakes. That is a really important part of what DAN is trying to do with the Project Dive Exploration for general diving, what the cave diving community is doing by analyzing cave diving fatalities, and similarly, for the database being developed for rebreather fatalities and incidents. As a community, we should all learn from the mistakes of people who learned the hard way.

RICHIE KOHLER: I know everybody wants to get to the bar just like I do, so I'll make this quick. Growing up, which I'm still doing, I was mentored by the Atlantic Wreck Divers. I've got friends from the UK who did the same thing. More experienced divers took you under their wing and showed you the ropes. Now, what I'd like to see is dive clubs where more experienced divers take rebreather students and drive home the fact that they've got to use checklists. The new divers need to be lead and shown the way. If they're just trained and let out on their own, they're going to take the easy path. If we do that, we establish groups of people who want to do big things which they are not prepared for. Lots of groups in the United States, whether wreck or cave diving, have taught each other and pushed all of us to this point in technical diving. There are fewer people who are willing to participate in clubs, now, and more lone wolves. Can the training agencies create dive clubs, if you will, to promote group learning?

TOM MOUNT: Richie, I don't think the training agencies are too good at making dive clubs. In south Florida where I am, rebreather divers have big lists, not commercial, of other rebreather divers. These guys know each other, "where are we going to dive this weekend?" These people put peer pressure on each other which is a good thing that's only come about in the last year. Before then, there weren't enough rebreather divers. You'd get on a boat and there were one or two rebreather divers. Now there are 10, 15, or 20 rebreather divers on the same boat. That's evolving now, and I hope it's going to happen everywhere in the world. And, yes, agencies can encourage instructors who teach down there to get our guys together, plan dives and check on each other. Some of the boat captains will actually say, aren't you going to do your checklist, although some captains still don't know what a checklist is.

KARL SHREEVES: You’re right on the money, and that’s why the PADI diving society was formed. If you look at the dive centers worldwide, particularly the U.S. and Europe, they’re doing well as they’ve developed this sense of community. It doesn’t matter whether it’s entry-level divers or top echelon tech divers. Diving is a lifestyle. So promoting the lifestyle promotes the business, safety, fun and growth of diving. Our approach with the diving society was to create a large umbrella that catches every diver who comes out and steers them back to the local dive center for their own activities as well as the society events. The beauty of it is none of us are in competition. We’re all part of it. It doesn’t hurt a PADI dive center for somebody to go to one of JJ’s events. It’s good for everybody. You’re right on the money. Group diving is probably one of the most important things we as leaders in the community can encourage.

JARROD JABLONSKI: This is very important. We do whatever we can to encourage the process. We’re building satellite groups around the world, and we encourage them to practice and set goals. We organize the groups around an environmental or cultural theme that draws divers in through local action. These little communities really grow when you have both social and diving objectives. It’s a vital and important part of the community.

KARL SHREEVES: You mentioned the environment. The environment is a huge deal to Gen Y, the 20-year-olds, and is a great social draw to diving. I would imagine most people in here are like me, into hardware, procedures, exploration, but Gen Y wants to do something to help the environment and there is diving appeal in that. The gray hair in this room should remember that when talking to Gen Y.

PETAR DENOBLE: Thank you very much. Clearly, there is a wide variety of opinions but that may be good. Unfortunately, we are out of time. I would ask you as agencies, is there anything else that DAN can do?

KARL SHREEVES: Let me jump on that one. We need more conferences like this. I’ve mentioned the topic of cultures and subcultures several times. I’m involved in fitness, and they can be a very divisive as well, but there’s not much exchange of information. I’m also involved in photography. Photographers all have egos and yet they talk and nobody is threatened. For our culture to grow, our subcultures need to communicate as we have this weekend so we can express our opinions. If you ask my opinion of what DAN can do, give us that venue.

WRITTEN ANSWERS TO TRAINING QUESTIONS

Jarrod Jablonski
Halcyon, GUE, Extreme Exposure
High Springs, FL

Steven Barsky
Marine Marketing & Consulting/Hammerhead Press
Ventura, CA

Jeffery Bozanic
Island Caves Research Center
Huntington Beach, CA

Sean Harrison
Technical Diving International
Topsham, ME

Tom Mount
International Association of Nitrox and Technical Divers
Miami Shores, FL

Karl Shreeves
Professional Association of Diving Instructors
Rancho Santa Margarita, CA

Paul Haynes
British Sub-Aqua Club
Cheshire, UK

David Pence
AAUS and University of Hawaii
Honolulu, HI

1. What are the three major objectives of training?

KARL SHREEVES:

- To give the diver the ability to function (perform productive work) while reasonably managing and reducing risks.

- To give the diver the ability to respond effectively to problems that occur.
- To make the diver aware of the limits of his or her present abilities.

TOM MOUNT:

- The most important end all objective is to teach someone how to survive underwater.
- Develop competency in skills and performance that result in the diver being comfortable, confident and competent.
- Instill an in-depth knowledge of theory, known physiology and academic appreciation compatible to the level of training. To do this sometimes requires presentations that students may not completely understand so they appreciate the complexity of issues such as oxygen physiology, decompression modeling, etc.

2. What are the three major issues concerning training?

KARL SHREEVES:

- Determining what skills and knowledge the diver must have.
- Identifying what problems are better engineered out rather than trained out and then having that happen. However, it should be noted that engineering out a problem isn't necessarily the best choice.
- Affective education that influences trainees to make choices based on what they've learned.

JARROD JABLONSKI:

- Decline in training standards
- Incentive to pass weak divers
- Declining instructor wage

TOM MOUNT:

- First is an effort to achieve learning as well as to complete training. While one may think these are the same, they are not. Training means doing skills, theory, etc. Learning, on the other hand, is knowing where the skill becomes a reflex rather than a behavior pattern that is consciously repeated. Learning allows adaptation whereas training frequently results in a textbook reaction such that in an actual emergency, the trained skill may not be appropriately adapted to the situation. This is reflected in survival research (Leach, Lunden and Seibert).
- Response training beyond simple examples simulate "real" problems that are not only technically correct but impose multiple simultaneous tasks (although not

harassment) to ensure students are challenged by extraneous muscle and mental tasks which can produce confusion in true emergencies. For this reason, skills should be demonstrated and performed briefly in isolated conditions (e.g., chewing gum) but numerous times in a more complex context (e.g., chewing gum and walking). Capt. George Bond, MC, USN emphasized the importance of this during a 1976 Hyperbaric Physician program NOAA with examples of divers trained to share gas in a simple structured situation, but when a real emergency occurred, resulted in double drowning.

- Practice of skills after first developing an understanding the physiological context that makes a particular task necessary.

Comments: In the areas described above, training may fail if instructors do not fully understand the underlying physiology or appreciate that simple lifesaving behaviors must be executed in confused circumstances. Lack of appropriate understanding or appreciation on the part of an instructor can lead to a dogmatic response that students cannot react to out of the "can" presentations in emergencies. Training often fails because upon course completion, certified divers simply do not practice skills they were proficient in at the end of the class. The issue is one of temporary memory to pass a course rather than internalized muscle memory that makes behavior reflexive. The bottom line is the most important issues are forgotten.

3. What are the three major differences between open- and closed-circuit scuba training in technical diving?

STEVE BARSKY:

- Training divers to recognize their own limitations versus the limitations of the equipment is essential to rebreather diving.
- Pre- and post-dive prep is crucial.
- Training for recovery from a complete system failure.

JEFF BOZANIC:

- Both OC and CC technical diving training require competency with the basic gear in benign environments before moving to advanced environments. With OC, this is generally not a problem. However, students in CC technical training programs often have minimal experience with rebreathers, having learned to dive them with the view towards applying them in technical applications as soon as possible. They often lack the degree of familiarity and kinesthetic awareness necessary to do so safely, even though they may feel competent due to their comfort level in the water gained in OC diving. This imposes a set of candidate pre-screening requirements needed for CC technical training beyond those generally needed for similar OC programs.

- CC training generally involves a set of hazards that are far more immediate in onset than those in OC training. These include (but are not limited to) hypoxia, CNS oxygen toxicity, hypercapnia, and caustic cocktail. Because of this, instructors must keep a much closer watch on students using rebreathers.
- As a community, we have a much better handle on the dangers and hazards associated with OC than with CC diving. Compared to CC diving, OC tables are better understood, operational procedures have a longer history, health consequences are better known, and more time has been devoted to analyzing and understanding past incidents. In addition, OC equipment is better developed and more robust. In general, technical CC diving is more inherently hazardous than OC diving, even though rebreathers offer significant safety benefits and alternatives when compared to OC configurations for many actual emergency scenarios.

DAVE PENCE:
The most obvious difference from OC diving is the dynamic nature of the CC breathing medium inherent in the recycling and replenishing process. Percentages of oxygen and inert gas are both variable. CO2 retention in the breathing loop is a real possibility. Instead of confidence that the next breath from the mouthpiece will be the same as the last, the diver must religiously monitor unit instrumentation to ensure that the gas mix (as indicated by pO2 readings) is what it is supposed to be. With the decoupling of CO2 elimination from oxygen addition, the diver must realize and guard against failure modes leading to life-threatening conditions that have no overt indicators. On the other hand, gas supply volumes change slower for CC rather than OC, so simply monitoring cylinder pressures is not particularly informative.

KARL SHREEVES:

- Closed-circuit gives you more time to deal with a problem than does open circuit, but a problem is more likely to be something easily overlooked. Training must emphasize the need to constantly monitor your gauges and analyze what they tell you.
- Closed circuit has more performance potential and provides added time to deal with emergencies, but that can also cause difficult situations such as unreasonable deco requirements. Training needs to emphasize this potential problem and how to stay within acceptable limits.
- Closed circuit is deceptively simple when everything works. Experienced open-circuit divers can get a false sense of security, get ahead of their closed circuit

experience, and find themselves in a tight spot with inadequate understanding of what to do. Training needs to emphasize obtaining experience gradually irrespective of open circuit experience.

JARROD JABLONSKI:

- Much greater complexity,
- Greater task loading,
- Greater equipment demands when kitted properly

TOM MOUNT:

- What is the difference between day and night? This could be stated as equal to OC and CCR technical diving.
- Different skills, more complex theory, requirement for greater awareness. The CCR diver needs more understanding of oxygen, carbon dioxide, etc.
- Most skills to survive are different.

Comment. This question should be a stand-alone session. It cannot be answered by a simple quickie response. I would invite all (as I think other agencies would do also) to go through our technical CCR text (*tec CCR*, and also the soon to be available exploration and mixed-gas diving encyclopedia, *The Tao of Underwater Survival*) to review the difference. So to answer this question properly would require writing an additional book which most of us have done.

4. Is there a difference between "recreational" and "technical" rebreather diving (e.g., depth, gas mixtures, real or virtual overhead environment, etc.)?

STEVE BARSKY:

Unless you are considering semi-closed circuit rebreathers, anything involving a fully closed circuit rebreather should be considered a technical dive.

JEFF BOZANIC:

Yes. Merely using rebreathers should not be considered "technical" in nature. The same constraints that differentiate OC "recreational" from "technical" diving should apply to rebreather diving. I would classify no-stop CC diving of less than 130 fsw/40 msw to be "recreational," and any diving in caves or wrecks, under ice, using helium based breathing mixes, or deeper than 130 fsw to be "technical." This list of technical diving activities is, of course, not complete. For example, some dives which might otherwise be considered "recreational" might be defined as "technical" due to other environmental considerations, such as swift current, extremely low visibility etc.

DAVE PENCE:
The definition of technical, versus non-technical generally revolves around the level of complexity of the diving, especially whether the diver incurs a barrier to direct ascent to the surface, either a decompression ceiling or a physical barrier such as during cave or structure penetrations. At this point, all rebreather diving should be treated as technical, rather than one suitable for entry-level training. Current rebreather equipment is still more complex and less standardized than open-circuit scuba, and the physiologic concepts are similarly so. By design, CC units require the use of mixed gas with high oxygen content, and have the potential to produce either hypoxic or hyperoxic conditions more readily that OC. A CC unit may be produced soon that is sufficiently reliable and requires less direct attention and decision-making by the diver, but we are there yet. If entry-level CCR training were developed, it would need to be more rigorous and longer than the standard entry-level open-circuit course today, both for conceptual and skills development. The more extensive conceptual base required (compared to entry-level OC) could potentially be offset in part by online study options. But nothing will replace direct contact with a mentoring instructor for skill training and, most important, the development of proper attitudes.

KARL SHREEVES:
Philosophically, yes. Recreational is no-stop diving, 130 feet or shallower with no or very limited overhead environment. CC machines are very different in their designs, too, particularly concerning the options the diver has in an emergency. For recreational, one may always be switch to open circuit and ascend, whereas a tec unit may have several options including manual bypass, semi-closed, etc.

PAUL HAYNES:
The use of an air diluent suggests diving in the “recreational” range (0 m to 40 m) and beyond that a helium-based diluent is required suggesting “technical” rebreather diving. The term “technical” though has a “machismo” image to it, and I feel it is time the term is phased out. As the use of mixed gas and rebreathers becomes more common, it is an ill defined and confusing description. There are simply different facets or levels to diving and simply describing the type of diving you undertake is all that’s required, i.e., I am an air-diluent CCR diver, normoxic trimix/mixed gas open circuit diver, air SCUBA diver, ERD diver, cavern diver, etc. If someone describes themselves as a technical diver, what does this mean?

TOM MOUNT:
Of course, the more complex the type of diving, the more additional knowledge and skill needed.

CCR cave skills share environmental issues with OC cave but employ different rebreather emergency skills, and this is true of deeper diving as well.
Recreational CCR skills are varied enough that additional skills and theory cannot be included in one course. Some of us learned cave, wreck, and deep diving through survival because no programs were available when we started. The disadvantage of learning by survival is that many people did not survive as I see when looking at my photos from the ’60s.
Comment: Armchair divers may theorize what they wish but surviving by doing is a great instructor.

5. What are the prerequisites for technical diving training?

STEVE BARSKY:
To a certain extent, technical diving, like recreational diving, is a self-selection process. Divers look at the amount of equipment they must use and the concepts they must master, and make the decision for themselves whether they can handle the training, equipment, and expense.

Unfortunately, there will always be people who do not recognize their own limits, or choose to ignore them. There will also be instructors who accept students for training who should not be trained. For this reason, the minimum prerequisites for any form of technical diver training should include advanced open water diver, recreational deep diving, and recreational nitrox diving. In addition, the diver should have a minimum of 100 logged dives, with 25 dives deeper than 100 fsw, and 25 dives made with nitrox. These dives must have been made within a 3-year period.

JEFF BOZANIC:
For most divers, 100 dives and 100 hours using the general type of equipment (OC/CC) should be used.

TOM MOUNT:
Best answer is to look at agency standards
Combination of knowledge – experience and attitude

6. Should non-divers be able to do entry-level training on rebreathers?

STEVE BARSKY:
Certain skills can obviously be more easily taught with open-circuit scuba, than with a rebreather. At issue is the need for the diver to repeatedly surface and converse with the instructor about how to perform fundamental skills. However, theoretically, for the person with the proper aptitude, there would be no reason why a person could not learn to dive starting with a rebreather, provided they were limited to the types of depths and situations normally experienced in recreational diving. If the rebreather could be programmed for sport diving depths and limitations, then this might be acceptable.

However, given the capacity for a rebreather to place people in situations that far exceed those of normal recreational diving, training individuals with no diving experience in the use of a rebreather is probably not a good idea. If a person was trained with no previous diving experience, the training course would need to include many of the fundamentals not normally taught in a rebreather course, such as physical oceanography, marine life, boat diving techniques, basic diving physiology, etc.

JEFF BOZANIC:
Yes. I see no reason that a person who wants to dive rebreathers should not begin on that equipment. While there will be of necessity some OC training involved (primarily for OC bailout), requiring an OC certification as a pre-requisite is both unneeded and counterproductive. Many of the habits learned in OC training are incompatible for rebreather diving, and must be unlearned before moving forward. In fact, some of my most "difficult" rebreather students have been those divers who had the most experience on OC (>5,000 dives).

KARL SHREEVES:
From an instructional-design perspective, there is no reason why they couldn't. From a dive community infrastructure point of view, at this time doing so would pose a lot of difficulties.

PAUL HAYNES:
Given the appropriate time, training and student aptitude, it is possible to train entry- level divers using rebreathers. Various military diving organizations have tried this over the years in an effort to save training time and expense. However, to my knowledge they have all reverted to entry-level training using SCUBA before progressing to rebreathers where the fundamentals of diving, diving physics and physiology are more readily acquired and with less risk.

JARROD JABLONSKI:
No.

TOM MOUNT:
Yes, although years ago, I would have stated a strong, NO, but developing skills early may be a plus. Then through continuing education, CCR or SCR develops more competent rebreather divers.

In a recreational OW Rebreather course, the approach should be to bailout to OC for any emergency, combined with shutting the unit or gas path off, if necessary. This is very much like SCR diver courses. The diver should be taught to flush but not as a means to remain on the unit if a real malfunction has occurred.

After a few years of working with this, I have been amazed by people trained as OW recreational CCR divers, who came to me for the full CCR diver program. Their buoyancy skills, bailout capabilities are usual good to great. They respond to the additional skills easily, and I believe digest and learn vs. just completing training, and on more complex skills, they do much better.

<u>Comment</u>. I would not make this a prerequisite to do additional rebreather training but do believe it makes a more safe CCR diver if they do.

7. If a trained rebreather diver elects to use another rebreather model, what level of "cross-over" training is needed (i.e., full, modified, none)?

STEVE BARSKY:
The course could probably be modified in most cases to omit the issues of the physiology of rebreathers.

JEFF BOZANIC:
It depends on the type of unit originally trained on, the type the user is going to, the amount of experience the user had on the original unit, and how recent that experience has been. In general, there is insufficient consistency between different manufacturers for there to be no cross-over training what-so-ever. At minimum, the user needs to be educated as to how to complete the pre- and post-dive checks, and any differing operational parameters (buttons, bailouts, etc). The greater the experience level with other systems, and the more recent that experience, the less time that should be needed to qualify them on a new unit. Looking at the continuum of possibilities, some previous CC divers will need to attend a full course, while others may only need an hour or two of orientation. Even with 1400

hours CC diving and experience on 12 different units, I still believe that I would benefit from some "cross-over" training prior to diving a new unit on my own.

KARL SHREEVES:
That can only be determined by being very specific about which two rebreathers you're talking about. The degree of training will depend upon the degree of uniformity between the two models in control placement, function and other characteristics that influence user actions and choices. Information that is generic in nature need not be re-introduced, but so far, unit operation is frequently non-standardized.

PAUL HAYNES:
A full CCR course would not be required as the fundamentals of closed circuit has been taught, experienced, and therefore should be understood. A modified course is required, the duration of which would depend upon the complexity of the unit's human interface and the previous CCR experience of the diver. As a general guide, a minimum of two to three days would normally be required for a basic air diluent cross over.

TOM MOUNT:
I believe cross-over training at the diver level on CCR is essential. This training should concentrate on the different electronics and or manual operations. This should not be a complete CCR diver program but should consist of lectures that review the electronics and idiosyncrasies of the new unit, and a confined water session on the unit followed by two dives. At the completion of the program, if the instructor is comfortable, the cross certification should be given, and the diver should be qualified to whatever level they previously held. This is why on CCR diver courses, IANTD issues brand specific certification similar to aviation class certification. On advanced rebreather courses such as cave, wreck, and trimix, the certification is not brand-specific as the programs are almost identical in gas, cave and wreck diving CCR or SCR skills.

Contradictions to this would be a SCR diver crossing over to CCR. In this case, a complete program must be completed as if it were the student's first exposure to rebreathers. An exception is that the instructor should have the ability to credit some dive time but to a minor degree only.

Comment. An active SCR diver would have to do a complete course plus or minus a dive or two to go to either a passive SCR or a CCR. A CCR diver would only need a brief program to go to Active SCR. The CCR diver would need to complete the bulk of a passive SCR course. A passive SCR diver needs to complete the bulk of a CCR diver course. ECCR and MCCR divers need a formal crossover but only same as crossover from ECCR to ECCR or MCCR to MCCR.

8. What is the role of the student in technical diving courses?

JEFF BOZANIC:
I expect technical dive students to be adults. By that, I mean that they should not be treated like automatons, teaching them “The Way” of technical diving. I do not believe that there is only one correct method for applying a principle. Stated in another fashion, “There are many ways to skin a cat!” They need to make decisions for themselves.

I feel that technical dive students should be exposed to various options, the pros and cons of those options, what we as a community “know,” versus what we believe, and the personal opinion of the instructor. Then, the students have to take responsibility for making decisions on their own, selecting what they believe will work and is safest for them. They also need to be taught to conduct realistic self-evaluation, so they continue to learn and grow after they leave their training program.

Courses are often longer when taught in this manner, sometimes far longer. Yet, I believe that the advantages to the students, and the technical diving community, justify the increased course length.
Basically, I think of technical dive students as “graduate students,” as opposed to “undergraduates.”

9. How many levels of training are appropriate? How many dives should each level require? What should be the basis for completion of a training level (e.g., examination, experience, etc.)?

STEVE BARSKY:
The training for technical diving will always need to be layered. Just because you are a trimix diver does not mean you are qualified to penetrate a wreck or use a dry suit.

The technical diver training agencies have done a good job of dividing up the different courses according to the subject matter and the prerequisites require the courses to build on one another.

The number of dives relates directly to the complexity and number of the tasks the diver must be able to complete to successfully complete the dive. Diving nitrox on open circuit is qualitatively different than diving trimix with a fully-closed circuit rebreather.

The basis for completion of training must always be a combination of demonstration of skills, written exam of knowledge and demonstration of judgment.

JEFF BOZANIC:
The OC agencies in general have too many certification levels. A generalized OC deep diving progression should be: (1) air to 130 fsw/40 msw [six (6) dives]; (2) Nitrox (to 40% oxygen) to the same depths with gas use as a primary breathing mixture [two (2) dives] (recreational programs); (3) decompression diving using EANx fractions to 100% oxygen for primary and decompression gases [twelve (12) dives if no previous doubles experience, eight (8) dives otherwise]; and (4) use of helium based gas mixtures to depths of 330 fsw/100 msw [eight (8) dives] (technical programs).

With rebreathers, there should be three levels: entry, decompression and helium diluent.

Entry level should qualify the participants to do no-stop diving to a maximum depth of 130 fsw/40 msw and should require eight (8) dives. The class should focus on gaining comfort in utilizing rebreathers in reasonably benign environments. Emergency drills should primarily be structured around the concept of, "Trouble? Bailout!" Each diver should carry sufficient OC bailout gas to be self-sufficient in reaching the surface.

Decompression should focus on air diluent, decompression diving to a maximum depth of 130 fsw/40 msw. Prerequisites should include at least 50 dives/50 hours on the rebreather being used, with 100 dives/hours recommended. Because the surface no longer represents safety, further training in coping with a variety of emergencies without having to resort to OC bailout should be taught. The team approach to bailout should be taught at this level, with all team members carrying larger bailout cylinders than utilized at the entry level. Lectures should focus on emergency procedures, tables, decompression models and limitations, and additional hazards associated with decompression diving. Eight (8) dives should be required at this level.

The final class in the progression should be use of helium-based diluents to depths of 330 fsw/100 msw. 100 dives/hours on the rebreather being used should be the prerequisite, along with completion of the decompression diving class. Course material should include further emergency procedures, basis and use of helium based tables or software, and additional hazards (such as thermal considerations, gas mix-ups, etc). Eight (8) dives should be required, with at least one to a depth of 235 fsw (70 msw).

Completion of courses at all levels should be based on an evaluation of academic material (written exams) as well as competency displayed during the final dives.

DAVE PENCE:
Training standards among the agencies have evolved over the past 10 years to a point at about what they should be. Extra dives or water time is always desirable to increase the intensity of the learning experience, but in the recreational world this is always going to be subject to the pressures of the market. I would hope good training instills an attitude toward continuous learning after certification rather than an endpoint.

The AAUS model is a bit different from that developed by the recreational training agencies, but actually results in a similar effect. According to AAUS standards, the traditional OC progression requires an initial 100 to 140 contact hours of training with about 30 dives under supervision needed at progressive depth intervals to gain a 130 fsw depth authorization (see AAUS Standards for details). Approximately 100 logged working dives are required prior to start of training in OC decompression-stop diving, which ensures mastery of basic diving skills. Again, prior to advancement into technical training the diving officer and/or trainer must ensure the diver's skills and, as importantly, attitudes are well matched to the increased discipline needed for technical diving. Further benchmarks in terms of accrued dive time and number of supervised dives are in place to qualify for deeper OC depth ratings, with both a 150 fsw and 190 fsw level available for standard scientific diving, although I suspect they are becoming less commonly bestowed.

At UH, we strongly encourage all our scientific divers who need to work deeper than 130 fsw to obtain training in decompression techniques and use of high oxygen mixes for decompression, and to use trimix to reduce narcosis if at all possible. For the dive officers and diving control boards, this is of course a safety consideration. Ultimately, the question that sways the scientists is how much they can trust their detailed observations at depth in the face of narcosis.

For CC work, approximately 100 logged OC dives and authorization to the target depth on OC are required prior to start of CC Level 1 training (air diluent, no-stop, 130 fsw limit). This training requires about 8 dives between 30 and 130 fsw. After training, another 4 working dives under supervision of a senior CC UH instructor are required before the diver may be authorized as a supervisor within his/her experience range, so the total number of dives required to reach full Level 1 status is actually 12. This training progression is a continually evolving and adapting. We are starting to support the use of a light trimix diluent for all diving deeper than 130', and even as shallow as 100'.

UH typically requires a minimum of 50 hours of CC flight time after Level 1 training before starting Level 2 training. Level 2 CC training (deco and trimix) mimics the OC AAUS progression, with 4 progressive, supervised dives on trimix diluent (minimum oxygen content 16%) in the 130' to 150' range, and another 4 in the 160' to 200' range, for a total of 8 dives. For Level 3, another 4 progressive training dives in 200 to 250' and 4 in the 250 to 330 is workable and I believe reasonable. On all these dives, the emphasis is on the practice of emergency procedures and protocols, as well as adapting the science methods needed, and the ultimate depth target is based on the expected mission for which the training is required.

The credit toward certification on a new unit that should be given based on prior experience with other CCRs is a topic for some discussion. That this has been over-used for the sake of expediency in some cases, and may be a source for concern. As in many aspects of CC diving, an interesting analogous model might be found by examination of the models use in flight training and certification.

KARL SHREEVES:
Only two factors determine training levels: instructional design and market demand. It is possible to create a single diver course that takes a non-diver all the way through full trimix. However, such a course would be so onerous that probably no one would sign up for it. Market demand calls for desired breaks in a training flow that allow divers to enjoy the activities for which they're trained, and to stop training, temporarily or permanently, when they reach the level that addresses their present interest level. Breaks also have an instructional advantage in that they give learners time to assimilate and progress at a pace they determine, and to allow branching down different instructional pathways. Any number of levels is possible. To accommodate these breaks, instructional design determines the in-points and out-points for each level, that is, what the minimum capabilities are for someone starting training, and the desired minimum capabilities at the end of training.

10. Should rebreather instructors be required to own and dive on the make and model of rebreather they are training a diver to use? How many hours should instructors have on the make and model they intend to train on, before being approved as trainers? Alternately, should the instructor always dive open-circuit, at least in early-stage training?

DAVE PENCE:
Instructors must have full mastery of both the techniques of CC diving and the operation of the specific unit being taught. They must be able to demonstrate skills and failure modes unique to that model. They also must have enough proficiency in operating the unit to do so while still attending to the safety and comfort of the students. To do this adequately, I believe instructors should own (or have permanent access to) and regularly dive the unit on which instruction is given. A minimum of 100 hours of dive time on the specific unit is probably a good benchmark for adequate experience, but this is something the instructor trainer must consider, beyond simply counting hours.
Early on, arguments were made for the instructor remaining on OC equipment while teaching CC, mostly based on the attention that the instructor must keep on his/her own CC unit possibly being a distraction to attending to the needs of the student. If the instructor is properly skilled in diving the unit, I think the ability to properly demonstrate unit handling and CC techniques outweighs the disadvantages. This consideration also is a strong argument for maintaining small student-to-instructor ratios.

11. Should some safety guidelines receive more emphasis during training than other guidelines? What three guidelines should receive the most training time and what is the order of their importance?

STEVE BARSKY:
Gas management.
Decompression procedures.
Emergency procedures.

JEFF BOZANIC:
Yes.
Completion of pre-dive checklists.
Monitoring PO_2.
Bailout procedures.
As a new diver again myself, I would also add a fourth: to re-emphasize the importance of the buddy system.

DAVE PENCE:
You could probably swap several of these around in priority, but I think the first two are probably in the correct rank as far as importance.

Always have a means to determine the PO_2 of the gas you are breathing.
Always have a reliable open-circuit bail-out path to the surface.
Obtain proper training for the equipment you plan to use.
Dive the unit only within the design limits specified by the manufacturer.
Use standardized checklists for unit pre-dive set-up and testing, operations, and maintenance of your unit per manufacturer's recommendations.
Maintain your unit meticulously; do not skimp on cost or effort in this regard.
Never start a dive with a unit with a known failure.

PAUL HAYNES:
Bailout gas supply and realistic RMV rates.
Pre-dive buddy checks.
Scrubber limitations and the consequence of pushing the life beyond the manufacturers recommendations.

JARROD JABLONSKI:
Yes. General suitability of candidate, stress management, skill refinement.

TOM MOUNT:
First and most important, properly prepare unit by ensuring accurate O_2 calibration. If possible, cross check PO_2 readings with milli-volt readings so sensor output is known. Mandatory pre-dive breathing on the loop. Diver should do a complete system check: warm up canister by allowing gas flow while breathing, check that solenoid is working on a CCR or on a MCCR, that the orifice allows correct flow. Ensure manual addition valves work. Ensure ADV (if available) functions. Check bailout system for functioning. Next, buddies check each other in water before diving.

In-water items dealing with survival should be covered in training first. Hypercapnia is often considered as the third most common cause in accidents, but I suspect it is the first or second as many divers deliberately pushing their CO_2 canisters. In any event, the solution is bailout which is the foundation for surviving a unit failure (particularly hypercapnia). The safest and proven method is bailout to open circuit and ascent. Do not flush and breathe as this drives more CO_2 into the diver if the canister has failed, and the CO_2 level may reach 10-20% SEV rapidly which will cause unconsciousness. The only survival mechanism is BAILOUT.

Hypoxia happens but is hard to understand why with automatic O_2 addition and readouts. It usually results if divers have not done the checks listed above. If hypoxia is suspected, go off loop and get a "sanity" breath. ("When in doubt, bailout.") If the problem is identified and can be solved, go back on loop and flush again to ensure safe PO_2. Then and only then, slowly add oxygen. Do not flush at depth with oxygen.

If counterlung starts inflating, potential causes include: (a) failed O_2 solenoid on CCR; (b) orifice on MCCR; or (c) Schrader valve on diluent bypass. Flush breathing loop with diluent, go off loop for a sanity breath, analyze problem, and if resolvable go back on loop, flush with diluent, regulate oxygen by solenoid, or shut-off automatic system and use bypass or manipulate the oxygen supply valve. If Schrader valve is cause, isolate and disconnect. Terminate dive.
On more technical dives, add out-of-gas management by using plug-in off-board gases or bailout and management of second low supply gas by training in the ability to switch cylinders.

What is most important depends on the situation, but each failure needs to be addressed in training and practiced until it is driven into muscle memory.
On OC gas management, training for out-of-gas situations are mandatory.
Train for managing positive and negative buoyancy such as a run-away drysuit or coordination of drysuit, counterlung, and buoyancy compensator gas volumes.

12. Discuss training for managing the following emergencies. Differentiate between open and closed-circuit: (a) an unconscious diver; (b) a convulsing diver; (c) drysuit over-inflation; (d) rebreather flooding; (e) open-circuit bailout; (f) single oxygen sensor failure; (g) low diluent supply; (h) low oxygen supply; (i) primary electronics failure… Please add other emergencies that are important and place the list in order of importance for discussion.

STEVE BARSKY:

Type of Emergency	Training for Open Circuit	Training for Closed Circuit
Unconscious diver	Train for management of airway and buoyancy.	Diver should be equipped with full-face mask to minimize inhalation of water. Train for rescuer management of airway and buoyancy.
Convulsing diver	Not normally a training issue.	Diver should be equipped with full-face mask to minimize inhalation of water. Train for rescuer management of airway and buoyancy
Drysuit over-inflation	Train to regain control of buoyancy.	Train to regain control of buoyancy with added emphasis on risks of DCS.
Rebreather flooding	N/A	Training should include using a full-face mask with a switch for open circuit bail-out.
Open circuit bailout	N/A	Training should include using a full-face mask with a switch for open circuit bail-out.
Single oxygen sensor failure	N/A	Training should be to terminate the dive as soon as possible.
Low diluent supply	N/A	Training should be to terminate the dive as soon as possible.
Flooded canister	N/A	Training should include using a full-face mask with a switch for open circuit bail-out.

JEFF BOZANIC:

A book could be written on this single question. In the event of an unconscious or convulsing diver (OC or CC), I believe we cannot teach effective (successful) management of the incident, especially with new technical divers. The reality is that these situations are generally unmanageable, and will likely lead to a fatality or significant injury. Instead, we should utilize discussion of these scenarios to build respect for the rules, and an acknowledgement of the risks we are accepting when we choose to participate in technical diving. The discussion should continue into the potential impacts on family, friends, and the dive community of the personal decisions made by every diver. Events include: rebreather flooding, OC bailout, low diluent/oxygen supply, primary electronics failure, battery loss, solenoid failure, hypercapnia. For entry level courses – BAILOUT!

For technical level courses, sanity breaths, followed by either bailout or responses particular to the type and amount of supplemental equipment carried. There are some emergency procedures currently taught that I believe place student divers at greater risk than the potential benefits they provide. For example, some agencies mandate that rebreather candidates at some levels remove and replace their rebreather underwater, sometimes at depths exceeding 20 fsw/6 msw. I have several concerns with this. The potential risk of embolism due to an uncontrolled ascent is too great to ignore, especially as the problem can generally be solved with less risk.

Many rebreathers incorporate integrated weight systems. If the skill must be done in water depths exceeding those of a typical pool, a wetsuit or drysuit is often worn. As soon as the unit is removed, the diver is positively buoyant, and the scuba unit is negatively buoyant. Should the two become separated, the diver is headed uncontrollably for the surface, with a greatly increased consequent risk of AGE or DCS. If students wear additional weight or shift weight to a weight belt for the exercise, they are not taught to handle the situation as it will occur, so there is no point to the skill.

Even if done as a pool skill, or with non-weight integrated systems, I believe removing the breathing apparatus is potentially more hazardous than beneficial. The only time I could justify equipment removal is in the event of entrapment or entanglement. This might be an appropriate emergency skill for an overhead environment specialty (like cave or wreck diving), where if the diver loses partial control of his gear, it will only float up as far as the ceiling. The skill is not, in my opinion, suitable for open water classes such as entry-level rebreather, decompression, or trimix. Response to entanglement in these courses should emphasize other procedures such as use of the buddy system. Examination of anecdotal reports such as, “this skill saved my life…” generally indicate errors of judgment earlier in the dive that later necessitated an extreme response. Thus, the need for the gear removal could have been avoided. Other skills are sometimes mandated inappropriately for the training level such as an entry-level rebreather diver carrying and deploying a lift bag during training. The primary reason to use a lift bag is for visual reference during decompression which is not needed in a no-decompression class. We do not require OC entry-level students to carry or deploy lift bags during training, why do we here? Lift bags are germane for a decompression level class and should be kept there.

TOM MOUNT:
Unconscious diver. A buddy should get his partner to the surface as efficiently as possible. If possible have OC regulator in mouth even though it may have been dropped. Try to depress diagram on surface. Tow to help while providing rescue breathing if possible. For an unconscious rebreather diver, action depends on situation. If mouthpiece is still in and buddy is aware of low PO_2, flush loop with O_2 or breathable gas (depending on depth) and get diver to surface, same as for OC. If mouthpiece is out or buddy is not sure of problem, keep mouthpiece out (perhaps there is CO_2 in loop) get diver to surface and try rescue breathing as for OC. Get help and treat for drowning.

Convulsing diver. Accounts of successful rescues did what I would have advised against and brought the diver up while convulsing. In one case I know, there was some water in lungs but no damage. This is counterintuitive for me, but it worked and is an area for research.

Drysuit over-inflation. Dump gas. If dump valve is not good, vent through wrist seal or neck as last alternative.

On a rebreather, must coordinate the drysuit volume (which should be used for warmth not buoyancy and so has minimal internal volume) and CL volume by exhaust valve or mouth or nose. As a last resort, hold mouthpiece above head and open and close mouthpiece valve but coordinating this is a challenge. Prevention is best.

Rebreather flooding. If just CL and not plenum-canister floods, simply clear loop according to unit-specific procedure. If a full flood, units with a hydrophobic membrane around canister may elect to do full-flood clear. (I use Cis Lunar canister quite often and can demonstrate full flood clears.) For a non-membrane canister, get off loop to prevent caustic cocktail and turn off the system according to unit-specific procedures. If electronics have a deco switch, then switch to OC position so deco is tracked. If no deco switch, put dive computer in manual mode or lowest PO_2 setting and consider shutting O_2 tank valve so solenoid in ECCR cannot fire or oxygen does not continue to flow in MCCR. Ascend on OC and do safety or real stops as required.

Respect caustic cocktail. Has caused near-fatal caustic injuries to some divers. This includes both manually packed and prepacked Micropore canisters.
Single sensor failure. Check milli-voltage if readout is available. Sometimes the PO_2 readout drops but milli-volt meter still works so sensor may or may not be putting out. Verify accuracy and agreement of two remaining sensors either by voltage or diluents flush to verify. I would stay on loop, terminate dive, and ascend.

Low diluent. Plug in off-board supply if possible, terminate dive, begin ascent when you can. You may be in cave or wreck and have to travel to place to ascend.

Primary electronics failure. Fly unit manually on ECCR or allow MCCR to continue work. Monitor the O_2 sensors using the secondary display, terminate dive, and ascend as soon as possible.

13. Should divers be taught techniques to maintain life-sustaining gas mixtures in the breathing loop without access to oxygen sensor readings, or should such situations always be regarded as open-circuit bailout situations?

STEVE BARSKY:
They should receive the training for maintaining the loop, but such situations should be regarded as open-circuit bailout scenarios.

JEFF BOZANIC:
Generally, these situations should be considered mandatory bailout scenarios. However, there are two exceptions. (1) If the diluent is breathable as an OC gas with a minimum PO_2 of 0.21 at the surface or shallowest depth used, a limited semi-closed circuit (SCR) mode may be used in mixed gas CCR diving with the diluent and a rule-of-thumb for rebreathed breaths prior to loop flush. For example, three repetitive inhalations before dumping the loop and replacing with fresh diluent with a complete loop flush prior to surfacing. (2) Use of a mixed gas CCR in less than 20 fsw/6 msw in oxygen only mode. First, turn off the diluent, then flush the breathing loop with oxygen. The concept of teaching a diver to “maintain” the gas composition in the breathing loop by maintaining counterlung volume or buoyancy is, in my opinion, worthless and unrealistic. Likewise, in the event of sensor disagreements, flushing the breathing loop with a known gas to determine which of multiple sensors still might be operational involves too much risk to the user and should probably not be done. While indicates a sensor may give an accurate reading at that time, there is no method for determining subsequent drift.

DAVE PENCE:
SCC operations of a CC rebreather become more important for aggressive operations. It should at least be addressed conceptually and practiced briefly in Level 1 training, but mastery is not really an absolute requirement since OC bailout is easily carried. Even in most exposures to 200 fsw that I can imagine, it is possible to carry or stage full open-circuit bailout using a dive team unless the bottom times are very long. Deeper than Level 2 (>200 fsw), mastery of SCC operation should be required and practiced periodically.

KARL SHREEVES:
This question can't really be answered without defining the diver and the situation. For recreational rebreather use, one can easily argue that open circuit bailout is more than ample to address loop issues. For a technical cave diver who may be a two-hour swim from the surface, the ability to extend the unit's life support capabilities may be highly desirable.

PAUL HAYNES:
Yes, for the diver, horizontal movement where the diluent provides an appropriate PO_2 and thus a safe breathing mix in the loop that can be used to save open-circuit gas until it is required for the ascent phase of the bailout. However, for it to be a viable "bailout" option under stress, it requires the appropriate allocation of time during training.

JARROD JABLONSKI:
Bailout should be primary solution. This is the key issue in rebreather fatalities.

TOM MOUNT:
Dependent upon diver training and experience levels, SCR correctly done with CCR is possible, but the first choice is OC bailout. SCR should be a rare occurrence as most CCRs today have independent readouts that make the complete loss of sensor readings unusual. More than likely, an erratic reading may occur due to moisture or a sensor beginning to fail. This is why divers should be aware of sensor voltage readings. On my last dive before this conference, I had to check voltage readings throughout the dive because of erratic sensor readings and a low battery that displayed on my handset just before we started ascent.

The more options divers have in their tool kits, provided they know how to use the tools, the higher is the probability of survival.

<u>Comment</u>. Skills learned in continuing education are very important. Skills need to be introduced in progressive manner not all at one time. Some skills must be presented as a last recourse as they may be very likely to be used.

14. Should divers be taught to breathe a closed-circuit rig in semi-closed mode (exhale every fourth breath)?

TOM MOUNT:
YES, YES, YES.
However, this may be a skill required in technical diving and absolutely requires an understanding of how OC gases drop in PO_2 in shallow water. Semi-closed circuit mode is not used in recreational OW CCR diver courses where bailout is the procedure for all emergencies.

15. How can rebreather divers be trained to use pre- and post-dive checklists more consistently?

STEVE BARSKY:
On the pre-dive side, it should be possible to build more of the checklists (possibly with lockouts?) into the dive computer used with the rebreather. Post-dive, it's difficult to get people to perform the maintenance they should. People tend to want to do the minimum they can get away with.

JEFF BOZANIC:
Emphasis by the instructor, requiring students to submit completed checklists in order to be certified, and strong review of accidents in which the use of a checklist would have prevented specific fatalities. It might also help if manufacturers were to incorporate checklists into unit manufacture such as laminating them on the inside of the Inspiration or Evolution shell.

KARL SHREEVES:
This question is about affective education (shaping the tendency to make a choice) rather than motor procedure education (creating the ability). Assuming the diver knows how to use the checklist, a forcing function such as an electronic list that requires entries before the unit will function might be feasible. The most effective forms of affective instruction are: (a) choice value that establishes the benefits of following and consequences of not following a procedure; (b) role modeling in which divers who are highly respect by the trainees are seen/shown/known to use checklists; and (c) community pressure that indicates everyone always uses checklists, and we wouldn't dive with an obvious dunderhead who doesn't. Forcing functions are very useful and most beneficial when they integrate with systems sensors that prevent involuntary automaticity from diluting their usefulness. Involuntary automaticity occurs if divers get used to routinely answering questions certain ways and stop assessing whether the answers really apply.

PAUL HAYNES:
Consistent and thorough use of checklists during training will encourage their use after training. However, in my experience, all rebreather divers quickly consider themselves familiar and confident enough with their unit to abandon the checklist. The results are occasionally poorly prepared units and near misses. Worldwide, a great number of military diving organizations require the rebreather diver to present the Diving Supervisor with a completed and signed checklist. In an environment where a Dive Manager (DM) is mandated for all diving activities, as in BSAC, presentation to the DM of a completed rebreather checklist could be introduced into dive management procedures, thus enforcing their use. However, where individuals are diving as a group without a DM, such discipline could not be enforced.

TOM MOUNT:
Grading of checklist use in class.
After class, the diver will chose to be safe or less safe. We can give the message, repeat the skills, emphasize the importance, and provide the training, but the student is the one who determines who will develop knowledge, understanding or how-to. This is apparent when you review accidents see that many do not follow the safety guidelines they were trained on with existing documentation of training.

16. Discuss two pros and two cons of solo and buddy diving regarding technical diving training. (e.g., self-reliance, rescue during hypoxia or convulsions, etc.)

STEVE BARSKY:

Solo diving pros
Each diver must be responsible for his own safety.
A properly trained solo diver with a cautious attitude will probably expose himself to less risk than a properly trained diver who believes his buddy will get him out of a jam.

Solo diving cons
In the event of unconsciousness underwater for any reason, a solo diver is at a higher risk of drowning.

Buddy diving pros
Trained buddy divers may be able to perform an immediate rescue of an unconscious diver in an emergency situation.

A trained buddy may be able to help a diver out of a potentially serious situation before it becomes catastrophic.

Buddy diving cons
A dependent buddy may cause injury or death to a more experienced buddy in an emergency situation.
Buddy diving can foster dependency.

JEFF BOZANIC:
Pros of buddy diving
You have redundancy in what is arguably the most important piece of dive gear, the human brain. Even the most experienced diver occasionally makes mistakes. The greater the experience, the more likely those mistakes will be small, resulting in a minor incident or non-event. But that is not always the case (take David Shaw, as an example[1]). A second person may provide a different view, see and correct a missed problem, or provide assistance in the event that a significant issue arises that is impossible for a solo diver to rectify, such as unconsciousness due to oxygen toxicity or hypoxia.

Diving is more fun with a buddy and generally more meaningful. We are social creatures. We naturally get more when there is involvement with others at some level.

In technical training, I believe that buddy diving is a MUST. At any level, solo diving is an advanced form of that type of diving. We should not put students at increased risk by allowing them to solo dive while they are actively working in an environment new to them. This may be differentiated from environments in which they are completely comfortable, and may already be competent in solo diving procedures, such as the 10-foot decompression stop in a benign and known condition.

Pros of solo diving
The more extreme the environment, the less likely that a buddy can render effective assistance. In some cases, trying to render appropriate aid would place the rescuer at risk, and is counterproductive. Thus, we want to instill an atmosphere and sense of self-reliance. At the training level, this is not “solo diving,” as we expect students to remain with buddies during training, and for some period after training while gaining experience.

Eventually, however, many technical divers go on to dive alone. Emphasizing self-reliance during training ultimately reduces risk when this begins to happen.

[1] Mitchell S. Respiratory issues in technical diving. In: Vann R, Mitchell S, Anthony G, Denoble P, eds. Technical Diving Conference; January 18-19, 2008; Durham, NC: Divers Alert Network; 2009: 12-37.

In addition, some environments do not permit effective buddy diving. In fact, some environments, like silty, restricted caves, may actually be safer when diving solo. Again, teaching the basis for self-reliance is appropriate when considering such post-training environments.

<u>Cons of buddy diving</u>
One of the biggest problems with buddy diving is the feeling of dependence it often teaches. Divers who are unsure of their own capabilities may rely (either psychologically or physically) on their partner, even if that partner is not any more competent than they are. This is often a false sense of security.

Further, buddy diving occasionally fosters going beyond reasonable personal limits. This happens either because of ego ("well, if she wants to do it, I would look bad if I said I wasn't ready, so I guess I'll go, too).

<u>Cons of solo diving</u>
Obviously, the comments I made earlier as to the benefits of buddy diving directly address this issue. The most consequential direct problem is lacking anyone to assist you if something serious occurs. The most obvious situation is any that involves unconsciousness underwater. Even if a full facemask is used, in most cases the solo diver has little or no chance of performing a self-rescue.

Solo diving usually adds a risk factor to diving, rather than reducing them. Exceptions might include extreme environments, or diving with a buddy of lesser competency and capability. An alternative response to these situations might be, "Why would you be stupid enough to dive under these circumstances? Just don't dive!"

Most of this response has been based on opinion. However, there is one disquieting fact that bears on this question. In both of the diving fatality databases I help maintain, solo diving is often associated with the incident. In the rebreather database, about 80% of the fatalities involved either dives which were planned as solo dives, or in which the diver was separated from his/her buddy at the time of the incident. In the cave diving database, it is associated with a minimum of 15% of the cases, possibly much higher, still a significant number.

I do not believe that we should attempt to "outlaw" solo diving in technical diving, as we did with standard OC recreational diving. The same thing would occur, we would pay lip service to the buddy system, but we would solo dive anyway. But we DO need to be honest and forthright about the risks of solo diving, being blatantly clear about the number of incidents that occur. Further, I believe we should establish a minimum recommended experience base for any particular mode of diving before solo diving is attempted, probably on the order of 50-100 dives with the equipment being used or environments similar to those contemplated for the solo diving activities.

DAVE PENCE:
What is the appropriate role of the buddy in technical diving? Should technical diving training focus on the organization as well as on the individual? If so, how can this attitude best be imparted? I am a strong proponent of every diver being trained to be as self-sufficient and capable of solving his or her own problems as possible. I also strongly support diving in a team-based system, using designated buddies. In occupational scientific diving, adherence to the buddy system for OC scuba diving is actually required by the U.S. Code of Federal Regulations for commercial diving. In practice, a team of similarly equipped and trained divers acting in a concerted manner has a wider array of options available to it in meeting unexpected situations. The key to fully realizing the potential however lies in the proper pre-dive planning, training, equipping and practice of team-based diving. At the same time, I am not a proponent of the idea that there is only one correct team method that works ideally in every diving situation or environment. Adaptation of the team-based approach must be modifiable to the demands of the mission to be maximally effective.

JARROD JABLONSKI:
Yes.

TOM MOUNT:
Divers should be taught to be self-sufficient. Agencies should avoid advocating solo and are requiring buddies.

All divers must know only I can breathe for me, and only I can swim for me. Realizing this, I must be responsible for myself and ensure I can survive. This makes me more capable of assisting others to enable them to survive.

The diver must chose how he dives, solo or with a equally competent buddy who is skilled. It is all about choice, as is all things in life.

An issue not addressed is being aware of how others (friends, etc.) can affect you and your ability to survive.

Individually, I chose to dive with a buddy I feel has good energy and is self-sufficient in diving capability. Thus, as a team we have a very high probability of "*surviving the seemingly impossible Bon Smith 1976.*"

For pleasure or exploration, I elect not to dive with a buddy I feel is not self-sufficient. Take this statement as you wish.

17. Is training in buddy-breathing valuable for technical diving?

STEVE BARSKY:
Buddy breathing is a last resort for the properly trained and equipped technical diver.

JEFF BOZANIC:
For OC technical diving, buddy-breathing training is valuable. For most types of OC technical diving, your buddy's gas supply is your only option. We have equipment and procedures which enable a team to effectively share gas in the event of an out-of-air (OOA) emergency. Generally, for CC technical diving, buddy-breathing training is unnecessary. A pair of users cannot efficiently share a rebreather. Therefore, in the event of an OOA scenario (for whatever cause, such as electronics failure, gas problems, etc.), the user must rely on an OC bailout supply. My philosophy is that for recreational CC diving, each user should have sufficient OC gas to get him/herself to the surface. In technical CC activities, a team approach is appropriate. In this situation, the concept of "buddy-breathing" should be limited to an emphasis on maintaining buddy contact and efficient passing of OC stage or bailout cylinders as appropriate.

KARL SHREEVES:
Sharing a single mouthpiece between two divers is completely obsolete in tec diving. Two open circuit tec divers should have a minimum of four second stages between them. The need to share air via one single one is unreasonably remote, making training it at best of questionable value.

PAUL HAYNES:
Any technique that offers a potentially lifesaving option in an emergency may one day prove to be useful. However, buddy breathing is a technique that is suspected of causing multiple diving fatalities (distressed diver and rescue/donating diver) and has long since ceased to be taught by the vast majority of recreational training agencies. As a result, buddy breathing should not form part of any diver training program let alone technical diving where depth adds significantly greater physical and psychological stress. The use of an alternative supply (AS), either a buddy's or one's own, is now the accepted emergency out of gas technique.

TOM MOUNT:
Gas sharing, yes, it is basic survival. Also, in CCR, cylinder exchanges ensure all divers have bailout.

18. What is an appropriate level of training in dive planning for technical diving courses given the many options among dive computers and decompression schedule planning software packages? How many levels of training are appropriate? How many dives should each level require? What should be the basis for completion of a training level (e.g., examination, experience, etc.)?

STEVE BARSKY:
The student must demonstrate competence with his own dive computer or decompression planning software. The student cannot be considered certified until this competence is demonstrated. Given that most dive computers today can be run through a simulation mode, student must invest whatever required amount of time to be comfortable using whatever method they choose to plan their dives.

JEFF BOZANIC:
We are at an interesting point of time in the evolution of dive instruction in this area. I was "brought up" on the U.S. Navy air dive tables. As a consequence, I generally compared the use of any newer tools (software planning packages or dive computers) to those. This is no longer possible. We have a plethora of options. We have a wide variety of printed dive tables, based on differing models and limits. We have dive computers in which we can select one of two, three, 10 or more preprogrammed models. We have dive computers with hybrid models, or with models that the user can set their own "safety factors," making the number of available algorithms virtually infinite.

Options and new tools are generally beneficial. Yet, what we lack is some manner of evaluating the options available to us as users. There is no recognized, independent database which allows a diver to make informed decisions as to which computer, model, or safety factor to use. I continue to hope that some of the research DAN is conducting will help with this. My perception of the current status is one of chaos. In my technical classes involving decompression, I currently provide an introduction to the tools and models available to us, and some of the reasons that one might select one tool over another. I go on to teach ways of building in safety margins, such as decompressing on a gas with a higher FO_2 than called for in the model, or increasing the time of dive by an arbitrary time period and decompressing based on that schedule, or adding "deep stops" in models that do not use them (decreasing bottom time by the time used in a deep stop), but all of these fudge factors really point to my own uncertainty in trusting any of the tools used. I then encourage my students to conduct further research on their own, before settling on a tool that we will all use for that group in our dive planning. I also preach that regardless of model or tools used, divers should have redundancy in operational considerations (contingency tables, timer and depth gauge to back up a computer, or multiple dive computers appropriate for the dive) whenever diving beyond no-stop limits is conducted. The issue is further complicated by an incomplete understanding of decompression physiology and other factors that might impact decompression.

Poor physical conditioning, exercise before or after dives, thermal comfort, dehydration, possible PFOs, prior insults or injuries, interactions between differing gas fractions during the dive, high PO_2s, the role of PCO_2, etc. all may play a part in observed incidents. We just do not have sufficient data in this area. I do not think that any of the tools being used are especially hazardous or of greater risk than another, or I presume we would be hearing of DCS incidents biased towards one tool or another. I personally have a greater degree of comfort with some models than others, but that is based on personal biases that may or may not ultimately prove to be correct. This basically sums up what I believe ought to be taught.

KARL SHREEVES:
Divers must be sufficiently trained to plan any dive they're qualified to make, within the limits of their qualifications or experience, whichever is less. In tec diving, this training necessarily includes the use of dive computers and desktop deco software because both are practiced in the tec community.

TOM MOUNT:
Multiple levels of training are required to meet increased demands of specific environments such as cave, wreck, deep, deeper, etc.

A second demand is the increased popularity of some of these pursuits. Once, divers entered these areas with great experience. Today, many chose to evolve more rapidly into more advanced diving, be it recreational or technical.

This transition is coupled with better equipment that provides more diver demand. The agencies and manufacturers have to this demand to maximize the safety of evolving divers.

All levels of training should be based on skill and performance including physiological knowledge and psychological adaptation.

Students should understand that they have to purchase training and earn certification.

To qualify a student, an instructor must feel the student demonstrates an ability to survive at the appropriate level of training and is competent to do unsupervised dives. This is in addition to meeting the agency standards.

19. Do technical divers dive as they have been trained? If not, should training be adjusted to emphasize the most important safety factors that are not being observed?

STEVE BARSKY:
Most divers deviate from their training from time to time. This is human nature. Divers who deviate from their training include recreational, technical, scientific, and commercial divers, i.e., all categories of divers. As the risk increases with the type of dive, the dangers of deviating from training increase. In my experience, I have seen cases at all levels of diving where divers have deviated from their training.

JEFF BOZANIC:
No, technical divers do not always dive as trained. Examples include cave divers conducting "visual jumps" or failing to place a line in to the permanent line at the entrance of caves, decompression divers diving solo, or rebreather divers not using pre-dive checklists, or performing technical dives "alpine" (i.e., without OC bailout). I do not think that adjusting training programs will effectively solve these problems. One of my favorite maxims is, "You cannot legislate stupidity!" It does not matter what rules are set, there will always be people who choose to break them. The more we try to educate divers, or the more we try to "enforce" rules, the more ways others will opt to break them. I believe that we are doing a generally adequate job in informing students of safety protocols. We cannot expect everyone to follow everything we suggest. The one area of improvement I would suggest is a greater emphasis on actual accidents in the various areas of technical diving that have occurred, and relating these same incidents on a personal basis to students in classes.

KARL SHREEVES:
Given that accident analysis commonly finds errors leading to the accident, we know that tec divers do not always dive as they've been trained. It would be interesting to learn if anyone has objective data that can quantify how much variation occurs between ideal (trained) practice and reality.

TOM MOUNT:
This is a stupid question. DAN should contact legal staff before even asking, which may apply to many of the questions on this form.

Why this question is even asked? Some do, and some do not. Regardless of training we cannot crawl into a divers mind once he leaves a course. I feel confident that all training agencies, manufactures, and instructors do all in our power to prepare a diver.

We can inform divers of risk, train them to recognize risk and train them to have knowledge and skills to deal with emergencies, but every individual can choose to ensure safety or to harm himself in whatever manner he chooses. All we can do is provide them the ability to chose a safe manner to dive. They will decide how to dive either per training or per their own dictates.

I think most instructors feel the majority of our students elect to use the skills and protocols we taught. Some elect to do variations or plain stupid things against the training they undertook.

Closing this response, the fact DAN would even place this question for discussion is totally beyond my ability to understand unless the goal is to create liability for training agencies, manufacturers, and instructors, and heaven knows, none of us need more issues to deal with.

20. Should there be training standards for technical diving courses and should courses be audited?

STEVE BARSKY:
Yes, there should be training standards for technical diving courses. It would be ideal if the courses could be audited, but this would probably be logistically and financially impractical.

JEFF BOZANIC:
We should have training standards… and do. The issue is they differ from agency to agency, and the manner in which they are interpreted may differ from one instructor to another. Auditing might partially resolve the inter-instructor concern, but it is not likely to be completely effective. Further, it would most likely be cumbersome, expensive, and tedious. I do not think it is a reasonable option. As to the first concern, to some degree we need variation in standards, techniques, and procedures. That is how we continue to improve as an industry (I would hope, making the sport safer for participants). I may vehemently feel that one agency's standards are inadequate or wrong, or that another's are "the best," but the underlying reality is we need both of those agencies' standards. It is only after trying alternatives for a period of time that we eventually evolve to something

that works, or later works better. And returning to variations between instructors, the same premise is true. If we do not allow our instructors some latitude to differ, to try something new, then we will become frozen in place, and nothing will ever improve. The key is to allow progress to occur without placing our students at significantly increased risk.

PAUL HAYNES:
There are training standards by all agencies. However it is widely known that in some instances the training provided falls short of the agency standards. A practical means of policing standards is to introduce a QA system where students are provided with the appropriate report form to independently comment on the instruction provided. Knowing the criteria against which the student is asked to comment will help drive the Instructor towards ensure minimum standards are maintained.

21. Should technical instructors teach a minimum number of students or courses per year to maintain currency?

STEVE BARSKY:
Yes. The minimum should probably be two courses per year.

JEFF BOZANIC:
Yes. However, it is difficult to quantify given the range of technical programs that might be taught. There are three concerns: (1) One must be active in instruction to maintain teaching skills. (2) One must be active in the particular discipline to maintain personal diving skills. (3) One must keep abreast of new or evolving developments in the industry. My off-the-cuff response is that a technical instructor must teach a minimum of one class per year to keep a single technical specialty qualification current, or a minimum of two technical classes at any level if you hold more than one specialty certification, PLUS you must log at least 10 dives annually in each specialty activity to maintain currency. (A single dive might count toward more than one category, for example, a trimix dive in a cave would count toward decompression, nitrox, trimix, and cave diving.) An alternate way at looking at the minimum diving requirement is to require a minimum or 10 dives in that specialty during the preceding 12 months, presuming that all other technical instruction currency requirements have been met. This would allow for an instructor who relocates to an area that doesn’t permit him or her to participate in a type of diving to move back after a period of time and renew their personal skills in that discipline before teaching again. We also should consider a regular recertification program for instructors, maybe to be conducted every four to five years. Instructors would be required to demonstrate teaching skills (academic and water), attend industry update sessions, and exhibit a personal fitness level and diving skill consistent with their qualifications. If health or

fitness issues prevent an experienced instructor from adequately supervising students in water, then as an industry we would need to make provisions for those persons to act as lecturers (conducting academic teaching activities), or as water assistants to another fully qualified technical instructor.

JARROD JABLONSKI:
Yes, they should also be re-evaluated to ensure capacity and update their training.

TOM MOUNT:
Yes, and I think all agencies state such.

22. Is there a minimum number of annual dives recommended to maintain adequate currency? Should technical divers be recertified?

STEVE BARSKY:
Yes, the diver should be required to log a minimum of 12 dives a year to maintain currency. Recertification is probably not necessary as long as the diver logs the minimum number of dives each year.

BOZANIC:
I believe that this question should be expanded in scope to look at recreational diving at all levels. I think that the concept of “certification for life” is unrealistic and hurts the community. At any given level, the participant should be required to log a minimum of 10 dives annually (or some other number jointly arrived at by stakeholders in the community) to keep their certification current. This should be administered (enforced) every two years. If the divers fail to do this, then they should be required to attend a review program (which may only be a few hours, depending on the level of certification being reviewed) to have their certification renewed. All major levels of certification should be incorporated into this type of program. Thus, if you are certified in rebreathers, you must log an average of 10 rebreather dives every year (20 biannually). For OC diving, at least 10 OC dives annually at any level of OC diving. For trimix dives, 10 trimix dives annually; etc. If you are OC trimix-certified, and did only 15 trimix dives in a two-year period, but also did 10 OC nitrox dives, then those would suffice to meet your general OC and nitrox certifications requirement, but you would need to attend a review program to renew your trimix certification.

I feel this would benefit the community many ways:

(1) We would have a better educated and more competent community of divers,
(2) We would have a more active instructor corps, as they would have more work to do,
(3) I would expect the number of incidents to decrease,
(4) I believe that resorts and other destinations would benefit, as there would be fewer "certified" divers coming through that have not been diving in many years,
(5) It would allow for the dissemination of new procedures, equipment updates and general introduction of current knowledge among all divers, and
(6) I believe that the "occasional" diver would be more comfortable with this type of program, as it would give them a low stress, does not threaten their egos, but allows them to "brush up" on their knowledge and skills. Active divers would be minimally impacted. Essentially, they would be charged a certification fee ($25 every two years), which would jointly benefit both the certification agencies, and possibly a non-aligned membership organization as discussed below.

DAVE PENCE:
Required minimums can become an issue of discussion on many levels. Once trained, technical dive skills are definitely a use-it-or-lose-it proposition. Even on non-technical OC diving, I now attempt to configure my kit as close to the way it would be for a technical dive, to retain muscle memory, and I have refrained from diving on at least one technical project because I did not feel I had enough work-up time before deployment. An OC technical diver should be required to make at least one dive in technical equipment every few months. Similarly CC divers not solely diving CC will need some retraining or work-ups after layoffs from CC. A similar philosophy applies to technical instructors or CCR instructors to some degree. If they aren't routinely and regularly diving technical or CC, they are not going to maintain the skills.

PAUL HAYNES:
A minimum of 20 dives per year using "technical" diving techniques may be sufficient to maintain skill levels Define technical diving techniques. Maintaining skill currency as "technical" diving evolves is a different subject though and will be dependent upon the individual person's philosophy toward study and self improvement. Because of the continuing evolution of "technical diving," it might be argued that recertification is required. However, introducing and mandating recertification would be a significant challenge and policing recertification would be extremely difficult.

JARROD JABLONSKI:
Yes, all divers should be recertified in all forms of diving.

TOM MOUNT:
On first, yes.

On second, how do you enforce recertification? If it were doable, recreational divers most likely need it more than tech divers.

To enforce an unenforceable standard imposes liability on agencies.
I think we would all agree, in an ideal world, one would start diving with a complete physical exam by a qualified hyperbaric physician who would do a stress or VO2 max test and a psychological evaluation. Divers would recertify annually at their level of competence. How many of you would do this, and what agencies truly believe they could 100% enforce it? We do live in a less than ideal world.

Once a diver has competed training and leaves, he has the right to make his choices. I and many in this room served in the armed forces to ensure that diver and everyone else would have the right to chose. Thus, I see no reason for us to act as some kind of God or big brother and totally control the individual rights of others to think, breathe, swim and make choices in life. To do so would violate the very rights of a free society.

23. Discuss physical fitness standards for technical diving.

STEVE BARSKY:
Technical diving usually requires carrying more equipment than recreational diving, places the diver underwater for extended periods of time, and may expose the diver to conditions that are more challenging than sport diving. For these reasons, a technical diver should be more fit than a recreational diver.

Prior to engaging in technical diver training, the diver should pass a minimum watermanship test, without the benefit of any swim aids, including 400-yard swim under 10 minutes, ability to tread water without swim aids for 10 minutes, and a 25- yard underwater swim. A full physical exam for scuba diving should also be required. This will help to decrease risk to the diver and the industry.

BOZANIC:
I have two conflicting beliefs that bear upon this question: minimum acceptable fitness versus freedom of choice. Technical diving places a number of stressors on the physiology of the participants. The associated equipment carried by the diver weighs a lot, sometimes equaling or exceeding the weight of the diver. Environmental conditions may impose thermal stress on the body, or necessitate high exertion rates (such as having to battle surf

during entries or exits, or currents to return to the exit point). There is also, of course, is the work required to move the equipment from storage locations to the dive location.

General participants should be sufficiently healthy to cope with these anticipated demands. They should be able to exert themselves for at least 30 minutes, have adequate skeletal and muscular strength to handle equipment, and of course meet all of the same “normal” health expectations of all divers, including freedom from seizure disorders, healthy pulmonary function, etc. The question becomes one of how to assess these criteria. To what level do we screen technical diving candidates? Many conditions may not be picked up on standard health screenings or physical examinations.

One well-discussed condition is PFO. The tests to screen for this are both expensive and intrusive. Yet, the condition can have a serious detrimental impact on the technical diver with a heavy inert gas load. Is it reasonable to screen everyone for this condition that impacts only a minor portion (estimated 5-20%) of the general population? I personally do not think so. Even if stringent physical exams are done, they may not identify underlying problems. On an anecdotal basis, I once had a student who was a policeman, extremely active in his day-to-day duties. He had annual physicals, with his last one being three months before his technical dive training. During his initial dives, he was fine; a very competent, experienced, fit diver. Halfway through the course we encountered water conditions colder by about 41°F/5°C. Shortly after that, he began experiencing pulmonary distress, and we aborted the dive.

His doctor attributed the problem to bronchitis and pneumonia, clearing him to dive several months later. Continuing his diving, he again was fine for four dives. Then, descending below the thermocline he again exhibited severe distress, leading to immediate termination of the dive. It turns out that he had a viral infection affecting his heart (with a later determined ejection fraction (EJ) of 27%). He was successfully treated for this and later cleared to dive, but the point is that the problem was not seen in his normal day-to-day high exertion activities, and was missed during two consecutive medical examinations. We cannot expect to identify every poor-risk technical diving candidate with medical/physical screening alone.

We have a further difficulty with physiological concerns with which as a community we just have no experience. One example is hyperoxic myopia. The military has been diving mixed gas closed circuit rebreathers for at least 20 years. But civilian divers are using them differently. Military divers generally maintained a set point of 0.7 atm, conducted dives of usually shorter durations (less than 3 hours), and generally did not dive more than 2-3 days in sequence. In the more extreme examples, civilian divers have been utilizing set points of up to 1.3 atm, diving eight or more hours daily, and occasionally diving 14 or more consecutive days. In some of these instances, divers have experienced nearsightedness presumably caused by exposure to high oxygen partial pressure. This is new, not seen in 20 years of history, seemingly because the equipment is being utilized differently.

One of the things I stress to my technical diving students is that, "We are all guinea pigs!" In some cases, we are involved in *de facto* table validation in a wide-scale, poorly controlled "experiment." We do not know the long-term effects on our bodies of utilizing different decompression tables, exposure to oxygen, or other factors. In fact, I personally wonder if some of the fatalities we are seeing in rebreather use in particular, which are often attributed to "heart attack," are actually signals of an unknown interaction between PCO_2 and oxygen, or some other poorly understood physiological interaction. We still have much to learn. Finally, to return to the second point in my original paragraph on this topic, while I believe that we have the right to expect healthy, fit candidates, we should not impose our value system or beliefs upon them. There are individuals, who despite known heath concerns, wish to participate in technical diving activities. These are people who any of us would unequivocally recommend that they not dive, but who wish to do so anyway.

Let me pose one hypothetical example: A long-time diver is diagnosed with lung cancer. He ceased diving for two years while treatment was administered, but now has been informed he only has two more months to live. His lifetime desire has been to dive the *Andrea Doria*. He is in extremely poor physical condition, and of course is in poor lung health. Who are we to tell him he cannot do this? What right do we have to deny training to him, potentially exposing him to even greater risk if he opts to make the dive anyway? Even if the likelihood is he will die during the dive?

I believe that even individuals who have contraindications to technical diving should be allowed to do so, so long as:

(1) They truly understand the risk,
(2) They fully disclose the risks to their families or significant individuals,
(3) The instructor is fully informed of the condition(s), and
(4) An appropriate physician has consulted, and signs a medical release stipulating that in his opinion, that such diving is contraindicated.

I know that this opinion runs counter to prevailing opinions that we need to protect people from themselves. Yet, I personally believe that everyone has the right to accept risk at any level they choose, so long as they understand the risk, the consequences, and do not place others in jeopardy (such as expecting someone to perform a body recovery should they fail to return from a dive).

I also believe this shift in perspective would also help increase the safety of the community. I have on multiple occasions had technical dive students lie about their medical history, because they knew that if disclosed, they would not be allowed to participate. This places not only them at risk, but also the other students, the instructor, and to some degree the dive store, dive charter boat, and local dive community. I believe it would be far more appropriate and reasonable to disclose the issues, and work accordingly from a position of knowledge and acceptance.

PAUL HAYNES:
Again we need a clear definition of technical diving to answer this. Training in the use of a CCR with an air diluent might fall into the definition of technical diving, however the use of a CCR with an air diluent requires no additional fitness above that required for open circuit scuba. The use of a twin set or CCR with multiple stages in challenging open water tidal/ocean current environments does require a level of fitness above that required for open circuit scuba.

JARROD JABLONSKI:
None really exist which is a notable problem. Fitness and aquatic proficiency should be established.

TOM MOUNT:
I am most likely the wrong person to discuss this. However, I do feel both physical fitness, psychological and mental fitness are mandated for any form of tech diving.

We must have efficient circulatory and respiratory health. If we do not, we are at great risk of every diving malady especially decompression sickness. So any diver should do some form of resistance training, brief or intense to prevent injuries. Some type of cardiovascular fitness program must be taken to provide good circulation, respiration, etc.

<u>Comment</u>. Divers do not need to be Greek gods or goddess, but they must be safe, maintain fitness and follow a correct diet. Today we have a population passing then 30 percent obese rate, thus a lot of rationalization of divers saying they do not need to be fit. However, not only on diving but also in all areas more and more research reveals the dangers of being obese and disease susceptibility. Decompression sickness may also be viewed as an immune system disease and thus the apparent increased risk. Yes, one can be overweight and retain good shape as do many tackles on pro football teams but a leaner version in the same condition is more likely more disease-resistant. Many of my good friends disagree with me, those who do have one thing in common, they are overweight and wish to rationalize how they differ from others and thus are not affected by increased

weight. If one is overweight, then exercise under realistic conditions is even more important to retain healthy circulation.

24. Should technical diving students be required to utilize a standardized equipment configuration?

JEFF BOZANIC:
Absolutely not!! There is no single equipment configuration that works for every person in every environment. Equipment should be mission-specific, and should be tailored to meet the needs of the individual using it.

25. What does the panel think about instructors who want to conduct courses designed around open circuit on rebreathers?

STEVE BARSKY:
There should not be a problem conducting specialty training in most diving specialties with people who have been properly trained to use a rebreather.

PAUL HAYNES:
Instructors should use the same equipment as the students on shallow dives where instructor demonstration and student imitation are essential instructional techniques at the early stage of skills training. Having equipment of very similar configuration is a necessity for this; however on deeper dives where instructor demonstration is no longer required but merely student prompting, the instructor may use a rebreather.

26. Can/should there be a common standard for technical diving? (This conference is not expected to develop standards, we would only just discuss the issues.)

STEVE BARSKY:
There should be a common standard for technical diving. The standard would have to be defined in terms of each different training course the diver completed with standards within each course. For example, a full-face mask course for technical diving would include a certain number of minimum hours of training, a specific number of open-water dives, and a specific set of skills the diver must master prior to certification. By developing a common standard, the industry would help to reduce risk.

JEFF BOZANIC:
NOTE: This is a direct copy from the “Should we have standards” question above. We need variation in standards, techniques and procedures. That is how we continue to improve as an industry (we hope, making the sport safer for participants). I may vehemently feel that one agency’s standards are inadequate or wrong, or that another’s are “the best,” but the underlying reality is we need standards of each agency. It is only after trying alternatives for a period of time that we eventually evolve to something that works, or later works better. The same premise is true with individual instruction. If we do not allow our instructors some latitude to differ, to try something new, then we will become frozen in place, and nothing will ever improve. The key is to allow progress to occur without placing our students at significantly increased risk.

PAUL HAYNES:
Common standards would be the ideal. However, as is common with large organizations, multiple training agencies adopting a common standard would likely result in a slowdown in the evolution of training/diving training technique as each agency would need to review, pilot and agree to the introduction of the new technique/training method/standard before it was accepted. Common standards cannot be achieved between the recreational air SCUBA training agencies and so is unlikely to ever be realized in the technical diving community.

27. What needs to be standardized in the tech community? What doesn’t?

KARL SHREEVES:
Anything that affects diver-to-diver actions benefits from standardization by reducing variables that must be considered in an emergency situation. The placement of anything used automatically should either be consistent, or so dramatically different that involuntary automaticity isn’t an issue, e.g., diluent and oxygen bypass valves should either be standardized left/right respectively, or placed some place completely different, such as on the side of an instrument panel. Otherwise, there’s potential for error when going from one unit to the next by automatically pressing the wrong bypass.

JARROD JABLONSKI:
Much higher minimum standards that evaluate capacity.

TOM MOUNT:
Lots of factors to consider, location, environment, equipment. There are some minimums observed already and these should be as is. And this is not a DAN responsibility. It is an agency and manufacturer task.

28. Is there a need for a committee (like the RSTC) to offer minimum training standards for technical diving?

STEVE BARSKY:
Yes, there is a need for minimum training standards for technical diving. This is important not only for boat operators and resorts, but also for instructors who accept individuals for additional training and for divers who participate in dives where there are other technical divers.

JEFF BOZANIC:
I personally do not believe that the concept of a committee to establish “minimum” standards is particularly effective. My observations of the process is that to achieve consensus, that the developed standard reflects the lowest common denominator of the participants and that the agencies which originally had more stringent standards gradually drift downward in their requirements to remain competitive. This does not, in my opinion, serve the civilian diving community well.

29. What is the appropriate role of “e-learning” in technical diving?

JEFF BOZANIC:
E-learning is a viable means of introducing or reviewing academic information as is a textbook. Neither can be used exclusively to present all academic knowledge although a good e-learning program comes closer to that goal than a traditional printed textbook. Of course, no e-learning program at this time can possibly take the place of hands-on equipment handling, or actual pool training or diving.

KARL SHREEVES:
E-learning either via computer-loaded programs or online is a form of instructional medium that is suited to transferring verbal information, establishing intellectual skills and previewing motor procedures. It has the added advantages of being able to provide basic interactions that allow the student to confirm learning and the ability to provide audible text for those who learn better by listing than by reading. Assuming it is used in an instructionally valid manner, e-learning would be an appropriate medium for developing a knowledge and intellectual skills base in tec diving, much as videos and manuals do now. Hands-on application and water skills-related training under instructor supervision would not differ substantially from present methods when using other media.

PAUL HAYNES:
E-learning can play the same role in technical diving as it can in any other training environment where a certain level of theory knowledge can be acquired before a course commences. Final theory assessments though should remain a training course activity so that the instructor can satisfy him/herself the student has learned and understood the theory aspects of the course, and where required, can reteach, if necessary.

JARROD JABLONSKI:
As a supplement to knowledge covered and implemented during training. It should not be a substitute for instructor knowledge.

TOM MOUNT:
Useful to speed up the process by divers who have limited free time for class and theory work. However, this should be backed up with essential needs by the instructor.

All practical skills have to remain in the observed world.

30. Would it be appropriate to add some cost to a rebreather training course to support a fund that would help to pay for the testing of rebreathers that had been involved in diving accidents? What additional cost would be reasonable?

STEVE BARSKY:
There are probably not sufficient revenues among the manufacturers to pay for this.

JEFF BOZANIC:
I believe that a more reasonable method would be to establish a not-for-profit organization for technical divers that would accomplish several objectives. One of the most important would be to gather information on the number of "safe" technical dives (defined as without major incident) that are being conducted annually. This information would dovetail nicely with projects that DAN is pursuing and would benefit the entire community. Members would have to submit dive log summaries annually for this to be realistic. It also could be used to provide funding for the testing of rebreathers (both those involved in accidents and those in general manufacture), lobbying for further support and mandated independent testing, acting as a non-denominational group for establishing and discussing technical diving training standards and procedures, etc.

These are all objectives that would benefit both OC and CC technical divers. An Internet-based newsletter would be cost-effective manner to communicate to the membership, providing them with information (value) for their membership. Other membership benefits might include negotiated gas fills rates, access to specialized technical training trips, etc. I think that incorporating the cost of belonging in each certification course is extremely reasonable. I feel that a fee of $25 per person per technical certification course would not be excessive. This would provide membership for the current year. Members would be encouraged to voluntarily renew after the initial period. The challenge would be to get support from all of the training organizations to ensure as complete a participation level as possible. Having mandatory initial participation is key in both initial funding, as well as promoting and building membership.

TOM MOUNT:
Again, what a stupid question. It is difficult enough to get diver registration fees sent to agencies. Instructors would find it hard to add cost for testing. The whole issue is impossible to manage and is not the responsibility of training agencies.

Manufacturers should establish standards of performance they agree on. CE is one thing but not the ideal by a long shot. Once manufacturers establish an agreed-on minimum, then all manufacturers should comply and use independent tests to verify their compliance. The testing should be built into the sale price of the unit, which is where it can be enforced. Many facilities can do this testing such as Micropore, Morgan Wells, various facilities in Europe who test for CE compliance.

On testing of accidents on units if such practice is performed, the manufacturers should develop pool based on their exposure per units sold versus accident rate and each contribute that amount or an amount based on company size, so a small company is not forced out of business by larger companies and large companies do not pick up the bill for everyone.

31. Does tech diving over task-load the diver?

KARL SHREEVES:
It can, but so can basic recreational diving in a novice. Task-loading results from multiple priorities, unfamiliar procedures, and little time. The greater the degree of any of these, the greater the potential to task-load.

JARROD JABLONSKI:
Only when inadequate criteria are utilized during evaluation of readiness.

TOM MOUNT:
Rather a dumb question. All divers, tech or otherwise, can over task-load. Task-loading is the result of giving a person more than he or she can react to at one time.

Thus, those who practice skills at any level can most likely deal with issues. Those who do not practice have tendency to over task-load.

Stress and inability to control stress (remember the 15% who will panic regardless) can cause task-loading in low task demands. Discipline and practice can allow divers to manage many tasks and as stated by Bob Smith in, *Sage Cave Diving* (1976), "survive the seemingly impossible."

32. What are three critical errors that training alone may not eliminate?

KARL SHREEVES:
All critical errors may not be eliminated by training because divers have the choice to not do as they've been trained.

TOM MOUNT:
According to Leach, Seibert, Ludam, and others and my observations, approximately 15% of the population at large (in all activities including risky sports, daily life, etc.) cannot be taught to use survival skills for real emergencies. These people will perform well in training and may be considered exceptionally disciplined. However, in real situations they are most likely to panic. An additional approximately 15% may be very capable but in such a deep state of denial, they might panic as well and not respond in time. This can cause a freeze reaction similar to the freeze of a panicked diver although if the diver gets over denial, he or she will respond correctly but possibly too late. The remainder of the population may respond based on how well they learned (from training or experience) either physically or by visualization practice of survival techniques.

A student who does not maintain skills will be unable to react due to loss of muscle response memory.

Human error, although hard to describe, results in numerous accidents, from DCS to drowning. Although training attempts to avoid this, only the divers can think, breathe, swim or react for themselves. When the human component breaks down from any source including complacency, distraction, or overconfidence (swelled ego), errors that cannot be resolved can occur.

Comment. An instructor who is too much of a “nice guy” and sympathizes with the students may let them “get by” with marginal skills. Everyone is tempted to do this at some time. To avoid this error in training, I advocate an agreement with students: training will continue until both you and I (the instructor) are confident that your capabilities and knowledge are satisfactory and that learning may have accompanied the training. This approach may break down unintentionally.

33. Given the time, hardware and other hard and soft costs involved with tec diving, what is the financial viability of tec diving for the various levels of service providers?

TOM MOUNT:
It is expensive but a choice many of us make. If one has to ask, they most likely will not do it as it is irrational and illogical from the point of view of expense. It is a activity one chooses to do independent of reasonable judgment.
Buying a CCR increases dive time and decreases cost per minute by cutting helium cost.

Tech diving is in the category of, “if you have to ask, don’t do it.” Tech divers will sacrifice as most of us do to enable them to do what they want. We all do that in all walks of life.

34. What motivates a rec diver to go to tech? Are rec divers having their expectations met?

TOM MOUNT:
Personality.
Competency.
Challenge.

Normal progression in life requires increases in expectations such as in one’s career, climbing, skiing, etc. This is what we want to do and are willing to work to achieve. Professionally or recreationally, all the same issues apply. We chose to do it because we wish to.

35. Should training agencies have required equipment prior to a student beginning a course?

STEVE BARSKY:
Students must train with the equipment they intend to use for their dives. All students should be required to purchase their own equipment. Given the expense of outfitting themselves for technical diving, purchasing their own gear demonstrates a level of commitment to the activity; this is not a casual interest. Given the increased risk in technical diving, this commitment is essential.

JEFF BOZANIC:
I do not understand the question as stated. If the intent is to ask, "Should students be required to utilize a standardized equipment configuration?" my response would be, "Absolutely not!!" Otherwise, please rephrase the question.

KARL SHREEVES:
The DSAT TecRec courses stipulate equipment requirements for participating in the course. Circumstances vary tremendously, so how the student gets access to that equipment is appropriately between the instructor and the student.

TOM MOUNT:
I would hope all of us do, but it is dependent on the level of diving.

36. Should technical diving training focus on the organization as well as on the individual?

KARL SHREEVES:
I'm not sure I understand what this is asking.

TOM MOUNT:
To the extent of the quality of instructors and standards to ensure a safe diver, yes. I wish everyone would do IANTD, but some chose other agencies and that is not a sin – heart breaking – but not sinful. All of us may differ on points, and each of us feels we offer a better program, but I do believe all of us strive to make diving safe at all levels.

APPENDIX A. Glossary

ADV	Automatic Diluent Valve
AGE	Arterial Gas Embolism
ANSI	American National Standards Institute
ATA	Atmospheres Absolute
ATP	Actual Temperature and Pressure
BC	Buoyancy Compensator
BMI	Body Mass Index
BSAC	British Sub-Aqua Club
BTPS	Body Temperature and Pressure
CBF	Cerebral Blood Flow
CCR	Closed Circuit Re-breather
CE	Certification European
CEO	Chief Executive Officer
CFD	Computational Fluid Dynamics
CI	Confidence Interval
CNS	Central Nervous System
CO_2	Carbon Dioxide
CPR	Cardio-Pulmonary Resuscitation
CPU	Central Processor Unit
DAN	Divers Alert Network
DCI	Decompression Illness
DCIEM	Defence and Civilian Institute for Environmental Medicine
DCS	Decompression Sickness
DEn	Department of Energy
DRDC	Defence Research and Development Centre
DS	Dead Space
DSO	Diving Safety Officer
EC	European Community
EN	European Norm
EOD	Explosive Ordnance Disposal
EU	European Union
EUBS	European Underwater Barometric Society
FAA	Federal Aviation Authority
FIO_2	Fraction of Inspired Oxygen
FMECA	Failure Mode Effect and Criticality Analysis
FSW	Feet of Sea Water
GUE	Global Underwater Explorers
H	Horizontal

HBG	High Bubble Grade
HSE	Health and Safety Executive
IANTD	International Association of Nitrox and Technical divers
ISO	International Standards Organisation
IV&V	Independent Validation and Verification
KSC	Kennedy Space Center
LEM	Linear Exponential Model
LSSL	Life Support Systems Laboratory
MSW	Metres of Sea Water
MVV	Maximum Voluntary Ventilation
NASA	National Aeronautical and Space Administration
NATO	North Atlantic Treaty Organisation
NEDU	Navy Experimental Diving Unit
NOAA	National Oceanic and Atmospheric Administration
NMRI	Naval Medical Research Institute
NPD	Norwegian Petroleum Directorate
NTSB	National Transportation Safety Board
O_2	Oxygen
OSS	Office Strategic Studies
OTS	Over The Shoulder
PADI	Professional Association of Diving Instructors
PC	Personal Computer
PCO_2	Partial pressure of carbon dioxide
PO_2	Partial pressure of oxygen
PPE	Personal Protective Equipment
PV	Pressure Volume
QA	Quality Assurance
QC	Quality Control
RIP	Respiratory Inductive Plethysmography
RN	Royal Navy
SCR	Semi-Closed Re-breather
SCUBA	Self-Contained Underwater Breathing Apparatus
SD	Standard Deviation
SEV	Surface Equivalent Value
SFAIR	So Far As Is Reasonably Practical
SIL	Safety Integrity Level
SMB	Surface Marker Buoy
STANAG	Standardisation Agreement
STPD	Standard Temperature and Pressure Dry
SWBO	Shallow Water Black Out

TDI	Technical Diving Instructors
TV	Tidal Volume
UBA	Underwater Breathing Apparatus
UHMS	Undersea and Hyperbaric Medical Society
UK	United Kingdom
US	United States
USN	United States Navy
V	Vertical
VGE	Venous Gas Emboli
VV&A	Verification, Validation, and Accreditation
WOB	Work Of Breathing
YMCA	Young Mans Christian Association

Heliox	Gas comprising a specified mixture of oxygen and helium, capable of supporting human life under appropriate diving or hyperbaric conditions.
Nitrox	Gas comprising a specified mixture of oxygen and nitrogen capable of supporting human life under appropriate diving or hyperbaric conditions.
Trimix	Gas comprising a specified mixture of oxygen, helium and nitrogen, capable of supporting human life under appropriate diving or hyperbaric conditions.

APPENDIX B. Schedule

Day 1: Friday, January 18
Morning
Physiology Workshop
- Respiration
- CNS Oxygen Toxicity
- Narcosis and HPNS
- Thermal

Afternoon
Decompression Workshop
- DCI Pathophysiology
- DCS Risk Factors
- Deep Stops
- DCI Therapy
- DCS Risk Assessment

Evening
- CO_2 Intoxication
- HSE CO_2 Toxicity Incident Presentation
- Chatterton & Kohler

Day 2: Saturday, January 19
Morning
Rebreather Workshop
- USN Testing Perspective
- UK Testing Perspective
- Rebreather Incident Investigation
- Manufacturers Panel

Afternoon
Training Workshop
- Risk Management in Deep Wreck Diving using CCR
- Risk Factors
- Training Panel Discussion

Evening
- O_2 Toxicity Incident
- Cave Penetration

APPENDIX C. Attendees

Alastair Ansell	Vantaa, Finland
Gavin Anthony MSc	Gosport, Hampshire
Heather C. Armstrong MS	Pensacola, FL
Brian M. Armstrong BS	Pensacola, FL
John R. Armstrong	Ball Ground, GA
Mark Bakunas	Atlanta, GA
Steven M. Barsky	Ventura, CA
Peter B. Bennett PhD, DSc	Durham, NC
Oded Ben-Shaprot	Eliat, Israel
Deann J. Blausey	Santa Rosa, CA
John C. Blausey	Santa Rosa, CA
Clifford E. Boehm MD	Ellicott City, MD
Jeffrey N. Boulter MD	Lima, OH
Jeff Bozanic PhD	Huntington Beach, CA
Francois Brisson	Laval, QC, Canada
Larry Brown	Raleigh, NC
David M. Brown	Marathon, FL
D. Paul Brown	Pago Pago, AS
Alex Brylske PhD	Cape Coral, FL
Kelly E. Buckley	Penngrove, CA
Gregg Buscombe	Ottawa, ONT, Canada
Lucinda A. Caldwell	Metairie, LA
Mark Caney	Bristol, UK
Chauncey Chapman	San Leandro, CA
John Chatterton	Harpswell, ME
Keith M. Chesnut	Reno, NV
Renee M. Cicchino	West Orange, NJ
John Clarke PhD	Panama City Beach, FL
Robert Cole	Kent, UK
Mike Convery BS	Munhall, PA
R. Craig Cook MD	Severna Park, MD
Michael J. Corbo	Somers Point, NJ
David E. Cowgill	Panama City, FL NEDU

Robert Cox	Mobile, AL
Dave Crockford Kelly Bray	Callington, UK
Jim K. Culter MS	Sarasota, FL
Francis L. Daly, III MD	Greensburg, PA Psychiatry
Alex Deas	Edinburgh, Scotland
Petar Denoble MD	Durham, NC
David J. Doolette PhD	Panama City, FL DC Physiology
Eric Douglas	Durham, NC
Richard V. Ducey PhD	Bethesda, MD
Richard Dunford	Durham, NC
Mark H. Easter	Tappahannock, VA
Cindi Easterling M.Ed.	Durham, NC
Douglas G. Ebersole MD	Lakeland, FL
John Effle	Durham, NC
Julie Ellis	Durham, NC
M. Celia Evesque BA, RN	MacClenny, FL
Jose Flores	New York, NY
Edward T. Flynn MD	Fairfax, VA
Andrew W. Fock MBBS	Victoria, Australia
Mike Fowler	Elizabethton, ON, Canada
John Freiberger MD	Durham, NC
Al E. Gainey	Milwaukee, WI
Brian M. Garby MD	Sarasota, FL
Suzanne Garrett	Washington, DC
Jim Gaston	Durham, NC
Forrest P. Gauthier	Maineville, OH
Paul T. Gernhardt	Ashburn, VA
Wayne A. Gerth PhD	Panama City, FL
Chris Gini MS	Hermosa Beach, CA
Jeff Godfrey BS	Groton, CT
Richard Goodin	Apex, NC
Marvin E. Gozum MD	Philadelphia, PA
Richard Graff	Ojai, CA
Grant W. Graves DMT	Malibu, CA
Capt. John G. Gray	Washington Navy Yard, DC
Scott Hagen	Sparks, NV

R.W. Hamilton PhD	Tarrytown, NY
Brian Harper	Durham, NC
Sean Harrison	Topsham, ME
Paul Haynes	Aberdeen, Scotland
Nicholas T. Heath	Apex, NC
Padrig C. Heraghty	Charlottesville, VA
Gene W. Hobbs CHT	Durham, NC
Kevin J. Horn	Quantico, VA
JR Hott	Panama City Beach, FL
Laurens E. Howle PhD	Durham, NC
Tom Huff	Chelmsford, MA
Karl E. Huggins	Avalon, CA
Jarrod M. Jablonski	Gainesville, FL
William R. Jackson	Fuquay Varina, NC
Craig J. Jenni	Boca Raton, FL
Steve Johnson M.B., B.S.	North Yorkshire, UK
Christopher Kareores DO	Haverhill, MA
Kira E. Kaufmann PhD	Ft. Lauderdale, FL
Dawn Kernagis	Raleigh, NC
Douglas E. Kesling MA	Wilmington, NC
Brian Knapp	Miami, FL
Carrie Kohler	Brick, NJ
Richard Kohler	Brick, NJ
Michael B. Lennon VMD, PhD	Groton, MA
Alan Lewis MD	Woodland Hills, CA
Jeff Lewis	Mesa, AZ
Mark A. Lombardo MD	Concord, NH
May Loo	Scarborough, ON, Canada
Eric R. Machum	Caracas, Venezuela
Ian D. MacKnight	Solebury, PA
Elizabeth MacNamara MD	Montreal, QU, Canada
Brenna Mahoney	Bethesda, MD
Kari Makiniemi	Vantaa, Finland
Kathy A. Mallon MS	Palos Verdes Estates, CA
Federico J. Mayoral	Caracas, Venezuela
Marty McCafferty	Durham, NC

Doug McKenna	Newark, DE
Tom McKenna	Newark, DE
Gene Melton	St. Augustine, FL
Sam Merrill	Durham, NC
Simon Mitchell MB, ChB, PhD	Auckland, New Zealand
Richard Moon MD	Durham, NC
Jeanette Moore	Durham, NC
Steve Mortell	Rancho Santa Margarita, CA
W. Tom Mount DSc, PhD, ND	Miami Shores, FL
Patrick W. Murphy	Manteo, NC
Capt. John W. Murray MD	Fairfax Station, VA
Jeff Myers	Durham, NC
Vahagn M. Nahabedian	Ojai, CA
Pete M. Nawrocky	Virginia Beach, VA
Matias Nochetto MD	Durham, NC
Dan Nord	Durham, NC
John C. Norris	Cleveland, OH
Marshall L. Nuckols PhD	Panama City, FL
Dan Orr	Durham, NC
Martin Parker	Helston, Ukl
Kim D. Parker	Brighton, MI
Lynn Partridge	Vancouver, BC, Canada
Bruce Partridge	Vancouver, BC, Canada
Daniel C. Patterson BS	Ocala, FL
David F. Pence MS	Honolulu, HI
Anthony Pessolano	Manahawkin, NJ
Christopher D. Phipps JD	Reno, NV
Neal Pollock PhD	Durham, NC
Scott M. Powell	Raleigh, NC
Richard Pyle PhD	Honolulu, HI
Virginia Ransom	Charlottesville, VA
Peter F. Readey	Lebanon, TN
Thomas A. Rhoad	Howell, MI
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