Review articles

Recreational technical diving part 1: an introduction to technical diving methods and activities

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Abstract

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Technical divers use gases other than air and advanced equipment configurations to conduct dives that are deeper and/or longer than typical recreational air dives. The use of oxygen–nitrogen (nitrox) mixes with oxygen fractions higher than air results in longer no-decompression limits for shallow diving, and faster decompression from deeper dives. For depths beyond the air-diving range, technical divers mix helium, a light non-narcotic gas, with nitrogen and oxygen to produce 'trimix'. These blends are tailored to the depth of intended use with a fraction of oxygen calculated to produce an inspired oxygen partial pressure unlikely to cause cerebral oxygen toxicity and a nitrogen fraction calculated to produce a tolerable degree of nitrogen narcosis. A typical deep technical dive will involve the use of trimix at the target depth with changes to gases containing more oxygen and less inert gas during the decompression. Open-circuit scuba may be used to carry and utilise such gases, but this is very wasteful of expensive helium. There is increasing use of closed-circuit 'rebreather' devices. These recycle expired gas and potentially limit gas consumption to a small amount of inert gas to maintain the volume of the breathing circuit during descent and the amount of oxygen metabolised by the diver. This paper reviews the basic approach to planning and execution of dives using these methods to better inform physicians of the physical demands and risks.

Key words

Technical diving, enriched air – nitrox, trimix, cave diving, wreck diving, rebreather, review article

Introduction

A recent and important trend in recreational diving is the use of specialised techniques to explore deeper depths for longer durations than are possible with the single-cylinder, open-circuit air diving configuration typically used by recreational divers. Exponents refer to themselves as 'technical divers'. There is no universally accepted definition of 'technical diving' but the term commonly refers to the use of helium-based 'mixed-gases' to conduct deeper dives with optimised decompression using self-contained underwater breathing apparatus (scuba). This is an important development for diving physicians for several reasons. Firstly, technical divers involve themselves in activities with a different risk profile to normal recreational air diving, and understanding what they do will inform evaluations of medical suitability. Secondly, a technical diving accident may differ from a recreational diving accident. For instance, deep, mixed-gas divers are at risk of omitting substantial decompression, and consequently of presenting with severe decompression sickness. Such mixed-gas diving has previously been the province of occupational diving and conducted with immediately available medical support, whereas technical divers are likely to present at a hospital. Understanding their activity will facilitate evaluation of diving histories and circumstances in accident scenarios.

The authors, both experienced technical divers, presented on various issues related to technical diving at the South Pacific Underwater Medicine Society Annual Scientific Meeting in 2011. These presentations are summarized here in two papers, of which this is the first. This paper explains the basic aims and methods used, thus providing an introduction for those unfamiliar with the field. The second paper discusses the controversial issue of optimal decompression from the short, deep dives typically undertaken by technical divers.[1]

An incomplete history of technical diving

There are no definitive resources describing the history of technical diving. This account has been constructed largely from the authors' own knowledge and may contain minor inaccuracies. Technical diving grew out of the drive to explore deep shipwrecks and underwater caves. Sporadic accounts of individual explorers experimenting with nitrox (nitrogen-oxygen mixes with a higher fraction of oxygen than air) to shorten decompression obligations began to appear in the mid-1970s. Similarly, individuals began experimenting with helium-based mixes (helium is non-narcotic and light) for deep diving around the same time. The first attempts to 'mainstream' recreational use of a breathing gas other than air came in the mid-1980s with the formation of two training organisations dedicated to nitrox diving. The International

Footnote: The units prevalent in the technical diving community are used for pressure measurements in this article. To use kPa would largely render the paper largely unintelligible to at least part of its intended readership (the divers themselves) and it would also fail to prepare physicians for the language they will hear technical divers using. The agreed format is: atm for partial pressures or gauge pressures (e.g., the typical PO_2 setpoint of a rebreather is 1.3 atm) and atm abs for ambient pressures at depth.

Association of Nitrox Divers (IAND) and American Nitrox Divers Inc (ANDI) remain active today, though IAND has become IANTD (T – technical) and both have broadened the scope of their teaching to include courses in which the use of helium-based gases is taught.

There are isolated, early accounts of deep, heliox scuba dives in caves: Hal Watts in 1970 (122 metres' freshwater (mfw), Mystery Sink), Dale Sweet in 1980 (110 mfw, Mystery Sink) and Jochen Hasenmayer in 1982 (205 mfw, Fontain de Vaucluse).[2] However, technical diving in its most common form at present (the use of trimix breathing gas mixtures and oxygen-accelerated decompression with multiple open-circuit scuba) can be traced to the mid-1980s in northern Florida where cave divers began developing these techniques to explore downstream from Sullivan Sink (part of the Wakulla-Leon Sinks cave system).[3] The late 1980s saw an increase in the use of mixed-gas techniques on some dives that were spectacular for the time. Well-documented examples include the exploration of the Andros Blue Holes by Rob Palmer, the early deep dives (90–95 mfw) in Wakulla Springs, and a record deep dive to 239 mfw in Nacimiento Mante by Sheck Exley.[4–6]

The early 1990s were a period of great controversy and change, with momentum slowly swinging in favour of the broader adoption of these advanced diving techniques. This was in no small part helped by the publication of the first dedicated magazine, *Aqua-Corps*, in the United States. Indeed, it was the editor, Michael Menduno, who in 1991 first coined the term "*technical diving*". Whereas nitrox training had been available through IAND and ANDI for some years, training programmes for diving with helium-based gases emerged around this time, with Billy Deans in Key West often credited with the first of these. However, opposition remained. Conspicuous examples include the initial banning of nitrox training providers from the 1992 DEMA show in Houston, Texas; a British Sub-Aqua Club ban on the use of any gas other than air in the same year; and a 1993 series of articles in *Skin Diver* magazine condemning nitrox and mixed-gas as unsafe in sport diving.

This opposition had little effect on motivated explorers for whom the advantages of mixed-gas techniques were simply too great to ignore, and throughout the 1990s the associated successes continued to be reported. One conspicuous example, the identification of the German submarine U-869 in 70 metres' sea water (msw) off the New Jersey Coast by John Chatterton on a difficult penetration dive using mixed gas, was notable because it was contrasted against earlier disastrous dives performed on the same wreck using air.[7] By the mid 1990s, even the large mainstream recreational training organisations such as the Professional Association of Diving Instructors (PADI) were starting to offer nitrox or 'enriched air' courses which, over time, has resulted in nitrox diving no longer being considered 'technical'. However, this era of growth was punctuated with high-profile setbacks, such as the deaths of Sheck Exley in 1994 and Rob Palmer in 1997. The naysayers were not entirely wrong about risk.

The mid 1990s also saw a development that would revolutionise technical diving: the mainstream emergence of rebreathers whose use had hitherto largely been limited to military applications. The Dräger® Dolphin and Atlantis were the first devices available. Both were semi-closed-circuit units designed for nitrox diving, although many owners modified them for use with other gas mixtures. Around 1999, UK company Ambient Pressure Diving Ltd® released the first mass-produced, commercially available electronic closed-circuit rebreather (eCCR): the Inspiration Classic™. This device, and its subsequent generations became (and remains) the most prevalent eCCR worldwide.

In the new millennium, technical diving has become progressively mainstream. By the middle of the first decade, PADI was teaching mixed-gas diving, and recently they entered the rebreather training market for the first time. There has been a proliferation of new rebreather manufacturers and in 2012 there is a new initiative to produce and teach 'recreational' rebreather devices for use in the shallow depth range usually associated with open-circuit, air scuba diving. In the meantime, extreme exponents are pushing the boundaries deeper and longer all the time (see "*current scope of technical diving*" below).

It is not possible to outline the history of technical diving without noting that its recent development has been coincident with widespread adoption of communication via the internet. Early internet user-group lists were forums for free exchange of ideas (and insults) between various groups or individuals worldwide. These internet forums and others that have subsequently appeared, can be credited for aiding the development and popularization of technical diving despite the fact that much of the information presented on them is unreliable or inaccurate.

Technical diving methods

Mainstream recreational divers conduct no-decompression dives using air in open water (that is, not in enclosed spaces) to a maximum depth of about 40 msw. These are dives that can be conducted 'safely' with a single cylinder of compressed air with an open-circuit demand valve. However, this equipment configuration significantly limits underwater duration at the deeper end of the recreational diving range because of the limited gas supply and the decompression obligation that accrues with extended bottom times. Moreover, the use of air for diving to depths greater than 40 msw would become progressively less appropriate because of its density and the high nitrogen and oxygen contents, which cause narcosis and an increase in the risk of oxygen toxicity respectively. Technical divers circumvent the disadvantages of single-cylinder air diving by using a variety of strategies that are described below.

NITROX DIVING

Nitrox diving was the first widely adopted departure from traditional recreational air diving and is now so widely accepted that it is generally no longer considered to be technical diving. The term nitrox refers to mixtures of oxygen and nitrogen in which there is more oxygen than found in air and, indeed, is usually a blend of oxygen and air. For these reasons, nitrox is often referred to as 'enriched air' or 'enriched air–nitrox' (EANx). By convention, the mix is described by reference to its oxygen content. Thus, if a nitrox mix contains 36% oxygen, then it is referred to as nitrox36 or EANx36.

Nitrox diving offers the following advantages over air, all of which relate to the reduced inspired nitrogen fraction. First, since the fraction of inspired nitrogen is lower, there is less uptake of nitrogen than would occur if air were used at the same depth. The nitrox diver can thus use a no-decompression limit or decompression plan calculated for air at a depth shallower than the actual depth of the dive. This shallower depth is referred to as the equivalent air depth (EAD) and can be calculated from:

$$\text{EAD (msw)} = ([\text{FN}_2 \times (\text{depth} + 10)] \div 0.79) - 10 \qquad (1)$$

Where: FN_2 = the decimal fraction of nitrogen in the nitrox mix; depth = the depth (msw) at which the nitrox is being used and 0.79 = the fraction of nitrogen in air.

Second, the nitrox diver could refrain from calculating an EAD and plan the decompression aspects of a dive as though he or she were breathing air. The resulting reduction in nitrogen uptake would reduce the risk of developing decompression sickness.

Third, as will be described later, nitrox is often breathed during the shallower (approx. < 40 msw) phase of decompression from a deep dive because the high inspired fraction of oxygen will accelerate inert gas elimination. The use of nitrogen avoids the consumption of costly helium at shallower decompression stops when its benefits (e.g., low density) are unnecessary.

Fourth, based on the assumption that oxygen is non-narcotic, nitrox may cause less narcosis than air at equivalent depths. The magnitude of this advantage is uncertain. Oxygen probably is narcotic, though not to the extent predicted by its lipid solubility because it is metabolized in tissues.[8]

Finally, there is controversy over whether nitrox dives result in less post-dive fatigue than air dives with identical time and depth profiles. In one tightly controlled randomized and blinded study involving pressure exposures in a hyperbaric chamber, there was no difference in post-dive fatigue between nitrox and air dives.[9] In contrast, a recent non-blinded field study did report an advantage for nitrox in this regard.[10] The underlying basis for any reduction in fatigue by nitrox is unknown, but a reduction in bubble formation from dissolved inert gas and some other non-specific oxygen effect are possibilities.[10]

Table 1

NOAA oxygen exposure limits over a range of oxygen partial pressures (P_iO_2)

P_iO_2 (atm)	Single exposure (min)	24-hour exposure (min)
1.6	45	150
1.5	120	180
1.4	150	180
1.3	180	210
1.2	210	240
1.1	240	270
1.0	300	300
0.9	360	360
0.8	450	450
0.7	570	570
0.6	720	720

The use of nitrox mandates extra care on several fronts. First, the scuba equipment (cylinder and regulator) usually need to be 'oxygen clean' to minimize the risk of oxygen fires or explosions, especially during blending of the gas. Second, because the inspired fraction of oxygen is greater, an inspired oxygen partial pressure (P_iO_2) high enough to cause cerebral oxygen toxicity will be encountered at shallower depths than when using air. Nitrox diving consequently limits depth in comparison to air. Because the first symptom of cerebral oxygen toxicity may be a grand mal seizure, this is an issue of significant clinical importance in technical diving.

Experimental evidence and anecdote suggest that cerebral oxygen toxicity is very rare if the P_iO_2 is less than 1.3 atm (133 kPa).[11] Many technical divers have consequently adopted this value as their maximum safe inspired P_iO_2 for routine use, although it is relatively common for divers to breathe a P_iO_2 up to 1.6 atm if at rest during decompression. A crucial skill is to be able to calculate the deepest depth at which a gas can be used so that the chosen maximum safe P_iO_2 is not exceeded. This is known as the maximum operating depth (MOD) for the gas given by:

$$\text{MOD(msw)} = ([P_iO_{2max} \div F_iO_2] - 1) \times 10 \qquad (2)$$

Where: P_iO_{2max} = the maximum safe inspired PO_2 (atm) and F_iO_2 = the inspired fraction of oxygen in the mix.

Another influence on risk of cerebral oxygen toxicity is the duration of exposure. Nitrox divers (and indeed all technical divers) are taught the concept of the 'oxygen clock' and the associated safe durations for exposure to a range of P_iO_2. A set of exposure limits was published by the National Oceanic and Atmospheric Administration (NOAA) (Table 1).[12] It is not widely appreciated that these limits were based on best judgment rather than objective data, and they can only be seen as a guideline.[11] The table provides limits for the P_iO_2 well below the risk threshold cited above for cerebral oxygen toxicity, reflecting a shift in emphasis from prevention of cerebral toxicity to that of pulmonary toxicity as one progresses to a lower range of P_iO_2. An additional use of these guidelines is tracking of the accrued exposure as a percentage of the recommended maximum, if necessary, by adding percentages from different P_iO_2 exposures. For example, if a diver breathes oxygen at 1.2 atm for 105 minutes and then 1.4 atm for 75 minutes (50% of the recommended exposure at both P_iO_2 levels; Table 1), the total represents 100% of the recommended exposure. It is common practice to degrade these percentage exposures with a half-life of 90–120 minutes between dives. There are few data to establish the validity of any aspect of this oxygen dose management paradigm, but those that exist have been expertly reviewed elsewhere.[11]

MIXED-GAS DIVING

If the maximum safe P_iO_2 during diving is considered to be 1.3 atm, then the MOD for air (calculated as above) is 52 msw. For deeper dives, the inspired fraction of oxygen must be lowered below that of air. Similarly, below 40–50 msw, the narcotic effect of nitrogen in air increases to progressively less tolerable levels. Air is also very dense at these depths, which increases both the work of breathing and the risk of carbon dioxide (CO_2) retention. The problems associated with the narcotic and density effects of nitrogen can both be ameliorated by substituting helium, a low-density, non-narcotic gas, for nitrogen in the breathing mix. This typically results in the diver breathing trimix: a combination of oxygen, helium, and nitrogen. Technical divers designate trimix by the fraction of oxygen and helium present. For example, trimix 8:60 would consist of oxygen 8%, helium 60%, and the balance (32%) nitrogen.

Nitrogen is rarely substituted completely with helium for several reasons of which the most important is the cost of helium. This is less of an issue when using a rebreather which recycles exhaled gas (see later), but in open-circuit diving pure oxygen-helium mixtures (heliox) would be very expensive to use. In addition, some decompression models tend to penalize the use of high helium fractions by mandating longer decompressions. Although this may be unnecessary (see the second paper in this series)[1] it remains a consideration for many divers in planning their gas mixes. Finally, in very deep bounce dives beyond 150 msw it is likely that the inclusion of nitrogen in the breathing mix helps to ameliorate the high pressure neurological syndrome (HPNS), which can cause troublesome tremors and cognitive impairment.[8]

The 'recipe' for the optimal trimix for use during the deepest portion of the dive (bottom gas) is based on the planned depth, the duration of the dive, the diver's perception of the maximum safe P_iO_2, and, if cost is a consideration, the maximum tolerable narcotic effect. To illustrate this, we will consider planning an appropriate trimix for a dive using open-circuit equipment to 90 msw where the ambient pressure is 10 atmospheres absolute (atm abs).

The first decision is how much oxygen the mix should contain. Divers will usually aim to breathe as much oxygen as is considered safe, since more oxygen means less inert gas uptake and therefore less decompression. For a very long dive, the diver may defer to consideration of the oxygen clock (see above) and choose a lower PO_2 for their various gases. However, assuming a maximum safe P_iO_2 of 1.3 atm is chosen:

$$\text{Ideal } O_2 \text{ fraction in mix} = 1.3 \text{ atm} \div 10 \text{ atm abs} = 0.13 \qquad (3)$$

The mix would therefore contain 13% oxygen for breathing at 90 msw. It is notable that such a lean oxygen mix should not be breathed at the surface, and so it would be necessary to start the first part of the descent using a 'travel gas' with more oxygen (air, for example). Once the diver has reached a depth where the trimix provides an P_iO_2 the same as breathing air at the surface (0.2 atm approximately), it will be safe to change to the trimix and continue the descent. This depth can be calculated as follows:

$$\text{Min. safe depth (msw) for hypoxic mix} = ([0.2 \div FO_2] - 1) \times 10 \qquad (4)$$

Where: 0.2 = minimum safe P_iO_2 in atm and FO_2 = fraction of oxygen in the mix.

For the 13% oxygen mix (FO_2 = 0.13) this gives:

$$\text{Min. safe depth for mix} = ([0.2 \div 0.13] - 1) \times 10 = 5.4 \text{ msw} \qquad (5)$$

Thus, the diver could safely change to the trimix once at 6 msw (rounding deeper) during the descent. More typically, the travel gas will be used to a greater depth to conserve the bottom gas. The travel gas is also often used during decompression.

The amount of N_2 in the mix is largely dependent on the degree of narcosis that the diver is prepared to tolerate, and is usually based on a comparison with air diving. Thus, assuming a diver is comfortable with the level of narcosis experienced during air diving at 40 msw, they might aim to breathe an equivalent PN_2 during the deepest phase of a trimix dive. This is easily calculated by multiplying the fraction of nitrogen (FN_2) in air (0.79) by the ambient pressure at 40 msw (5 atm abs) which gives a PN_2 of 3.95 atm. Therefore:

$$FN_2 \text{ in the mix} = 3.95 \text{ atm} \div 10 \text{ atm abs} = 0.4 \qquad (6)$$

The trimix should therefore contain 40% N_2. This calculation assumes oxygen is not narcotic, but a more conservative approach assuming equal narcotic potency for O_2 and N_2 yields only a small difference.

Table 2

Dive plan for 90 msw for 15 minutes based on a proprietary implementation of the Buhlmann ZH-L16 model with gradient factors 50/80 (see part 2 for explanation of gradient factors)[1]

Depth (msw)	Stop time (min)	Run time (min)	Gas mix
90	n/a	15 (bottom time)	Trimix 13:47
Ascent to 42	5 (ascent time)	20	Trimix 13:47
42	1	21	Trimix 13:47
39	1	22	Trimix 13:47
36	1	23	Trimix 13:47
33	1	24	Nitrox 32
30	1	25	Nitrox 32
27	1	26	Nitrox 32
24	2	28	Nitrox 32
21	2	30	Nitrox 32
18	2	32	Nitrox 32
15	4	36	Nitrox 32
12	6	42	Nitrox 32
9	9	51	Nitrox 32
6	15	66	Nitrox 32
4.5	19	85	100% O_2

Having calculated the ideal FO_2 and FN_2 for the trimix, the helium content (FHe) simply makes up the balance, thus:

$$\text{FHe required} = 1 - FN_2\ (0.4) - FO_2\ (0.13) = 0.47 \quad (7)$$

This planning process has determined that an appropriate trimix for a dive to 90 msw is 13% oxygen, 47% helium and 40% nitrogen, designated trimix 13:47. Another parameter often ignored in such planning is the density of the resulting gas at the target depth. There is an increasing risk of CO_2 retention as the inspired gas density increases, and this can result in debilitating dyspnoea and mental obtundation.[13] Hypercapnia also increases the risk of cerebral oxygen toxicity, probably because it causes cerebral vasodilatation and the consequent delivery of a bigger dose of oxygen to the brain.[14] While there is no clear consensus on where the upper density limit should lie, proposed criteria for design and testing of underwater breathing apparatus, based on physiological limitations which include a gas density of 8g L^{-1}, seem reason enough to draw the line at this point.[15] Calculation of gas density at a target depth is easily achieved based on proportions and adjustment for ambient pressure if given the following densities (g L^{-1}) at 1.0 atm abs: air 1.29; oxygen 1.43; nitrogen 1.25; helium 0.18. In the above example, trimix 13:47 at 90 msw (10 atm abs) would have a density of 7.7g L^{-1}.

Planning of mixed-gas dives

The nitrox and mixed-gas methods described above are typically combined in the execution of a deep dive. A decompression obligation rapidly accumulates in such dives, and decompression can be accelerated by making gas switches to mixes with less inert gas and progressively more oxygen during the ascent. There are many combinations and permutations of gas choice for decompression but, continuing with the example of a 90 msw dive using trimix 13:47, one simple but plausible example would be to decompress back to 33 msw using the trimix, then switch to nitrox32 (PO_2 = approx. 1.3 atm at 33 msw) for stops between 33 and 6 msw (inclusive), and then complete a final decompression stop at 3 msw breathing 100% oxygen (PO_2 = 1.3 atm). The issue of whether there is a decompression advantage of substituting nitrogen for helium in the shallower stage of the decompression is addressed in the second paper in this series.[1]

Having decided on a basic gas plan such as the above, the next step is to input the depth, bottom time, and gas plan into technical diving decompression planning computer software to obtain the decompression regimen. There are multiple decompression algorithms and computer implementations available and few issues are debated as hotly as the optimal approach to decompression from deep technical dives. This is discussed further in the second paper in this series.[1] The output of one such algorithm, based on a bottom time of 15 minutes at 90 msw, is shown in Table 2. Note that even this relatively short bottom time results in a substantial period of prescribed decompression and, although obvious, it is worth stating that this decompression profile forms a virtual ceiling through which the diver should not pass. If problems occur which necessitate omission of decompression, then serious decompression sickness is possible. Technical divers must train, plan and equip themselves to minimize the possibility of such events.

Once the depth, bottom time, gas plan and decompression plan are known, the diver can calculate the actual gas requirements for the dive. Many of the decompression planning algorithms will do this for the diver, though they all require the provision of an estimation of the diver's surface respiratory minute volume (RMV) for the level of exercise expected during the dive. Early in their careers all technical divers must conduct an exercise in which they measure gas consumption during typical underwater swimming at a known and constant depth. This is indexed back to surface pressure, and becomes the surface RMV. It is an important number that they will use many times. Many divers calculate the RMV during typical underwater swimming and at rest, with the resting number used for calculating gas consumption during decompression. For a given segment of the dive, the gas consumption is given by:

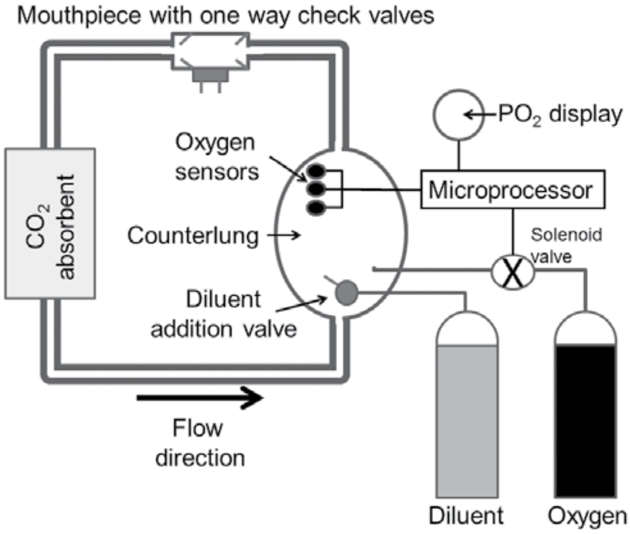
$$\text{Gas consumption (L)} = P_{amb} \times \text{surface RMV} \times \text{duration} \quad (8)$$

Where: P_{amb} is the ambient pressure in atm abs; surface RMV is the respiratory minute volume (L min^{-1}) for equivalent activity at 1 atm abs and duration is the duration of the dive segment in minutes.

Once the gas requirements are established in this manner, the diver must decide on the cylinder configuration required for its carriage. In the above example, one plausible plan would be to carry the trimix in twin cylinders worn on the back,

Figure 1
Technical diver configured with multiple open-circuit scuba systems for carrying different gases

Figure 2
Simplified functional layout of an electronic closed-circuit rebreather (see text for explanation); this is highly stylized, for example, the oxygen cells are not actually placed in the counterlung in a real rebreather.



and to carry one cylinder of each of the decompression gases (nitrox32 and oxygen) slung on either side. The gas-carrying capacities of the cylinders must be carefully compared to the calculated gas requirements, and it is customary to build in a substantial safety margin for unexpected events. Such safety margins are often a variation of the basic cave diving 'rule of thirds' in which one third of breathing gas is retained for emergencies, notionally because if one third is used to enter a cave and one third to exit, the remaining third can be shared to rescue an out-of-gas buddy. An illustrative multi-cylinder configuration is shown in Figure 1.

REBREATHERS

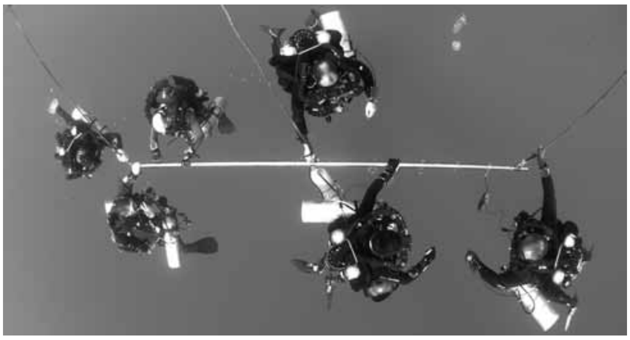
The increasing use of rebreathers is arguably the most important development in technical diving over recent years. A rebreather is a circle circuit containing one-way check valves, one or more counterlungs, a CO_2 absorbent canister, and systems for maintaining both the volume of the circuit and an appropriate P_iO_2. Rebreathers are categorized by the nature of the system for maintaining the P_iO_2 and it is beyond the scope of this article to detail the operation of all of them. The most prevalent is the so-called electronic closed-circuit rebreather (eCCR). The typical (and simplified) functional layout of one of these devices is shown in Figure 2.

During use, the diver exhales into the counterlung through a CO_2 absorbent, and then inhales from the counterlung. The one-way check valves ensure that flow around the circuit is unidirectional. Three galvanic fuel cells are exposed to the gas in the circuit. These are essentially oxygen-powered batteries that produce an electric current directly proportional to the PO_2 to which they are exposed. After calibration against a known PO_2, the averaged output of the three cells indicates the circuit PO_2 and this is constantly monitored by a microprocessor. A target P_iO_2 (PO_2 'setpoint') is selected by the diver, and as oxygen consumption reduces the circuit PO_2 below this target the microprocessor opens an electronic solenoid valve to allow oxygen into the circuit to restore and maintain a relatively constant PO_2 near the setpoint. This setpoint is typically 0.7 atm at the surface, and is increased to a higher target (such as 1.3 atm) once the dive is underway.

The volume of the circuit is maintained during descent by the addition of a diluent gas. When the counterlung is compressed by increasing ambient pressure, the diver will begin to generate a negative pressure in the circuit during inhalation. This opens a mechanical diluent addition valve (Figure 2) allowing diluent gas into the circuit and restoring its volume. For safety reasons, the diluent gas typically contains a FO_2 high enough that the gas is breathable, but low enough that the circuit PO_2 can still be lowered to the desired setpoint at the deepest point in the dive. Thus, for a dive to less than 50 msw with a PO_2 setpoint of 1.3 atm, air could be used as the diluent gas. Its oxygen fraction of 0.21 still allows a circuit PO_2 of approximately 1.3 atm at 50 msw (ambient pressure of 6 atm abs x 0.21 = 1.26 atm) and at shallower depths the rebreather will add oxygen to maintain the PO_2 at 1.3 atm. The diver will be breathing a nitrox mix whose oxygen and nitrogen content varies with depth, but whose PO_2 remains constant. For a deep dive, the diluent gas (usually trimix) is chosen using virtually the same principles as described earlier (mixed-gas diving).

It should be obvious that the crucial advantage of a rebreather is the recycling of exhaled gas thus preserving expensive components like helium. Indeed, in theory, the use of diluent gas effectively ends on arrival at the deepest depth provided there is no up-and-down depth variation from that point on. In contrast to open-circuit diving, gas consumption changes

Figure 3
Decompression stage with multiple rebreather divers decompressing at the same depth; note that all are carrying an open-circuit 'bailout' cylinder in case of rebreather failure



little with depth, and the absolute amounts of gas used are vastly smaller.

Another major advantage is the breathing of optimal gas mixes for minimizing inert gas uptake and for accelerating decompression throughout the dive. In open-circuit diving, for each gas carried, the F_iO_2 can only be optimal at one depth. Thus, in the example shown in Table 2, as the diver ascends shallower than 30 msw breathing nitrox32 they are no longer breathing the pre-defined maximum safe F_iO_2 (required to produce a PO_2 of 1.3 atm) until they switch to 100% oxygen at the 3 msw stop. In contrast, an eCCR will raise the F_iO_2 to maintain the 1.3 atm PO_2 setpoint throughout the ascent.

Other rebreather advantages include the breathing of warm, humidified gas, and production of few or even no bubbles. The major disadvantages are that the devices are complex, costly, maintenance intensive, provide numerous opportunities for user error and have many potential failure points. This potential for failure mandates the requirement for access to open-circuit gas supplies (commonly referred to as 'bailout') appropriate for all depths visited, and adequate to allow decompression from any point of the dive plan. Planning the carriage of bailout gases is very similar to the planning of an open-circuit deep dive as described above. Notwithstanding this precaution, it is perhaps not surprising that crude estimates suggest that rebreather diving is associated with higher mortality (perhaps an order of magnitude higher) than open-circuit diving.[16]

Logistics of technical diving

Technical diving frequently involves complex logistics to support these ambitious dives. Deep wrecks usually lie in open ocean and diving them requires large boats for safe and reliable surface support in weather conditions that are rarely optimal. Accurate GPS and sounding equipment are vital, and teams develop considerable skill in accurately dropping a shot line down on to a wreck in deep waters. Divers usually descend and ascend on these shots lines, but strong currents can complicate such plans and necessitate the use of drifting decompression shots underneath large buoys so that the divers can complete long decompressions without having to hold onto a shot line against the force of the current. Purpose-built decompression stages with bars at the depths of the long stops help divers accurately maintain stop depths and allow multiple divers to comfortably occupy the station at the same depth (Figure 3). To enhance safety, teams often arrange themselves into bottom diver and support diver roles. Bottom divers actually visit the wreck, and support divers help with surface logistics and visit the bottom divers during decompression. This allows any developing needs to be met and messages to be relayed to the surface.

The exploration of long and frequently deep caves has a different set of logistical challenges. Sequential dives, often very dependent on the use of battery-powered diver propulsion vehicles, are used to penetrate progressively further into the cave and to lay lines into new sections. As there is progress to greater distances, it may become necessary to stage gas supplies at strategic points on the way in before 'pushing' the cave further. In this setting, divers may arrange themselves into large teams with specific roles for each individual. Lead divers perform the long pushes. The support divers may be required to stage gas prior to the dive, and visit the lead divers during their decompression which, as in deep wreck diving, allows any developing needs to be met and messages to be relayed to the surface. In some major cave penetrations, support divers may even install dry underwater habitats (such as an upside-down rain-water tank filled with air) in which the lead divers can actually leave the water whilst still under pressure in order to rest, eat, drink and warm up.

In both wreck and cave settings, there are numerous logistical considerations which are vitally important but too numerous to discuss here. These include thermal protection and temperature management, hydration and nutrition, gas logistics, medical support and evacuation plans. It should be obvious from this discussion that merely training in the technical diving methods described above is only the start of the process of becoming an exploration-level technical diver.

Current scope of technical diving

The boundary between technical diving and mainstream recreational diving is fluid because technical diving methods and equipment are being adopted by and becoming part of recreational diving.[17] It is difficult to imagine now but the use of nitrox, presently considered 'mainstream' in recreational diving, was viewed as highly technical and fiercely opposed by the recreational diving industry in the early 1990s. In what may prove to be a similar development, there are current plans to develop and promote simplified closed-circuit rebreathers for mainstream recreational diving.[18]

Open-circuit and rebreather trimix dives to a maximum of about 90 msw for bottom times of 30–60 minutes represents the current state of typical technical diving. Several training agencies specialize in training for this type of diving and several of the large recreational training agencies have also entered this market. Depth record-setting dives (now in excess of 300 msw on open-circuit equipment) typically involve immediate ascent from the maximum depth. However, technical divers are conducting purposeful exploration dives in excess of 200 mfw with substantial bottom times. A notable recent example is the exploration of the Pearse Resurgence cave system in New Zealand to 221 mfw. In addition, some dives of remarkable duration are now being undertaken to explore caves over long distances. The most conspicuous are those conducted by the Woodville Karst Plains Project in northern Florida. This team has conducted exploration out to 7.9 km in Wakulla Springs: a dive requiring 11 hours of bottom time at an average depth of 80 mfw, followed by 16 hours of decompression.

Summary

Technical recreational divers tailor gases to target depths and for optimised decompression, and utilise specialised equipment configurations to extend their gas supply. This has markedly enhanced depth, duration, and range capabilities in recreational diving. This paper has provided a basic outline of these methods for the non-technical diver or diving medical officer. The second paper in this series discusses the optimization of decompression in more detail.

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Dedication

For Col. James (‘Jim’) Miller, 1960-2011, explorer