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# Insights on Deep Bounce Dive Safety From the Technical Diving Community

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## Abstract

During the past fifteen years, recreational divers have been developing and experimenting with advanced diving equipment and techniques. This so-called "Technical Diving" includes a wide range of extended-range diving activities, but primarily involves deep bounce dives incorporating multiple breathing gas mixtures, ranging from a few minutes to several hours in duration, to depths of 60-150 meters or more. During these years, a large collective body of anecdotal observations has yielded interesting trends, and suggests possible avenues for future hyperbaric research. Specific decompression strategies developed by the technical diving community include deep initial decompression stops and slow final ascents to the surface. A conglomeration of four factors coinciding with the end of a typical dive (sudden drop in ambient pressure, sudden decrease in inspired oxygen partial pressure, sudden increase in physical exertion, and sudden shift from immersion to gravity) may together serve as a "trigger" for the onset of decompression sickness (DCS) symptoms. The practice of In-Water Recompression (IWR) has been embraced by members of the Technical Diving community, who are both in greater need for it, and are better prepared to properly perform it. A variety of unusual physiological symptoms have been observed by Technical Divers, including Oxygen-induced Myopia, Oxygen Narcosis, "Shallow" HPNS, successful use of Heliox for decompression, and the possibility of oxygen-induced DCS. The technical diving community has much to offer for preliminary hyperbaric investigations, and collaborations between the two communities should be maintained.

**Keywords:** Technical Diving, Mixed-gas, Decompression, DCS, In-Water Recompression, Narcosis, HPNS

## Introduction

Prior to the mid-1980's, use of helium in breathing gas mixtures for divers had been almost exclusively limited to commercial and military applications, often in conjunction with saturation dive profiles. Beginning around 1985, a number of intrepid civilian scuba divers around the world began experimenting with helium in their breathing gas mixtures, to extend the depth capability of their (primarily recreational) diving activities. The advent of this so-called "Technical Diving" is well documented in the form of various periodicals and books published during the early 1990's, and continuing through to the present (Fig. 1). While "Technical Diving" encompasses a wide variety of equipment such as closed-circuit rebreathers, diver propulsion vehicles, and other technology, as well as more and more finely honed techniques and practices matched to specific diving environments and regimes, the most common activities involve deep bounce diving. That is, dives with bottom-times ranging from a few minutes to several hours, at depths of 60 to over 150 meters, using various breathing mixtures (but primarily involving helium).


Fig. 1. Sampling of publications concurrent with the advent of "Technical Diving".

With several major dive training agencies now offering advanced courses in deep mixed-gas decompression diving, the number of certified divers engaged in this sort of diving activity has grown into the thousands, and the collective body of experience likely spans several tens of thousands of dives. While controlled scientific investigation into the dive practices of this group of divers remains almost non-existent, the shear number of dives taking place has led to various compelling observations relating to decompression and other related aspects of diving physiology. While the anecdotal nature of these observations limits their scientific value, several observed patterns are consistent enough over a large sample of individual dives and individual divers, that they provide compelling insight into possible underlying phenomena, and suggest avenues for future controlled scientific research.

The three areas this article focuses on include: Decompression Strategies; In-Water Recompression; and Unusual Symptoms related to Diving Physiology.

## Decompression Strategies

With the amount of deep bounce-diving decompression taking place within the Technical Diving community, it's little wonder that a great deal of trial-and-error experimentation is taking place when it comes to decompression strategies. Generally, custom decompression schedules are created on desktop decompression software, or in some cases within real-time mixed-gas dive computers. With few exceptions over the history of Technical Diving, these decompression schedules have been based on one of several different compartment-based ("neo-Haldanian") decompresssion models; in particular Bühlmann's ZH-L16 model. Because these models are largely extrapolated for use with technical-diving depth ranges and gas mixtures, they (not surprisingly) haven't been entirely successful at eliminating either overt symptoms of Decompression Sickness (DCS), or post-decompression symptoms not classically regarded as DCS, but likely to be a result of general decompression stress (e.g., fatigue). Through ad-hoc experimentation and incidental observation, Technical Divers have begun to incorporate several strategies that depart from conventional practices, but have yielded qualitative improvements in decompression success.

### *Deep Decompression Stops*

The first and perhaps most noteworthy observation to have come from the Technical Diving community is the empirical support for so-called "Deep Decompression Stops". I first began this practice nearly 15 years ago, when I regularly made air dives to 60 m in search of fish specimens (1, 2). My usual dive profiles consisted of about 15 minutes of time on the bottom, followed by a decompression schedule calculated by a real-time decompression computer based on a typical Bühlmann-style decompression algorithm. In most cases on such dives, the first decompression stop required by the computer would be at a depth of 12.5 m. On some of these dives I would feel high levels of fatigue for several hours after the dive, but other times I would feel perfectly fine. I eventually realized that I felt fine primarily after dives that I had collected fish specimens, and fatigued after dives when I collected no specimens. When I collected specimens, I needed to stop for a few minutes during my initial ascent in order to vent the swimbladders of the fishes, using a hypodermic needle. This had the effect of adding a deep decompression stop at around 30-40 m (Fig. 2). After I began inserting this additional deep decompression stop on all of my dives, regardless of whether or not I collected fish specimens; I no longer felt unusual fatigue.

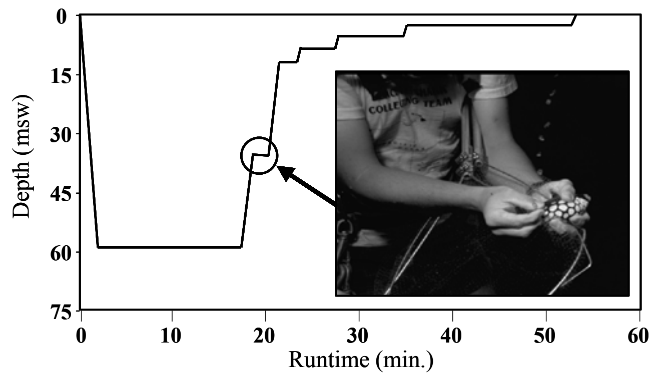


Fig. 2. Typical air decompression schedule, modified with additional "deep" decompression stop to allow venting the swimbladders of collected fishes.

Similar experiences have been shared by many people in the Technical Diving Community; so much so that a variety of informal methods for inserting these so-called 'deep stops' have been developed. This pattern of observation is particularly interesting because these 'deep stops' often closely resemble the initial ascent profiles suggested by the newer bubble-based decompression models (3, 4, 5), and may indeed constitute at least partial empirical support favoring such decompression strategies.

### *Slow Final Ascent*

Another decompression strategy that the Technical Diving community is only beginning to adopt is a protocol for very slow final ascent to the surface. It is common practice among Technical Divers to perform the time for the final 3-meter decompression stop breathing 100% oxygen at 6 m. Because the breathing mixture is pure oxygen, the decompression schedule predicted by the compartment-based models are not affected by spending the 3-m time at 6 m, and the extra depth during the final stages of decompression is thought to enhance safety by maintaining higher ambient pressure. However, this doubles the distance traveled during the final ascent to the surface, and there is usually a strong tendency after completing long decompression dives to ascend immediately to the surface at the end of the final decompression stop.

Experience by many within the technical diving community suggests that an immediate final ascent can dramatically increase the likelihood of DCS symptoms soon after the dive. Although not widely published or investigated with controlled experimentation, the pattern does appear to be consistent and widespread. To mitigate this problem, many Technical Divers have begun to greatly extend the time of final ascent, by perhaps as much as 10 to 20 minutes. Initial indications are that such slowed final ascents have reduced the incidence of DCS, and other symptoms apparently related to decompression stress.

***"Quadruple Whammy"***

A clear pattern has emerged in the body of Technical Diving experience that when Decompression Sickness symptoms occur, they almost always occur very soon after the diver surfaces. Symptoms only rarely manifest after a long time lag following the dive, and almost never occur during the decompression portion of the dive. Thus, the pattern seems to be that symptom onset is triggered by the termination of the dive.

There are four potentially important variables which all occur almost simultaneously at the end of the dive. The first of these is described above – the relatively dramatic and sudden drop in ambient pressure while ascending from the final 6-m decompression stop.

The second factor is that the diver suddenly shifts from breathing oxygen at 6 m, with an inspired oxygen partial pressure of 1.6 atm, to air at the surface, with an inspired partial pressure of 0.2 atm. Due to the vaso-constricting effects of elevated inspired oxygen partial pressures, such a sudden and dramatic shift will likely have effects on the circulatory system during the period of time immediately following surfacing.

The third factor is the sudden change from a relaxed and sedentary period of decompression, to heavy physical exertion. This exertion comes in the form of climbing out of the water with very heavy dive equipment, or fighting rough seas. Such kinetic muscular activity can have a number of effects on the body relevant to decompression sickness, perhaps most significantly the formation of large numbers of bubble micronuclei (6, 7).

The fourth and final factor involves the potential effect of gravity on blood distribution after long periods of full-body immersion. A sudden transition from virtual weightlessness to the world of gravity might lead to blood shifts away from the body core and into the lower extremities.

When all four of these factors are combined simultaneously; one involving a sudden ambient pressure change, one involving the increased production of micronuclei, and two involving potentially profound effects on the circulatory system, it may represent the perfect recipe for decompression disaster. With this in mind, some technical divers have begun actively trying to break up these four factors, so that they do not all happen simultaneously. For example, a diver might follow a very slow ascent rate after the final decompression stop as discussed previously, then continue to breathe pure oxygen while remaining in the water for a 10-15 minutes, then breathe air for another few minutes at the surface before exiting the water, then take steps to avoid physical exertion for perhaps 30 minutes after exiting the water.

Initial anecdotal indications are that such steps to break up the "Quadruple Whammy" are reducing incidence of DCS and DCS-like symptoms. Of these four factors, the last one – the effects of Immersion on blood distribution – may perhaps be the most under-appreciated. Among other things, it may have important implications for the practice of in-water recompression (see below).

*Deep Decompression Threshold*

Although growing numbers of Technical Divers are actively and routinely conducting dives to depths of up to 100 m or so, relatively few divers regularly descend to depths of 120 m and beyond. Certain specific projects have involved dives to such depths, but not with enough frequency and regularity that obvious patterns have begun to emerge from the community as a whole. As my own diving experience to depths in excess of 110 m grows, one pattern is beginning to emerge with alarming consistency: an apparent decompression "threshold" effect for dives with maximum depths exceeding about 110-115 m.

Over the past five years, all of my deep diving activities have been conducted using a Cis-Lunar MK-5P electronically-controlled mixed-gas closed-circuit rebreather. This particular model of rebreather includes triply-redundant real-time decompression computers, based on the DCAP model developed by Bill Hamilton. My overall decompression strategy has followed the profiles suggested by this computer model, modified with generally slow (~10 m/min) initial ascents and consistent and structured "deep-stops" (1,2). The MK-5P rebreathers store detailed electronic event logs for each dive, and a database containing such logs from about half of my own deep rebreather dives, along with additional dives from other divers using the same rebreather model and decompression strategy, is representative of a larger collection of several hundred mixed-gas dives to maximum depths in the range of 60 to nearly 150 m.

The database includes 194 logged dives to depths in excess of 60 m, of which 24 logged dives were conducted to maximum depths in excess of 110 m. Of the 170 dives shallower than 110 m, which spanned a range of depths and other conditions, there was not a single incident of DCS or DCS-like symptoms. However, of the 24 dives to depths in excess of 110 m, there were 3 cases of *Cutis Marmorata*, 2 cases of joint pain, and 3 cases of ambiguous DCS-like symptoms (excessive malaise, fatigue, etc.) likely related to decompression stress (Fig. 3). Despite very similar patterns of hydration, exertion, general decompression strategy, and other factors, there is a somewhat stark distinction between a 0% incidence rate on dives to less than 110m (n=170), compared with a 33% incidence rate on dives to greater than 110 m (n=24).

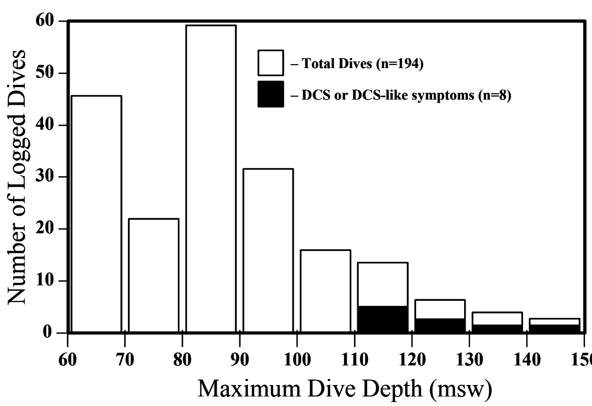


Fig. 3. Logged dives to maximum depths in excess of 60 m, showing incidence of DCS and DCS-like symptoms.

While not scientific, and acknowledging lack of rigorous controls, this anecdotal but very empirical pattern is that, all other factors being similar (including basic decompression strategy), there appears be a sharp increase in DCS likelihood for dives to depths in excess of 110 m.

## In-Water Recompression

In-Water Recompression (IWR) is defined here as the attempt to treat symptoms of DCS by returning an afflicted diver to the water. The Technical Diving Community did not invent this practice; rather, it had been independently developed by commercial harvest divers around the world, particularly in Australia and in Hawaii. It has been discussed in several review articles, both in general terms (8-17), and with specific reference to the Technical Diving community (18, 19).

Four formal methods of IWR have been published. The oldest is the “Australian Method”, which involves a descent to 10 m breathing 100% oxygen, ranging in duration from 30 to 90 minutes depending on severity of symptoms, followed by a slow ascent back to the surface and subsequent periods of surface oxygen (13). The second method 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 (11). 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, direct, continuous ascent to the surface (10). The fourth method, sometimes referred to as the “Pyle Method”, was modified from the Australian and Hawaiian methods for use specifically by Technical Divers (19).

The practice of In-Water Recompression has been generally discouraged, if not outright condemned by the mainstream hyperbaric medical community for many years, and for very good reason. The potential complications of returning a DCS-stricken diver to the water are many: risks of more absorbed nitrogen (if using air), acute oxygen toxicity (if using oxygen), uncontrolled environment, drowning, hypothermia, hampered communication, and hazardous marine life, among others. The only real theoretical advantage of IWR is the immediacy with which afflicted divers can be recompressed. This theoretical imbalance notwithstanding, the actual track record of IWR attempts has painted quite a different picture.

Data from a study by Frank Farm and collaborators (11) shows an amazingly high rate of success among IWR attempts by diving fishermen (Fig. 4a). Data from subsequent IWR attempts (19), both from within and outside the Technical Diving Community, shows a similar trend (Fig. 4b). In response to this empirical success, the Technical Diving community has been more willing to embrace IWR as a planned immediate response to the onset of decompression sickness symptoms.

There are good reasons why Technical Diving lends itself to IWR protocols. First, there is a greater 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. Secondly, 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 spike, and various other factors relating to general technical diving equipment and techniques.

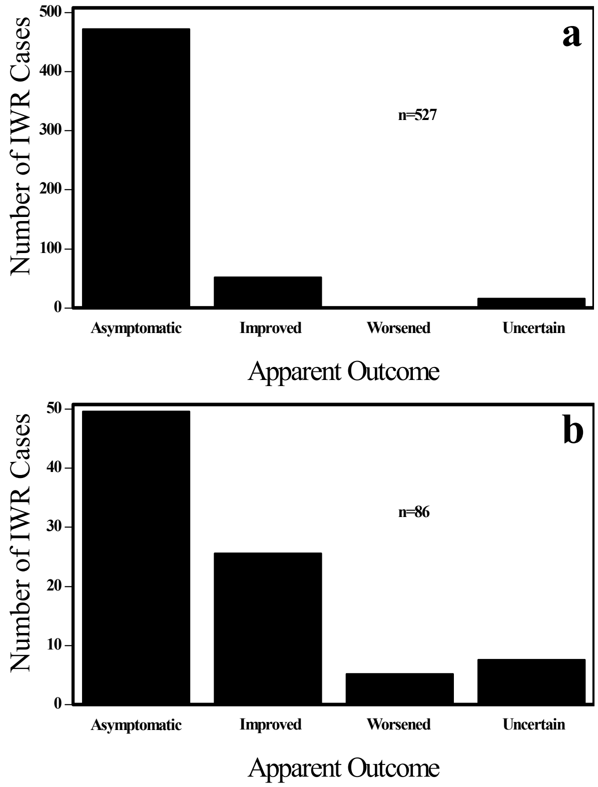


Fig. 4. Success rates of In-Water Recompression attempts: a, data from Farm et al. (9); b, data from Pyle (17).

### *Immersion Without Recompression*

Many issues involving the practice of In-Water Recompression remain unresolved. However, one additional point warrants consideration. As mentioned earlier, the effects of immersion on blood distribution may have profound effects on decompression symptoms and their onset. If there is merit to this, 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 the success rate data in Figure 4 is that nearly all of those IWR cases involved air as the only breathing mixture, and did not follow any set protocol. Indeed, the general success of air-only IWR (20) 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 blood redistribution effects. Compelled by this idea, we developed an emergency DCS plan during a deep-diving cruise aboard the NOAA ship, Townsend Cromwell in 2000, involving the use of an onboard live well (21, 22). We filled the 3-meter deep live well with water to serve as an immersion tank in the event of DCS. This system would enable full-body immersion in a controlled environment, while the ship heads towards a shore-based hyperbaric facility. Although we did not have a need to invoke this system, the approach might represent a useful compromise between in-water recompression, and surface-oxygen; perhaps yielding the best of both approaches.

## Unusual Symptoms Related to Diving Physiology

The Technical Diving community has made a number of other observations relating to diving physiology, some of which may offer insights into avenues for future research. Among the best documented of these is Hyperoxia-induced Myopia (23). Several technical divers have independently encountered symptoms of moderate to severe Myopia after prolonged chronic exposure to elevated oxygen partial pressures. Typically, this occurs after multiple consecutive days or weeks of long-duration dives using closed-circuit rebreathers (24). The extent of Myopia varies from diver to diver, and can be reduced by reducing the average oxygen partial pressure exposed to the diver. It usually only manifests after several weeks of daily diving, and the symptoms generally abate weeks to months after termination of the chronic exposure; although in some cases there seems to be a permanent damaging effect. While not representing a new physiological phenomenon, observations by the Technical Diving community nevertheless demonstrate the potential implications outside the context of hyperbaric chamber treatment. As more and more divers embrace closed-circuit rebreather technology for use on multi-day, extended dive-time scenarios (e.g., on a live-aboard dive boat), hyperoxia-induced myopia may become more commonplace.

Less-well documented, but equally compelling, is the notion of oxygen narcosis. Several interesting anecdotal experiences by technical divers suggest that elevated oxygen partial pressures can dramatically exacerbate symptoms of nitrogen narcosis. (25) The effect appears to be complex, involving both nitrogen and oxygen in a synergistic fashion, and only when the inspired oxygen partial pressure exceeds about 1.8 atmospheres. For this reason, it is mostly a question of academic interest, although interesting nonetheless.

Another interesting observation made by many technical divers is the consistent onset of subtle but unambiguous symptoms similar in nature to mild High Pressure Nervous Syndrome (HPNS). The symptoms, which include nervousness, jitters, and impaired muscular coordination, only seem to manifest when heliox is breathed at depths greater than about 80 m. While this seems much too shallow for classical HPNS, the symptoms can be eliminated by introducing limited concentrations of nitrogen into the breathing mixture. Perhaps the extremely rapid descents practiced by Technical Divers lead to unusually shallow onset of true HPNS symptoms.

One practice that is gaining support among some closed-circuit rebreather divers is the use of heliox or trimix breathing mixtures throughout the entire dive, including decompression. While conventional wisdom suggests an advantage to switching to an enriched air nitrox mixture during decompression as soon as the depth allows, several divers who use constant oxygen-partial-pressure rebreathers are opting to forgo the gas switch entirely. Theoretical support for this practice comes from bubble-based decompression algorithms (5).

Finally, several observations made by Technical Divers raise the question of whether oxygen can contribute to decompression sickness, even when breathed at relatively safe (<1.7atm) concentrations. The observed symptoms only seem to occur following dives with very long decompression stops on pure oxygen, and usually involve severe acute joint pain that arises within minutes of surfacing, and abates almost as quickly. The hypothesis that these symptoms are caused by oxygen-filled bubbles is suggested by the acute nature of the pain (in contrast to the typical dull ache caused by non-oxygen bubbles, which might be in part masked by localized hypoxia in the surrounding nerve tissues – a situation that would be mitigated if the problem-inducing bubbles contained relatively high concentrations of oxygen). Furthermore, the sudden abatement of symptoms could be explained by the rapid off-gassing of oxygen from the bubbles into the surrounding tissues, in the event that circulation is impaired. Ominously, these symptoms tend to foreshadow the onset of much more sinister symptoms of *Cutis Marmorata*.

## Discussion

I have made a special effort to avoid pretending in this article that these insights and observations constitute findings subjected to scientific scrutiny. Nevertheless, the Technical Diving community, in their efforts to “push the envelope”, so to speak, may provide interesting insight into various aspects of diving physiology. With the shear number of such dives being conducted, the consistent observed patterns described herein provide compelling rationale for closer scientific scrutiny. Because they are often willing to play the role of test subjects for exploring physiological questions, such as experimenting with new decompression protocols, active communication between Technical Divers and the academic hyperbaric research community should be maintained.

Many of the more advanced dive computers and rebreathers allow for detailed data collection about the parameters of the dive. In the right hands, these data might provide a wealth of information concerning various aspects of diving physiology. The technical diving community and the academic diving physiology community have much to offer each other. Future collaborations between the two groups can only enhance the progress of our understanding

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