The first deep rebreather dive using hydrogen: case report

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Keywords
Helihydrox; High pressure neurological syndrome; HPNS; Hydreliox; Hydrox; Technical diving; Trimix

Abstract

(Harris RJ, Challen CJ, Mitchell SJ. The first deep rebreather dive using hydrogen: case report. Diving and Hyperbaric Medicine. 2024 31 March;54(1):69–72. doi: 10.28920/dhm54.1.69-72. PMID: 38507913.)
Bounce diving with rapid descents to very deep depths may provoke the high-pressure neurological syndrome (HPNS). The strategy of including small fractions of nitrogen in the respired gas to produce an anti-HPNS narcotic effect increases the gas density which may exceed recommended guidelines. In 2020 the 'Wetmules' dive team explored the Pearse Resurgence cave (New Zealand) to 245 m breathing trimix (approximately 4% oxygen, 91% helium and 5% nitrogen). Despite the presence of nitrogen, one diver experienced HPNS tremors beyond 200 m. The use of hydrogen (a light yet slightly narcotic gas) has been suggested as a solution to this problem but there are concerns, including the potential for ignition and explosion of hydrogen-containing gases, and accelerated heat loss. In February 2023 a single dive to 230 m was conducted in the Pearse Resurgence to experience hydrogen as a breathing gas in a deep bounce dive. Using an electronic closed-circuit rebreather, helihydrox (approximately 3% oxygen, 59% helium and 38% hydrogen) was breathed between 200 and 230 m. This was associated with amelioration of HPNS symptoms in the vulnerable diver and no obvious adverse effects. The use of hydrogen is a potential means of progressing deeper with effective HPNS amelioration while maintaining respired gas density within advised guidelines.

Introduction

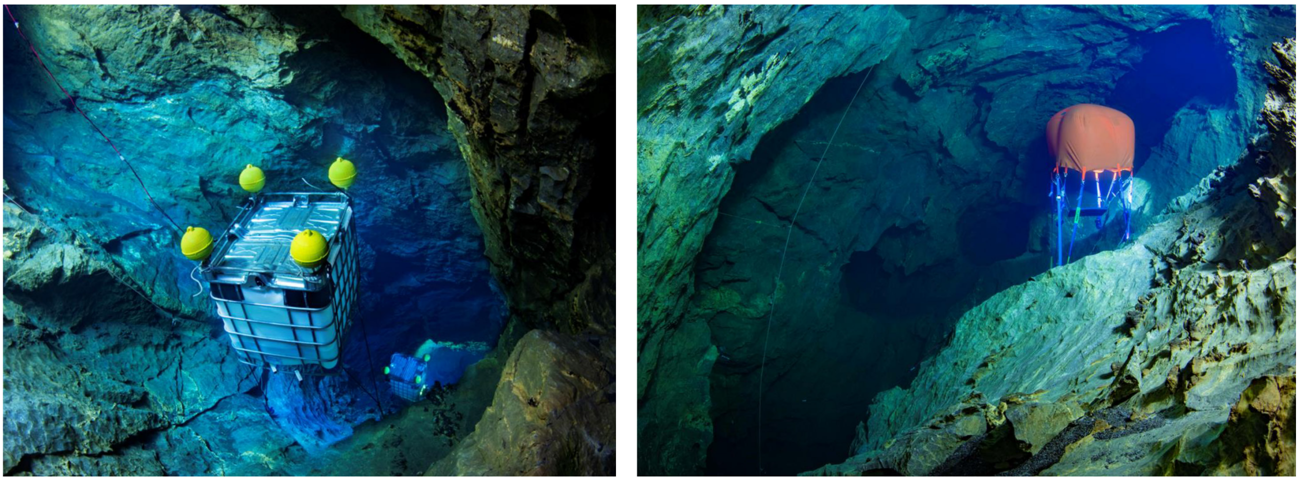
In 2020 the Australian 'Wetmules' technical diving team explored the Pearse Resurgence cave in New Zealand to a depth of 245 metres of fresh water (mfw). The dive was achieved using electronic closed-circuit rebreathers with the 'diluent gas' for the deep phase of the dive being trimix 4% oxygen, 91% helium and 5% nitrogen (Trimix 4/91); a composition very similar to what the divers would actually be breathing at the deepest point. The purpose of the small fraction of nitrogen was that its narcotic effect is known to help ameliorate symptoms of the high-pressure neurological syndrome (HPNS),[1] including troublesome tremors, that may arise during the fast ~35 minute descent to 245 mfw. One diver (author RJH) was more affected than the other (author CJC) consistent with previous observations of inter-subject variability,[2,3] with tremors appearing around 200m depth. Four dry habitats at 40, 27, 16, and 7 mfw (Figure 1) and active drysuit heating were utilised to facilitate the 16-hour dive in cold (6°C) water. At the deepest point reached, the cave continued descending meaning any further exploration would require visiting depths beyond 250 mfw.

The desire to descend beyond 250 mfw in future dives introduced two problems whose solutions are somewhat mutually exclusive.

First, the density of the mix utilised at 245 mfw was approximately 7.2 $g \cdot L^{-1}$. The risk of carbon dioxide (CO_2) retention during rebreather diving appears to increase at respired gas densities greater than 6 $g \cdot L^{-1}$,[4] albeit almost always when denser gas is breathed during diving-relevant levels of exercise (e.g., peaking at 125 Watts).[5] In turn, CO_2 retention may produce unpleasant / dangerous symptoms, although some divers do not appear to develop or notice early progressive symptoms and may be at risk of sudden cognitive impairment.[6] Moreover, whether symptomatic or not, CO_2 retention almost certainly increases a diver's risk of cerebral oxygen toxicity.[7] Progressing deeper using the same trimix diluent would result in potentially hazardous gas densities.

Second, HPNS symptoms (primarily tremors) experienced by RJH from 200 m on the previous 2020 dive would progressively increase with descent to 250 m and beyond.

Figure 1
The 40 and 27 mfw habitats (left) and the 16 mfw habitat (right); the 7 mfw habitat was identical to the 16 mfw habitat. The 40 mfw habitat was not used on the hydrogen dive



Any attempt to ameliorate this by increasing the fraction of nitrogen in the diluent mix would significantly worsen the gas density problem. Conversely, removing the small amount of nitrogen in the mix would improve gas density but may exacerbate the likelihood of experiencing HPNS.

The solution would be a gas that is both light and slightly narcotic, thus allowing elimination of nitrogen from the mix and thereby reducing gas density whilst reproducing nitrogen's anti-HPNS effect. It was largely for these reasons that commercial and military groups had previously undertaken experimentation with hydrogen for deep diving. During World War II the Swedish Navy conducted six hydrox (hydrogen and oxygen) dives as deep as 160 metres of seawater (msw).[8] The 'hydra' program conducted by the French company COMEX over three decades from 1968 had seen hydrogen used in dry and wet compressions (primarily in saturation diving conditions) as deep as a dry dive to 701 m equivalent.[8] These trials demonstrated that hydrogen could be safely breathed by humans with no obvious toxicity although its use accelerated heat loss. Hydrogen did exert a narcotic effect which helped ameliorate the HPNS, but it was too narcotic as an oxygen-hydrogen mix ('hydrox') beyond about 160 msw, necessitating blending hydrogen with helium and oxygen ('helihydrox' or 'hydreliox') to avoid excessive narcosis. An overarching concern throughout these trials was the potential for hydrogen to burn or explode if combined with oxygen in suitable stoichiometric blends. Previous work has shown that the minimum oxygen concentration for burning in hydrogen – helium mixtures is within the range 4.2 to 6 volume % with the tolerated fraction slightly increasing as ambient pressure increases.[9]

Case report

With the goal of deep diving while controlling the anticipated problem with HPNS and keeping gas density within safe limits, the Wetmules undertook the first deep rebreather dive using hydrogen at the Pearse Resurgence in February 2023. Initial plans included the dual aims of using hydrogen and pushing beyond the 245 mfw mark set in 2020, but as the expedition evolved the goal was distilled down to evaluating hydrogen on a dive to 230 mfw which, based on past experience, was likely to provoke HPNS in RJH.

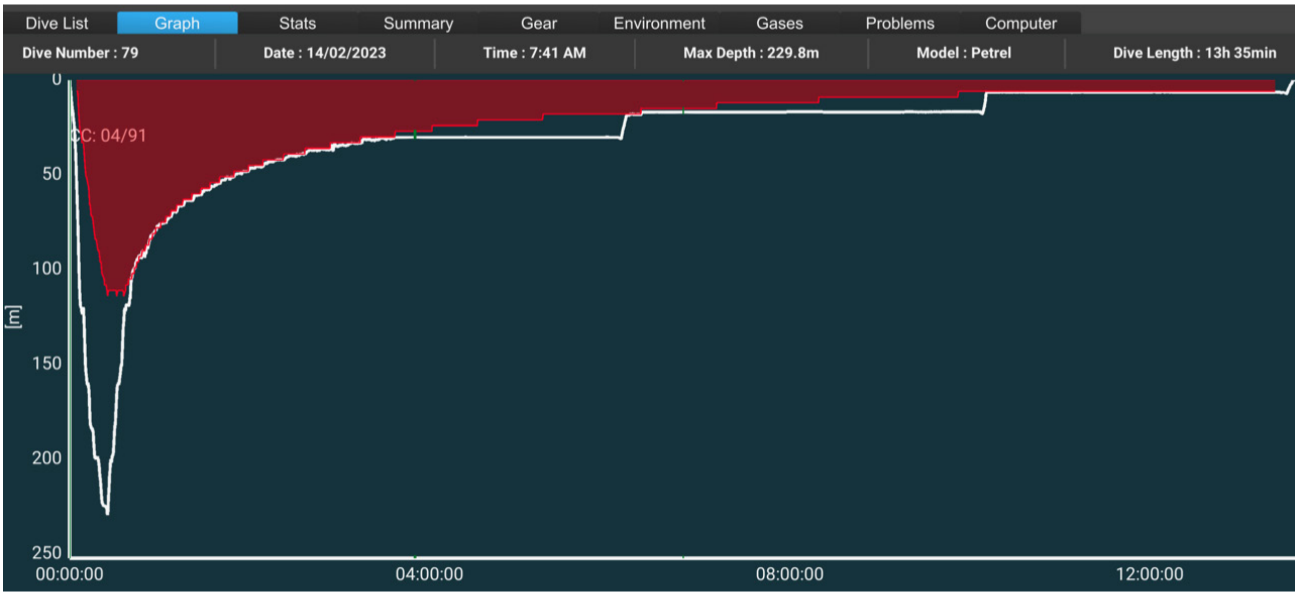
A G-size cylinder (50 L water capacity) of hydrogen was transported to the dive site with other expedition equipment. Hydrogen was decanted from this cylinder into a small 2 L carbon composite cylinder for use during the dive. The source hydrogen cylinder was only pressurised to 13.7 MPa thus necessitating careful use of a Haskell pneumatically driven booster pump to achieve adequate pressure (≥ 15 MPa) in the target cylinder.

The dive was undertaken by two divers (RJH and CJC) each using twin Megalodon™ rebreathers (Innerspace Systems, Centralia, USA) to provide gas supply redundancy without the need to carry large numbers of open circuit 'bailout' cylinders. These twin systems comprise two independent rebreathers joined by a common mouthpiece that allows easy switching between rebreathers. Only one diver (RJH), selected for his previous susceptibility to HPNS, used hydrogen and only in his primary rebreather.

The divers descended to 200 mfw over approximately 18 minutes using trimix 4:91 (4% oxygen, 91% helium, 5% nitrogen) as the diluent and (for RJH) with the PO_2 'setpoint' at 70 kPa (0.7 atmospheres absolute [atm abs]) which, at 200 mfw resulted in 3.3% oxygen in the rebreather loop. At this point RJH introduced hydrogen by exhaling gas into the water (initially one small tidal volume), and replacing the volume from the hydrogen cylinder, now being the source of diluent gas. After establishing there were no obvious adverse effects, several more tidal volumes were exhaled into the water and replaced with hydrogen; a procedure based loosely on RJH's perception of what it would take to replace

Figure 2

The dive profile with depth (mfw) on the Y axis and time (hours) on the X axis; the red shaded area represents the decompression ceiling. Note the three long periods at constant depth which correspond to occupation of the habitats during segmented staged decompression



approximately 30% of the loop volume with hydrogen. The divers then continued the descent to the target depth of 230 mfw with hydrogen feeding into the loop via the automatic diluent addition valve on RJH's rebreather. Subsequent back calculation from the hydrogen cylinder pressure and the rebreather loop volume suggested RJH was breathing approximately 38% hydrogen at 230 mfw.

There were no apparent adverse effects and the most significant observation was that having experienced onset of HPNS tremors on this occasion at 180 mfw, RJH noticed they had disappeared at 230 mfw; a very atypical event for him. The gas felt easy to breathe, no change in temperature perception was noted, and there was no subjective sensation of narcosis. The accompanying diver (CJC), who based on past experience was less vulnerable to HPNS, had minor HPNS tremors using trimix 4:91 at the same depth.

At approximately 25 minutes run time the divers began ascending and at 27 minutes reached 200 mfw where the hydrogen cylinder was isolated. With the aim of eliminating most of the hydrogen from the loop, a large breath was exhaled and replaced with trimix 4:91 at 200 mfw and every 10 mfw thereafter up to 150 mfw where a complete loop flush was undertaken. The PO_2 setpoint was then increased to 130 kPa (1.3 atm abs) for the remainder of the decompression.

Other logistics included the use of three dry habitats at 27, 16 and 7 mfw during decompression (Figure 1). Thermal protection included O'Three crushed neoprene drysuits (O'Three, Portland, UK) and heated undergarments (Santi, Gdynia, Poland) with unlimited 12-volt power supplied from 40 mfw upward via a cable from the surface. Seacraft diver propulsion vehicles (Seacraft, Krosno, Poland) were used to minimise exertion at depth. The dives were controlled by Shearwater NERD 2 and Petrel 3 computers (Shearwater, Vancouver, Canada) programmed with 80/85 gradient factors. For decompression the use of hydrogen was effectively ignored because hydrogen could not be programmed into the computers, there was no previously researched basis for adjusting decompression from a bounce dive of this nature using hydrogen, and the exposure to hydrogen was very short; approximately 11 minutes below 200 mfw and another 8 minutes of progressive rebreather loop flushing between 200 and 150 mfw in the context of a 13.5 hour dive. The decompression was controlled based on the use of Trimix 4:91 in the deep phase.

After reaching the 27 mfw habitat, decompression differed from a typical dive in that the divers cleared decompression to the depth of the next habitat before leaving the one currently occupied (Figure 2). Harris has coined the termed 'segmented staged decompression' for this approach. Small Triton rebreathers (M3S, Toulon, France) were used inside the 27 mfw habitat which was air-filled, while the habitat atmosphere (nitrox 50 and 80 at 16 and 7 mfw respectively) was breathed in the shallower habitats which were equipped with carbon dioxide scrubbers. Multiple support dives were undertaken to facilitate habitat entry, egress, and transfers.

The divers emerged after a 13-hour 35-minute run time with no adverse effects other than mild pulmonary oxygen toxicity symptoms.

Discussion

This dive represents the first use of hydrogen as a breathing gas in an ultra-deep rebreather bounce dive. With the obvious and important caveat that the dive represents a single datapoint, there are some related observations that can be made.

First, there was no problem with ignition, fire or explosion in any of the processes where hydrogen was handled in relation to this dive. These included: a preliminary unmanned pool test conducted by RJH, where the rebreather's electronic oxygen addition solenoid valve was operated, and the counter lungs vigorously manipulated when the loop contained hydrogen and more than 4% oxygen; boosting hydrogen using a Haskell pump; and the dive itself where the loop oxygen fraction was kept ≤ 4% when hydrogen was present. There was (and remains) anxiety that despite the latter, there could be transient 'micro-regions' of much greater oxygen concentration where the solenoid injects oxygen to the loop.

Second, the use of hydrogen did appear to ameliorate HPNS symptoms in a susceptible diver more effectively than nitrogen. It is acknowledged that nitrogen was not completely eliminated from the loop by the hydrogen addition procedure, but the initially greater fraction of nitrogen did not prevent the onset of symptoms which subsided after hydrogen was introduced.

Third, there were no obvious adverse physiological effects such as thermal stress or decompression issues. There was also no narcotic effect noted at the PH_2 respired (approximately 922 kPa or 9.1 atmospheres absolute). This is perhaps not surprising because hydrogen has previously been breathed at an inspired pressure of 1,287 kPa or 12.7 atmospheres absolute during a 120 m hydrox hyperbaric chamber dive with only 'very slight' narcosis reported.[10] It is acknowledged that on our dive the duration of exposure to hydrogen breathing was relatively short. We cannot exclude the possibility that problems related to factors like decompression stress and heat loss might become more challenging with longer exposures.

Conclusions

With the $n = 1$ caveat in mind, this dive suggests that the use of hydrogen is a potential means of progressing beyond 250 mfw with effective HPNS amelioration while maintaining respired gas density within advised guidelines. However, the potential hazards of hydrogen are not disproved. Progress should be cautious and incremental.

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Conflicts of interest and funding

Professor Simon Mitchell is the Editor of *Diving and Hyperbaric Medicine* Journal. The peer review process and decision-making regarding publication were managed entirely by the European/Deputy Editor Dr Lesley Blogg. No sources of funding were declared.

Submitted: 6 February 2024
Accepted after revision: 4 March 2024