Rebreather Forum 4

20-22 April, 2023 · Valletta, Malta

Photo by Fan Ping

Workshop Proceedings

Editor **Neal W. Pollock, PhD**

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Rebreather Forum 4 was developed as a conference to address safety, physiology, technology, training, and knowledge gaps relevant to rebreather diving. The primary goals were to: 1) consolidate the knowledge base and enhance knowledge transfer, and 2) promote best practices within the community. The meeting organizer was Michael Menduno. The program committee (in alphabetical order) included John Clarke, Michael Menduno, Simon Mitchell, Neal Pollock, and Frauke Tillmans.

Thanks to sponsor and partners supporting the workshop:

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RF4 Organizer and Program Committee

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Appendices

EDITOR'S NOTE

The papers in this proceedings document reflect the thematic material presented in Rebreather Forum 4. The question and answer exchanges that followed each presentation are included after each paper. The post-presentation exchanges and the later consensus discussions were captured by a court reporter. Comprehensive editing of the transcript was completed to ensure clarity and remove extraneous and repetitive text. Every effort was made to retain the spirit and intent of the original discussion. Reference citations were added where key to the narrative. The consensus statements reflect the final form generated through the discussion and post-meeting editing and review.

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Université Laval, Canada

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An Overview of the Tech Rebreather Market: A Technologist's Perspective

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Abstract

Though it would be more than a decade before rebreathers were commercially available to the sport diving community, early tech pioneers recognized that rebreathers would be needed for exploration from the very inception of technical diving. Today, they represent the dominant platform for exploration and deep diving, and have greatly extended our underwater envelope, though ironically, only a relatively small percentage of technical divers own a rebreather. This paper traces the development of tech rebreathers from their inception in the mid-to late 1980s to the cutting edge of diving today. It provides estimates of number of rebreather divers and units in the field, details the growth of rebreather vendors and analyzes the current economics of rebreather diving. The paper examines the impact rebreathers have had on extending the range of technical diving, discusses rebreather diving safety and trends such as the growing use of rebreather bailout.

Keywords: diving, eCCR, helium shortage, hydrogen diving, mCCR, rebreather bailout

Introduction

Although it would be more than a decade before rebreathers were commercially available to the sport diving community, early tech pioneers recognized that rebreathers would be needed for exploration from the very inception of technical diving. Today, rebreathers represent the dominant platform for exploration and big dives, and have greatly extended our underwater envelope, though ironically, only a relatively small percentage of technical divers own a rebreather.

The story of technical rebreather diving might best be highlighted by considering the juxtaposition of two remarkable images that represent the alpha-omega of tech rebreather diving: its initial inception to the cutting edge today. As such they serve as book ends that highlight how far rebreather technology has come, the role it has played in exploration, and the enormous progress that the tech community has made in a little more than 35 years.

Figure 1 shows cave explorer and engineer Dr. Bill Stone in the water column outside the novel, variable-depth decompression habitat stationed at 10 m (33 ft) that he and his team created for his 1987 Wakulla Springs Project at Wakulla Springs, Florida. He is wearing a 95 kg (209 lb) prototype, fully redundant, electronic closed-circuit rebreather called the failsafe rebreather for exploration diving (FRED) that he designed and built for the project.

His dual rebreathers were charged with a heliox (oxygen-helium) diluent. Stone argued that with a rebreather, heliox was superior to the trimix blends (oxygen, helium, nitrogen) that early tech pioneers like Sheck Exley were using with open-circuit scuba. Note however that in the 1980s, only a couple of explorers were diving beyond 150 m (492 ft), and consequently, no one, including Stone, had thought much about high-pressure nervous syndrome (HPNS) in conjunction with tech diving, and the need to add a narcotic gas such as nitrogen, into the breathing mix to ameliorate its effects.

Figure 1. Photo courtesy of the US Deep Caving Team (USDCT).

At the time the ever-prescient Stone, who could be considered the father of modern tech rebreathers, realized that rebreathers would not only be needed for cave exploration due to their gas and decompression efficiency, but that explorers would need rebreathers for bailout as well; the ability to carry and or stage open-circuit bailout gas was limited by same logistics.

Stone was also concerned about rebreather reliability versus that of open-circuit, specifically that a component failure, for example, one compromising the integrity of the breathing loop, could result in a system failure (Stone 1995). Stone calculated that a rebreather was 23-times more likely to fail than an open-circuit system. Based on his analysis, he concluded that a redundant rebreather could effectively mitigate that risk.

Stone's goal was to prove the efficacy of FRED by remaining submerged for 24 h, while the open-circuit mixed gas push divers on the project explored the Springs to depths of more than 100 m (328 ft). Of course, in 1987, what would eventually become known as technical diving, was still very much in the closet. The only rebreathers on the market were military units and not readily available to sport divers.

To add further historical context, one year earlier former National Oceanic and Atmospheric Administration (NOAA) Deputy Dive Director Dick Rutkowski founded the International Association of Nitrox Divers (IAND) to bring nitrox to the sports diving community. At the time of Stone's Wakulla project, however, the majority of the sports diving industry did not understand nitrox and its uses, and had minimal if any knowledge about helium blends or rebreathers. There was no mixed gas infrastructure in place in the sport diving community like there is today.

We flash forward 36 years from Stone's 1987 dive to one in New Zealand in February 2023. Figure 2 shows explorer and anesthesiologist Dr. Richard Harry Harris, in the water column decompressing next to the 17 m (56 ft) decompression habitat in Pearse Resurgence. He was wearing dual Megalodon closed-circuit rebreathers weighing 45 kg (99 lb), connected by a bailout valve, and shown following his 230 m (754 ft) test dive using a hydreliox (oxygen, hydrogen, helium) diluent—the first reported hydrogen closed-circuit rebreather (CCR) dive, which lasted 13 h.

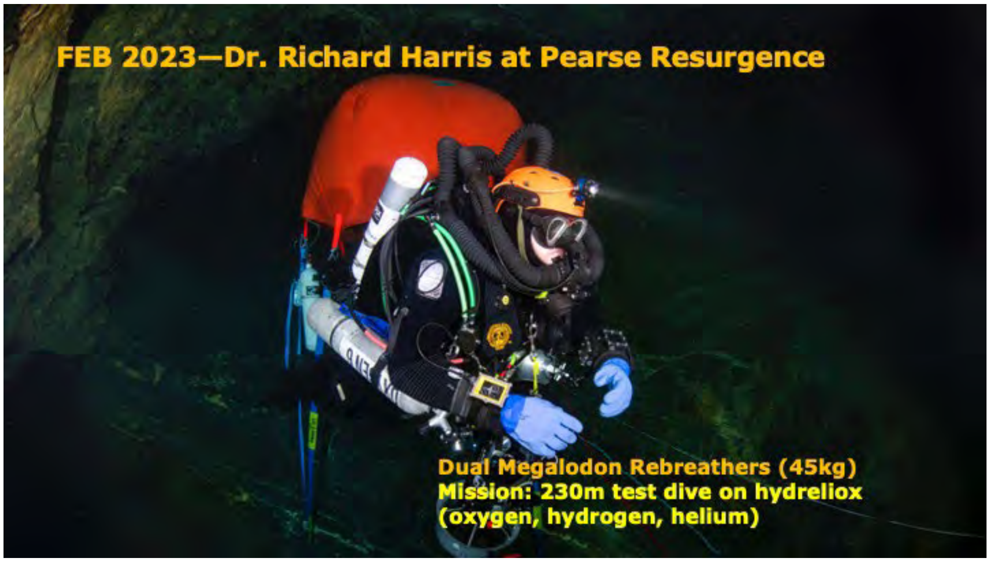


Figure 2. Photo courtesy Richard Harris.

To a non-diver, it may reasonably seem like not much had changed. Both men were diving dual redundant rebreathers, though that of Harris was about half the weight of Stone's, and they both used decompression habitats. Both were breathing exotic gas mixes, though Harris had added an additional gas, hydrogen, to his mix.

To technical divers the progress from Wakulla to Pearse is extraordinary, both in terms of the development of rebreather technology and the degree to which the tech community has extended the range of self-contained diving.

This paper highlights the journey from Wakulla to Pearse. It presents a brief history of tech rebreathers, describes the market today, in terms of the technology and its use by technical divers, discusses trends surrounding rebreather diving, and identifies issues that need to be addressed as the community moves forward.

The Technical Diving Revolution

Viewed from today, it seems obvious that rebreathers were the ultimate goal of the technical diving revolution. The word revolution is not hyperbole. The adoption of mixed gas technology by the sport diving community, which was first showcased at Stone's Wakulla Springs Project 1987, as shown in Figure 3, was nothing less than a technological revolution analogous to the personal computer revolution in the world of computing. Similar to the personal computer, mixed gas proved to be a novel, disruptive technology that dramatically changed the world of diving.

Like the military and commercial divers before them, early tech divers turned to mixed gas technology to improve their safety and performance in contrast to the perils of deep air diving. Retired Master Diver Sam Huss, from the US Navy Experimental Diving Unit (NEDU) summarized the concept this way, "*We make our divers safer, so they can go deeper and stay down longer*." (Menduno, 2016). Is not that what tech diving, indeed the history of diving, is all about?

Clearly the introduction of open-circuit mixed gas technology into the sport diving community, what could properly be called the mixed gas revolution—helped improve deep diving safety, and in doing so enabled tekkies to safely go far deeper and longer than the recreational no-decompression diving limits.

As tech pioneer Capt. Billy Deans once put it back in the 1991, "*We have doubled our underwater playground.*" (Figure 4).

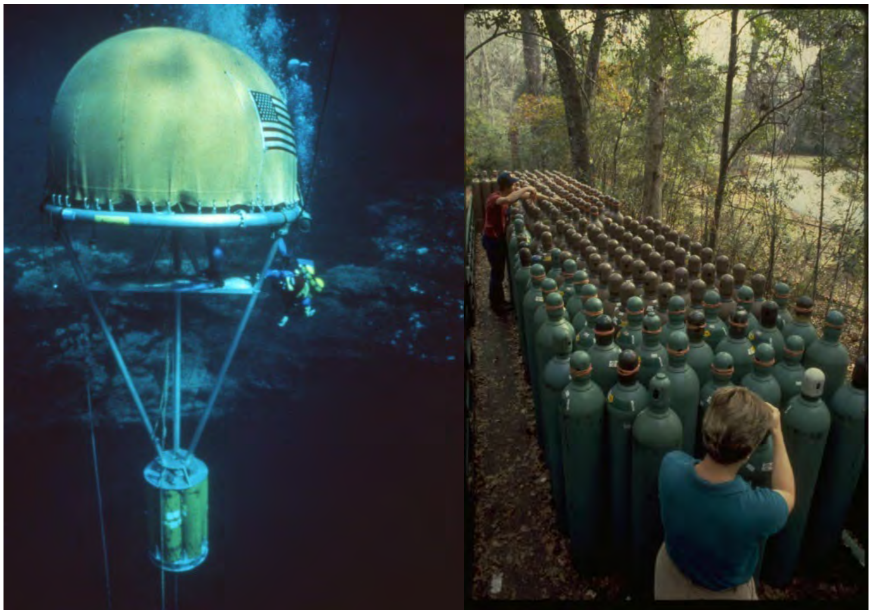


Figure 3. Wakulla springs gas (photo courtesy US Deep Caving Team).

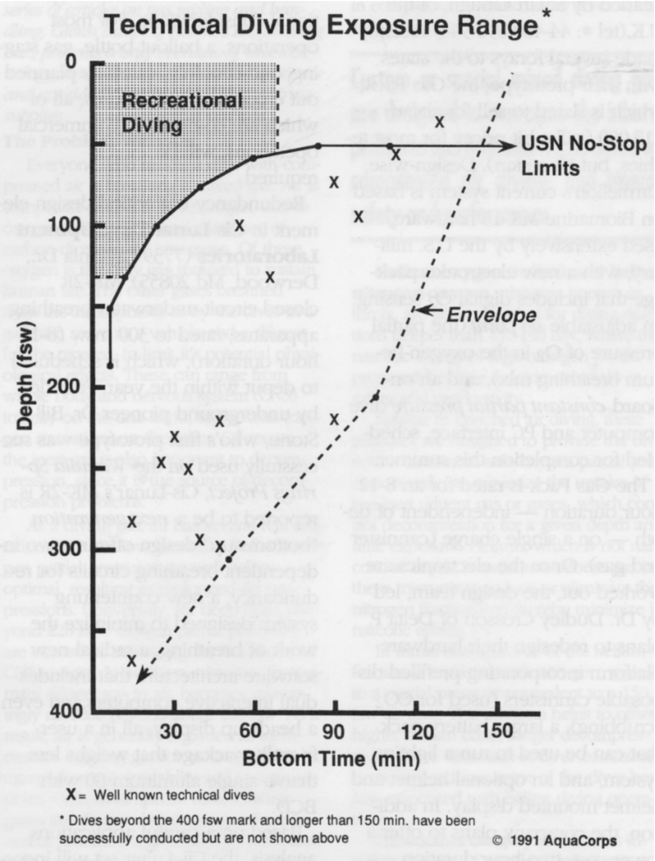


Figure 4. Technical diving range (1991). Courtesy aquaCORPS archives.

CCRs, arguably the ultimate mixed gas diving platform, have enabled us to push our underwater envelope further to access some of the most remote underwater environments on the planet (Figure 5). However, more work needs to be done to improve rebreather diving safety. Before getting into the details, two additional points need to be made.

First the adoption of mixed gas technology and rebreathers by the sport diving community can be seen as a natural and fundamental paradigm of technology. As shown in Figure 6, technologies are typically developed by governments, which have deep pockets needed to fund basic research and development. They are next adopted by private enterprise, which seeks to commercialize the technology. Finally, technologies are adopted by consumers, who typically then drive the market and further innovation.

Figure 5. CCRs, the ultimate mixed gas platform. Photos courtesy USDCT and JFD Global (https://www.jfdglobal.com/products/commercial-divers-equipment/rebreathers).

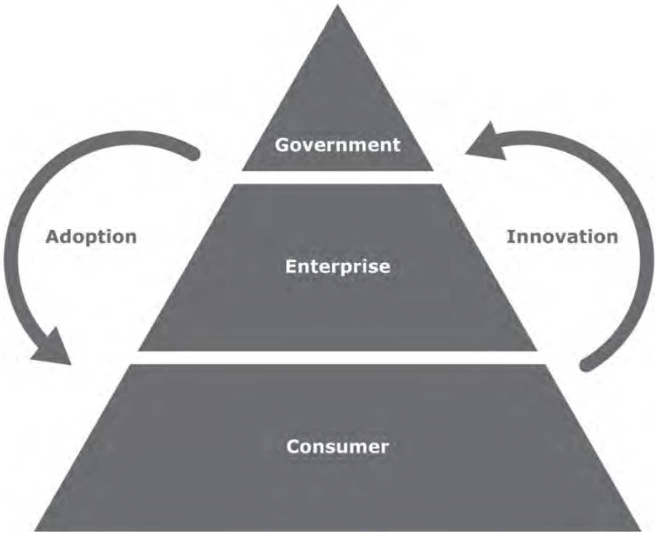


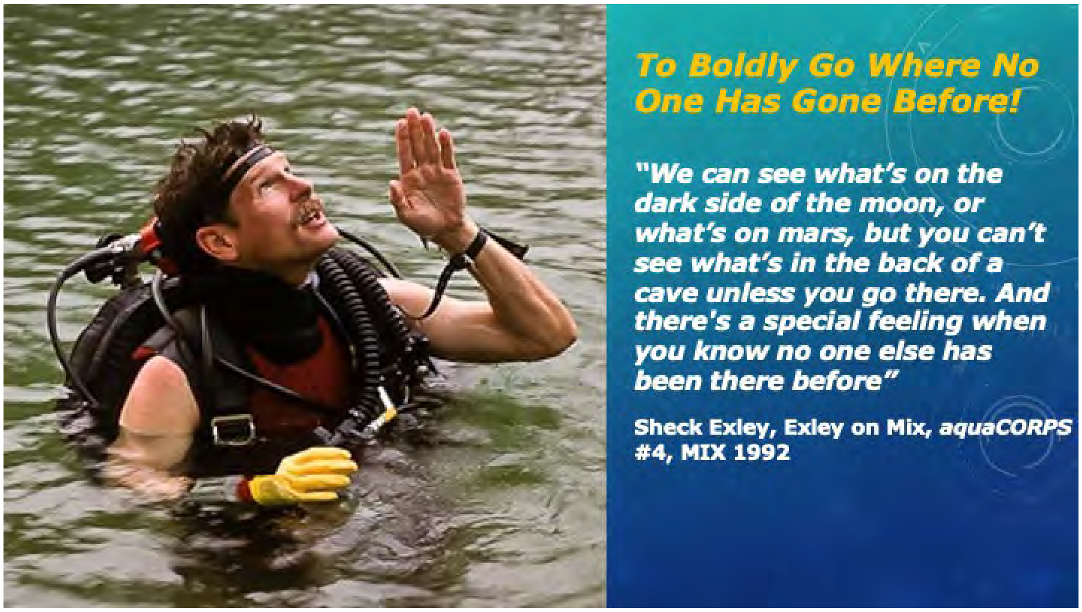
Figure 6. Technology development cycle.

This general paradigm applies to a host of technologies including transportation, communication, photography, computing, in addition to diving. In fact, this is precisely what has happened with mixed gas technology, which was originally developed for military divers in the 1930s so that they would be able to reach downed submarines beyond the air diving range (Figure 7). It was later adopted by the commercial diving industry in the 1960s as offshore oilfield diving got deeper (Figure 8), and eventually was adopted by sport divers. A similar pattern happened with rebreathers.

The second point concerns motivation. While military divers dive for the mission, and commercial divers dive for work, technical divers arguably do it to explore the unknown. Blame it on our DRD4-7R explorer gene. As legendary cave explorer Sheck Exley (1949-1994) once explained, "*We can see what is on the dark side of the moon, or what is on Mars, but you cannot see what is in the back of a cave unless you go there. And there's a special feeling when you know no one else has been there before*." (Menduno 1994; Figure 9).

Figure 7. Military divers dive for the mission. Photo by US Navy.

Figure 8. Commercial divers dive for work. Photo courtesy Oceaneering.



To Boldly Go Where No One Has Gone Before!

"We can see what's on the dark side of the moon, or what's on mars, but you can't see what's in the back of a cave unless you go there. And there's a special feeling when you know no one else has been there before"

Sheck Exley, Exley on Mix, *aquaCORPS* #4, MIX 1992

Figure 9. Technical divers dive to "*go where no one has gone before*." Photo courtesy Brian Udoff.

Of course, Exley was unaware at the time that his protégé Bill Stone would one day create an autonomous cave exploration robot named Sunfish that could see what was in the back of the cave, but his point remains valid. No doubt, even recreational divers tap into those feelings of exploring the unknown when they drop down on a reef or a kelp forest for the first time.

A Bit of Early Tech History

Stone's iconic Wakulla Springs Project 1987 was the first large scale mixed gas exploration project in the sport diving community, and could well be considered the launch of what would soon become known as technical diving (Figure 10). At that time, small groups of highly experienced cave divers in the US and Europe were beginning to conduct open-circuit mixed gas dives with trimix (oxygen, helium, nitrogen blend) using protocols developed by Dr. RW Bill Hamilton (Menduno 2018). For the most part, these dives were kept quiet, lest less experienced divers be led to their doom.

The initial focus of mix technology was on open-circuit diving; there were literally only a handful of tech pioneers experimenting with mixed gas rebreathers, which were not readily available to sport divers. Though there were a few homemade units like Stone's, several other individuals were diving converted military units like the Carleton Technologies MK 15 with modified electronics enabling users to adjust the oxygen setpoint above 0.70 atm. Dive retailers were just beginning to add mixed gas infrastructure making it possible for divers to get oxygen, nitrox, and helium gas mix fills.

Eight years after the Wakulla Project, military rebreather maker Dräger launched its Atlantis nitrox semiclosed rebreather (SCR) designed specifically for recreational divers in 1995. Though we were all excited that a large rebreather manufacturer would be interested in the sport community, clearly, tech divers needed and wanted mixed gas closed-circuit units.

Then in 1997, 10 years after Wakulla, AP Diving launched the Inspiration, the first production line, mixed gas electronic closed-circuit rebreather (eCCR) built purposely for sport divers (Figure 11). Note that the first commercial eCCR was the Electrolung, launched in August 1968 by Walter Starck, principal of Oceanic Equipment Company, Miami. FL and marketed to sport divers as well as government and commercial users (Starck 2021). The unit was withdrawn from the market in 1971, after a series of high profile fatalities.

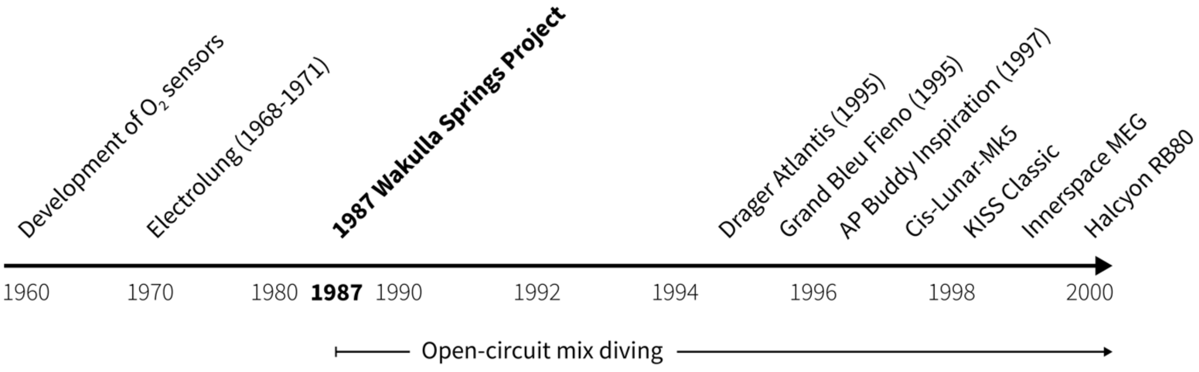


Figure 10. Historical timeline: early sport rebreathers.

Along with the Inspiration, Stone's company Cis-Lunar Development Labs released the fifth generation of its fully redundant exploration rebreather, the MK5, and put it on the market for sale. Thus began the rise of technical rebreather diving.

Figure 11. AP Diving Inspiration production line. Photo courtesy AP Diving.

Over the next two years, Jetsam Technologies launched the KISS, a mechanical CCR (mCCR), Innerspace Systems launched its Megalodon eCCR, and Halcyon Dive Systems released its RB-80 SCR. Training agencies followed suit by offering training courses. A more detailed history of early tech rebreathers can be found in the RF3 proceedings (Menduno 2012).

Enter The Rebreather Forum

Before examining the rebreather market today, it is useful for background to review the Rebreather Forum meetings, which have been convened periodically over the last 30 years. These industry/scientific symposiums have served as a focal point for the community to address issues and developments surrounding rebreather technology and share best practices.

Rebreather developer Tracy Robinette, principal of Divematics, and the author on behalf of *aquaCORPS: The Journal for Technical Diving*, organized the first Rebreather Forum in Key West, FL in May 1994 (Figure 12). The purpose of the industry-only meeting was to learn more about rebreather technology, interest existing rebreather manufacturers in producing rebreathers for tech divers, and to help facilitate their adoption by the tech community.

Figure 12. Capt. Ed Thalmann at RF1. Photo courtesy aquaCORPS archives.

The first forum, which was held in cooperation with the US Army's Combat Diver School, drew 90 participants, nine military rebreather manufacturers, training agencies, and government representatives. Special guests were US Navy diving medical officer Dr. Ed Thalmann and engineer Alan Krasberg, founder of General Diving Systems, considered one of the godfathers of CCRs.

Rebreather Forum 2.0 (RF2) was held in September, 1996 in Redondo Beach, CA following Drager's release of the Atlantis in 1995 (Figure 13). A Japanese company Grand Bleu also released the Fieno, a $2800^{US} SCR unit aimed at recreational divers that same year. RF2 drew 114 participants and 17 manufacturers. The following year, Stone and AP Diving managing director Martin Parker—*the Henry Ford of Sports Rebreathers*—put their respective machines on the market.

Figure 13. RF2 audience. Dr. John Clarke in foreground. Photo courtesy aquaCORPS archives.

It would be 16 years before, Divers Alert Network (DAN), PADI, and the American Academy of Underwater Science (AAUS) held Rebreather Forum 3.0 (RF3) in Orlando, FL in May 2012 (Figure 14). RF3 was the largest meeting yet with over 400 industry and scientific participants, and 12 manufacturers producing rebreathers for sport divers. The primary focus of the meeting was rebreather diving safety.

Figure 14. RF3 meeting main room. Photo by Karl Shreeves

In February 2015, the National Park Service, DAN, National Oceanic and Atmospheric Administration, and AAUS, held the Rebreathers and Scientific Diving symposium at the Wrigley Marine Science Center, Catalina Island, CA (Figure 15). There were 54 participants.

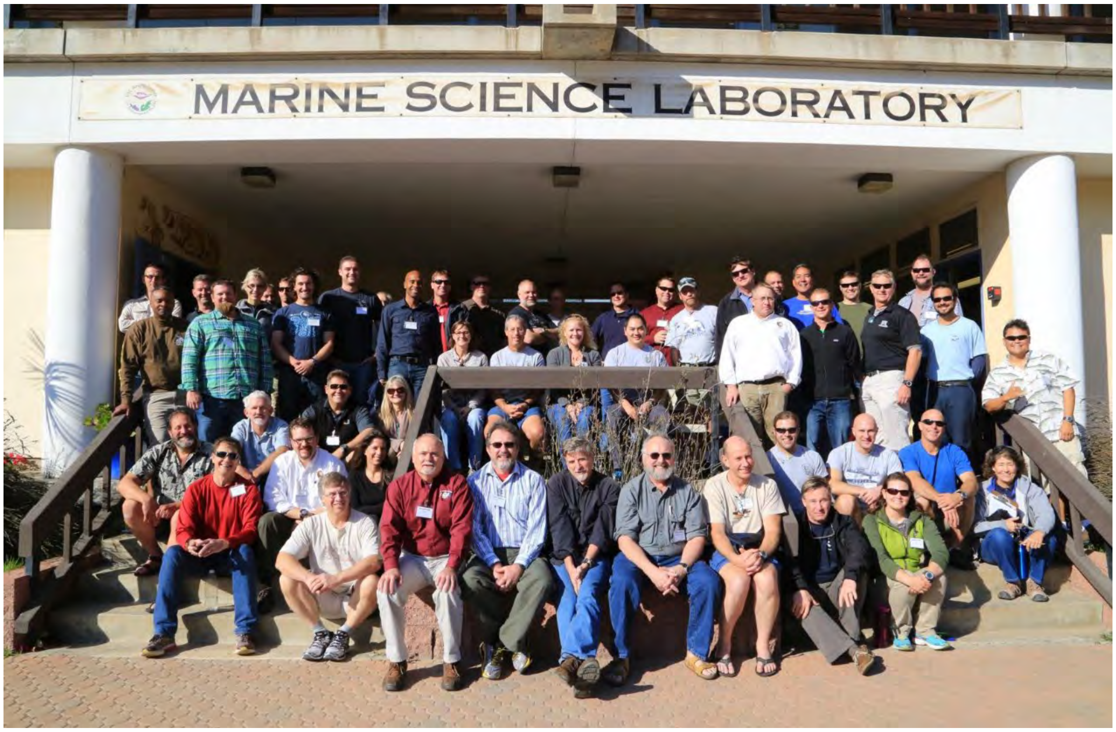


Figure 15. Rebreathers and scientific diving meeting participants. Photo courtesy Neal W. Pollock.

Finally, in late 2021, after discussions throughout the community, planning began for Rebreather Forum 4 (RF4; Figure 16). The tech community had made substantial progress with rebreather technology on a number of fronts, and there were new issues such as diver monitoring and rebreather bailout, and new data, such as on the efficacy of mouthpiece retaining straps.

Figure 16. The author speaking at Rebreather Forum 4. Photo by Jason Brown.

RF4 was held in Valletta, Malta on 20-22 April 2023. There were 300 participants and a dozen rebreather manufacturers. Reports and or the proceedings from each of these meetings are available at RebreatherForum.tech.

How Many Rebreather Divers Are There?

How many technical rebreather divers are there? For that matter, how many tech divers are there? The answer to both of these questions is that we do not know. As most diving professionals recognize, sport diving is a data-challenged industry. Thanks, however, to RF4, we are able to provide our current best estimates on rebreather users.

Based on data from 22 of 24 rebreather manufacturers, the total installed base of sport rebreathers, that is, the total number of units that have been sold to recreational and tech divers, is estimated to be approximately 25,000-35,000 rebreathers (Tillmans 2024). Of course, some of these units are likely now out of commission and some divers own more than one rebreather.

The pre-RF4 survey (Kieran 2023) of persons registered for RF4 found that, on average, registrants owned 1.8 eCCR, 0.7 mCCR and 0.4 SCR, for a total of 2.9 rebreathers. Remember, however, that RF4 attendees were mostly long-time, experienced rebreather users. If we make a reasonable guestimate that, on average, rebreather divers own 1.25 units then we can estimate the number of rebreather divers as approximately 20,000-28,000 rebreather divers.

Note that by comparison, at RF3, the number of "active" tech rebreather divers was estimated to be 10,000-15,000 divers, based on an estimated total of 30,000 divers that had received rebreather training (1994-2010) indicating that not all certified divers remain active or that some divers held multiple certifications. This paper refrains from using the term "active" to distinguish them from inactive or retired divers since there are currently no data to draw that distinction.

An estimate can also be derived from training data. At RF4, eight training agencies (compared to three at RF3) consolidated their rebreather training course data from the last 10 years into three buckets - basic, intermediate, and advanced. It is noteworthy that both basic and intermediate courses may represent divers taking their first rebreather class in some instances. For example, Global Underwater Explorers (GUE) CCR1 course is considered an intermediate level course aimed at relatively experienced open-circuit mixed gas divers.,

Based on an analysis of that data, it is estimated that agencies have trained a minimum of 1400- 2000 new rebreather divers per year on average over the last 10 years, reflecting basic and intermediate certifications issued minus estimated duplicates (Tillmans 2024). Consolidating this data with the estimated 10,000-15,000 divers in 2012, would yield an estimate of 24,000-35,000. Given dropouts and individuals receiving training on multiple units or multiple levels of training, the actual numbers could be reduced.

For our purposes, we will estimate the number of tech rebreather divers as 20,000-30,000, or about double the 2012 estimate. As we will see, this doubling roughly corresponds to a doubling of the number of rebreather manufacturers providing products to technical divers. Note that this compares to about 2000-3000 untethered Navy rebreather divers (Menduno 2016).

As mentioned, though rebreathers represent the dominant platform for exploration and big dives requiring significant gas, and essentially all of the tech training agencies offer rebreather training, it is evident from the numbers that relatively few tech divers actually own rebreathers. Interestingly, according to Brian Carney, president of Technical Diving International, rebreather courses are not in their 40 most popular courses.

The number of active scuba divers is currently guestimated to be approximately 7.3 million divers: 2.4 million in North America, 2.5 million in Europe, 2.7 million in the rest of the world (Kieran 2019). The number of technical divers has been guestimated to be 3-7% of scuba divers (Divesoft, PADI, TDI personal communication, Meissner 2019). This would suggest that there could be 219,000-511,000 technical divers of various levels.

Extrapolating from the guestimates, it is possible that only about 4-14% of technical divers at most, with a midpoint of 9%, own a rebreather. In other words, about one in 10 technical divers owns one or more rebreathers. Not surprising, the price tag for a rebreather and training has been cited as a major inhibitor as discussed below. As such they remain an aspirational tool for many technical divers.

RF4 also shed light on rebreather diver demographics. According to data drawn from the DAN hotline, RF4 participants, and the caustic cocktail survey (Tillmans 2024), the demographics for tech rebreather divers could approximate the following:

- mean age: 42-46 years
- sex: 84-95% male
- certified for 6 years on average (RF4 participants: 12 years)
  - 40% <5 years
  - 10% >20 years
- median self-reported experience: 200 rebreather dives/300 rebreather hours

Supply Side Economics: Technical Rebreathers

Having estimated the number of tech rebreather divers, that is the demand side of the equation, it is also useful to examine the supply side in order to better understand the size of the market and the growth of tech rebreather manufacturing over the last three decades.

Figure 17 shows the growth of tech rebreather manufacturing, beginning in 1996, when the Drager Atlantis and Grand Bleus Fieno were the only two commercially available, purpose-built for sport diving.

It is also noteworthy that at RF2 held that year, the total number of mixed gas rebreathers in active use and inventory by the US and British forces, which represented the largest group of military rebreather divers, was estimated to be around 600 units, after nearly 30 years since the introduction of military mixed gas CCRs (Menduno 2012).

As discussed, by 2000 there were five commercially available tech rebreathers; three eCCRs (Cis-Lunar Mk5, Inspiration, Megalodon), one mCCR (KISS) and one SCR (RB-80). Drager and Fieno had dropped out of the market by that time. The Pelagian, an mCCR, was also offered in kit form, but apparently remained on the market for less than a decade. The number of manufacturers grew to 12 by the time of RF3 (2012), and then doubled to 24 companies between RF3 and RF4 (2023), representing some 40 specific rebreather models.

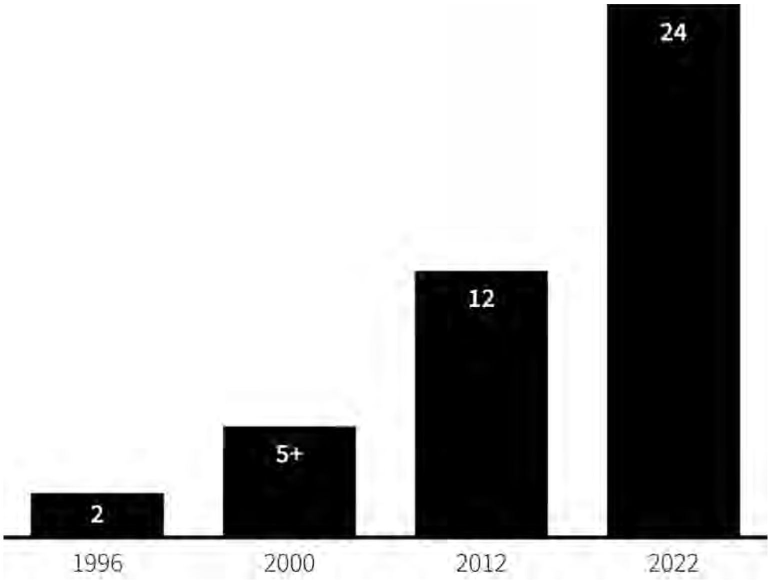
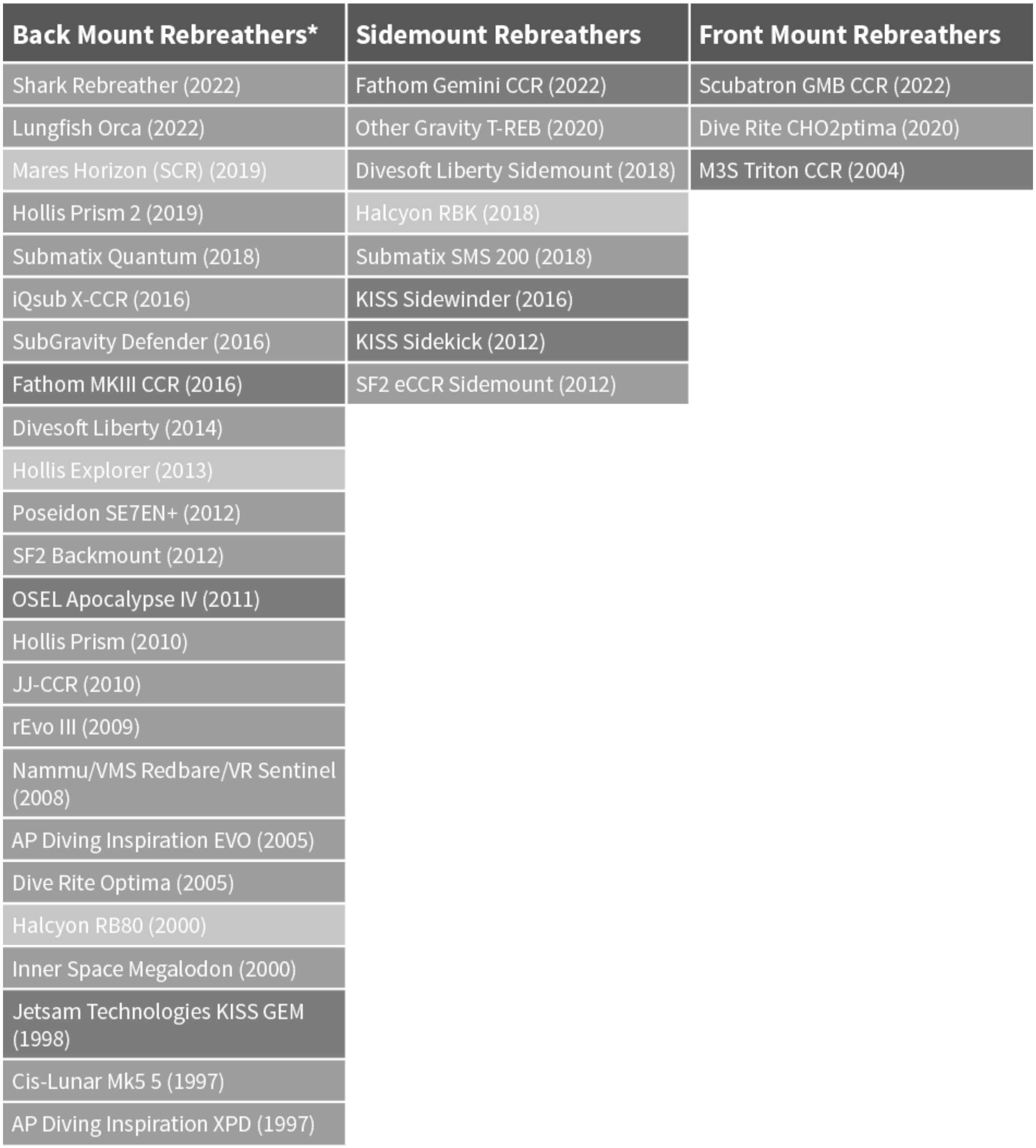


Figure 17. Growth of technical rebreather manufacturers.

Table 1 provides a list of tech rebreathers currently on the market, showing manufacturer, model, the type of rebreather, and the date the release date. Note that 36 primary models are shown out of estimated 40 models actually in production (Menduno et al. 2022).

Table 1. Rebreather listings. Source: InDEPTH holiday rebreather guide (Menduno et al. 2022)



Back Mount Rebreathers*	Sidemount Rebreathers	Front Mount Rebreathers
Shark Rebreather (2022)	Fathom Gemini CCR (2022)	Scubatron GMB CCR (2022)
Lungfish Orca (2022)	Other Gravity T-REB (2020)	Dive Rite CHO2ptima (2020)
Mares Horizon (SCR) (2019)	Divesoft Liberty Sidemount (2018)	M3S Triton CCR (2004)
Hollis Prism 2 (2019)	Halcyon RBK (2018)	
Submatix Quantum (2018)	Submatix SMS 200 (2018)	
iQsub X-CCR (2016)	KISS Sidewinder (2016)	
SubGravity Defender (2016)	KISS Sidekick (2012)	
Fathom MKIII CCR (2016)	SF2 eCCR Sidemount (2012)	
Divesoft Liberty (2014)		
Hollis Explorer (2013)		
Poseidon SE7EN+ (2012)		
SF2 Backmount (2012)		
OSEL Apocalypse IV (2011)		
Hollis Prism (2010)		
JJ-CCR (2010)		
rEvo III (2009)		
Nammu/VMS Redbare/VR Sentinel (2008)		
AP Diving Inspiration EVO (2005)		
Dive Rite Optima (2005)		
Halcyon RB80 (2000)		
Inner Space Megalodon (2000)		
Jetsam Technologies KISS GEM (1998)		
Cis-Lunar Mk5 5 (1997)		
AP Diving Inspiration XPD (1997)		

Several trends are worth noting. Backmounted counterlungs are growing in popularity on backmount rebreathers vs over-the-shoulder counterlungs prevalent on early units such as AP's Inspiration and the Megalodon. Divers are essentially trading reduced clutter on the chest for slightly increased work of breathing (WOB).

However, there has also been new interest in front or chest-mounted rebreathers, which are optimal from a WOB perspective. Finally, the tech market has seen growth in mCCRs, which appear to be unique to the tech diving community; they are not used in military or commercial diving.

Table 2 shows the tech rebreathers that are no longer in production, though some of these units are still in use. Note that with the exception of the RB80, SCRs have been primarily targeted for recreational divers by virtue of their comparative simplicity to CCRs, although they evidently have not fared well in the sport diving market to date.

Table 2. History of out-of-production rebreathers

Unit	Type	Years of production	Units sold
Drager Altlantis, Dolphin, Ray	SCR	1995-1999	
Fieno	SCR	1995-200?	
Cis-Lunar Mk-5	eCCR	1997-2001	~100
Mares Azimuth	SCR	1997-2000?	
VR Technology Ouroboros	eCCR	2005-2008	~200
Hollis Explorer	SCR	2013-2017	~1500
VR Technology Sentinel	eCCR	2008-2017	~500

In the early days of sport rebreathers many held the belief that tech divers would migrate to CCR, while recreational divers would adopt SCR over open-circuit—*Who wouldn't want to be diving a rebreather?* This gave rise to the concept of offering a simplified rebreather, either a SCR or simplified CCR, designated Type R, to recreational divers, a concept which was presented at RF3.

The move to SCR (and Type R rebreathers) never materialized to an appreciable degree in practice. Experts have speculated that the reason is that SCRs, though less expensive than their CCR counterparts, still require 80% of the work of a CCR, but do not offer anywhere near the performance. Currently the only SCRs currently being produced are Halcyon's RB-80 and RBK, which are used as open-circuit 'gas extenders' in exploration, and the Mares Horizon, launched in 2019, which is aimed at the recreational market.

Stone's Cis-Lunar Labs discontinued selling the MK5 in 2001, and in 2005, licensed its technology to Poseidon Diving Systems. VR Technology's Sentinel was acquired by Vobster Marine Services in 2017 and rechristened the VMS Redbare. In 2022, VMS was acquired by UK-based NAMMU Tech, and the Redbare was discontinued. However, NAMMU has announced that it plans to rename and re-issue a version of the rebreather.

Driving Rebreather Innovation

Bill Stone characterized the state of tech rebreather technology by asserting that the community was still in the "*test pilot era*" at RF3. By RF4, that sentiment had clearly changed as a result of advances in rebreather technology. While a decade earlier, a rebreather instructor beginning a class might have posited, "*This machine is going to try and kill you. Your job is to not let it.*" [The author's initial CCR instructor actually said that.] Today, an instructor might begin her class by pointing out, "*This machine is going to try and keep you alive. Your job is to make sure that it does!*"

As shown and discussed previously (Figure 6), technologies tend to be developed by the government/public sector, which have the resources to fund basic research and development. Technologies are then capitalized on by enterprises and eventually scaled to address the consumer market which then typically drives innovation. This is primarily the case in the rebreather market, though commercial diving, which relies almost entirely on surface-supplied gas, may use rebreathers for saturation diving bailout.

Table 3 lists the key innovations that have primarily come out of the tech rebreather market and in many cases have been adopted and or incorporated into military rebreathers. Some of this was a direct technology transfer. For example, rebreather engineer Kevin Gurr, who designed and built three innovative sport rebreathers, sold his company VR Technology and went to work for military rebreather manufacturer Avon Protection bringing his technological innovations.

Table 3. Innovations in rebreather equipment

Innovation	Estimated number of manufacturer users
Vibrating sensors	>2
Digital head-up display	>3
Buddy light	>2
Temperature sticks	8
Gaseous CO_2 sensor	6
Solid state O_2 sensor	1
Pre-packed scrubber canister	3
Acoustic helium sensor	1
Smart semiclosed-circuit rebreather	1
Redundant electronics	1
Adjust-on-the-fly needle valve	1
Sidemount closed-circuit rebreather (CCR)	7
Dual CCR bailout software	1

Of particular note are sidemount rebreathers, which are unique to the tech market, and whose development has opened the way for bailout rebreathers, as has the development of CCR bailout software pioneered by Divesoft, and Shearwater Research, which has bailout software in development.

There is considerable continuing interest in improving onboard gas monitoring systems. Solid state oxygen sensors were discussed in detail at RF3. The general consensus was that solid state oxygen sensors were potentially more reliable and accurate than galvanic sensors. At the time in 2012, Poseidon was just releasing an auxiliary sold state sensor that worked with its rebreather, and the presumption was that other vendors would follow suit. Surprisingly, that has not occurred (Stewart 2021).

There is also considerable interest in carbon dioxide (CO_2) monitoring systems for both rebreather and diver. Numerous vendors offer in-loop gaseous CO_2 sensors, which measure CO_2 in the loop, as well as thermal sticks that measure the heat from reaction front in the rebreather scrubber, thus giving an indication of its remaining capacity. However, the best option for diver CO_2 sensing would be end-tidal CO_2 monitoring, similar to that used in anesthesiology that measure CO_2 levels at the end of exhalation. Such technology is not yet available in rebreathers, but it was identified as a research priority/goal in the RF4 consensus statements (Mitchell and Pollock 2023).

The Economics of Rebreathers

A primary reason that only a small percentage of technical divers own rebreathers is their relative expense. According to one survey of 425 technical and recreational divers and instructors who did not own rebreathers, 57% said it was likely or extremely likely that they would eventually dive with a rebreather, 23% were unsure, and 21% said it was unlikely (Kieran 2022).

Respondents rated the factors that stopped them from buying a rebreather, on a scale of 0 (not a significant factor) to 10 (very significant) in order of priority. Cost was the cited as the primary inhibiting factor with a weighted score of 7.8, followed by personal preference and safety.

Table 4. Self-reported factors limiting non-rebreather divers from purchasing rebreathers (n=425)

Determining factor	Weighted average (0-10 scale)
Cost	7.8
I like how I currently dive	5.1
Safety	5.0
Complexity	4.6
Logistics	4.3
Limited availability of training	3.0
Limited number of dive charter and resorts welcoming rebreathers	2.8
Do not see the advantages	2.0

In comparison, when asked to rate the factors that could increase usage of rebreathers among tech divers, the 517 respondents that were rebreather divers ranked safety first, followed by logistics (rebreathers require significantly more work compared to open-circuit), then cost and availability of training. Note that cost scored similar in importance (7.1 vs 7.8) among non-users and users though the relative ranking was different. Rebreathers are not inexpensive.

Table 5. Self-reported factors that could increase usage of rebreathers among technical divers (n=517)

Determining factor	Weighted average (0-10 scale)
Safety	8.3
Logistics	7.8
Cost of equipment	7.7
Availability of training	7.3
Number of dive charters and resorts welcoming rebreathers	7.3
Complexity	6.5
Better communicate the advantages	6.5
Have people try it	6.3
Cost of training	5.9

How much do rebreathers cost approximately? We used manufacturers' recommended base retail prices from InDEPTH's rebreather guide (Menduno et al. 2022), that lists 24 manufacturers and 32 models of rebreathers organized into backmount, sidemount and frontmount, including their specifications and factory pricing.

According to the guide, the average base cost of a backmount rebreather is 8307^{US}, the average cost of a sidemount rebreather is 7292^{US}, and the average cost of a front or chestmount rebreather is 5923^{US}. Note that the actual configured price of a unit can be higher. For example, while the basic cost of a backmount Divesoft Liberty rebreather is 9026^{US}, the cost of the author's personal unit, configured with a titanium backplate, air-integrated sensors and other items was $13,356^{US}$. Add in several thousand dollars for training, which often involves travel, and it is clear that rebreather represent a sizeable investment.

Not surprising given price levels, there is a robust resale market for rebreathers at sites like Rebreather World, Buy & Sell Rebreathers Worldwide group on Facebook that currently has 21,100 members, Facebook's Rebreathers for Sale page currently with 13,700 members, eBay Rebreathers, Scuba Board, and others. According to the pre-RF4 survey, 34% of RF4 attendees said that they had purchased at least one secondhand rebreather.

The Price of Helium

While the cost of rebreathers is evidently a limiting factor for their use by tech divers, the rising cost and shortages of helium, which is needed for deep diving, provides a powerful incentive for tech divers to consider a rebreather if they are interested in deep diving.

The gas industry currently characterizes the state of the helium market as helium shortage and prices are not expected to stabilize until 2024-2025 or later. Experts forecast that helium supplies should match demand by the end of the decade easing price pressure, as additional production capacity is added in Qatar and Russia (Stewart 2023). At current prices in the US, a set of double 100 ft^3 tanks (12 L) filled with trimix 18/45 could cost $216-275^{US} or more.

According to an analysis conducted last year, based on GUE courses (Shockey 2022), if a beginning tech diver continued their deep open-circuit training and conducted about fifty 60 m (198 ft) trimix dives, they could alternatively have purchased a JJ-CCR along with the requisite training, and have much lower diving operating costs going forward.

The break-even number of deep open-circuit dives, of course, depends on the dive and location (the latter which can impact helium prices). As of early 2024, the cost of helium has increased at least 25% lowering the break-even point further.

Extending Our Underwater Envelope

Similar to open-circuit mixed gas diving, rebreathers have enabled tech divers to greatly expand their underwater envelope. In order to appreciate the extent of their impact, a pair of articles in InDEPTH examined the deepest tech shipwreck dives today compared to those conducted in the 1990s (Menduno 2022); and the deepest cave dives today compared to dives in the nineties (Menduno and Gomes 2021). Note that these dives are not representative of typical tech rebreather diving profiles, rather they represent the extremes.

Figure 18 shows deep tech shipwreck exploration dives conducted over nearly three decades. Note that rebreathers clearly became the dominant platform after 2000 and have arguably enabled tech divers to extend their range.

The 10 deepest shipwreck dives today average 176 m (577 ft) in depth compared to 121 m (397 ft) for the deepest dives in the 1990s, or 55 m (180 ft) deeper. Average bottom time for the deepest dives today was nearly the same as in the 1990s (15 versus 17 min), while not surprising, average run time was 316 min compared to 192 min in the 1990s, due to the increased decompression obligations resulting from the increased depth.

Similarly, Figure 19 shows the deepest cave dives conducted over three decades. Note that the move to rebreathers has perhaps been a little slower in the cave diving community, due to the ability to stage open-circuit gas supplies. This is arguably also the reason that mixed gas technology was first adopted by the cave community and later adopted by their open water counterparts. All of the extreme deep dives in the study since 2004 were conducted on CCR.

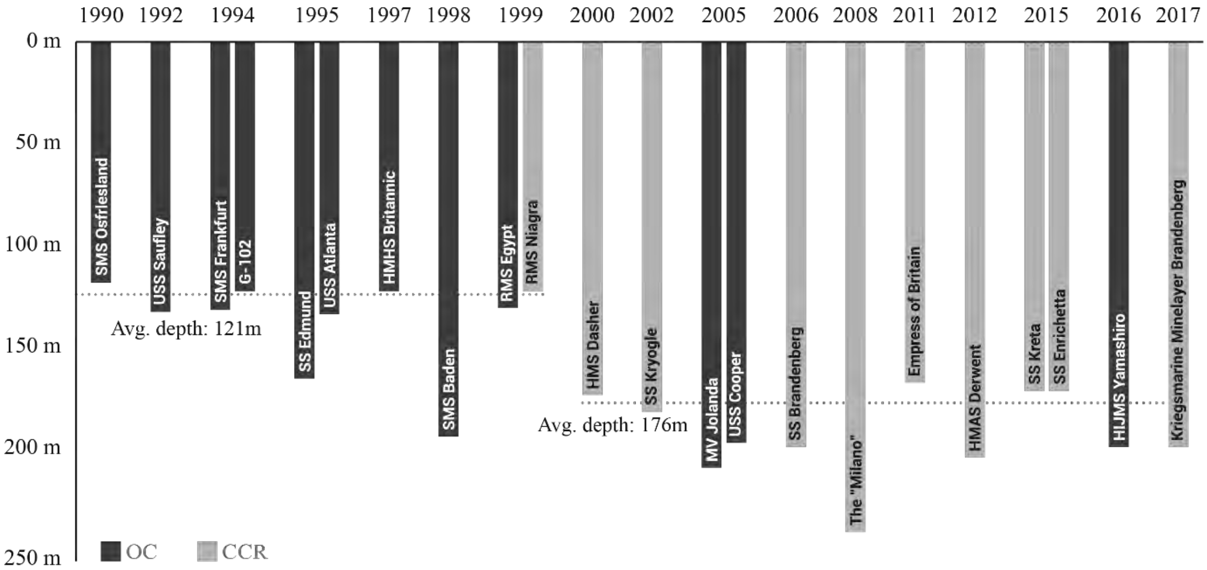


Figure 18. Rebreathers have extended tech divers underwater envelope: deep shipwrecks.

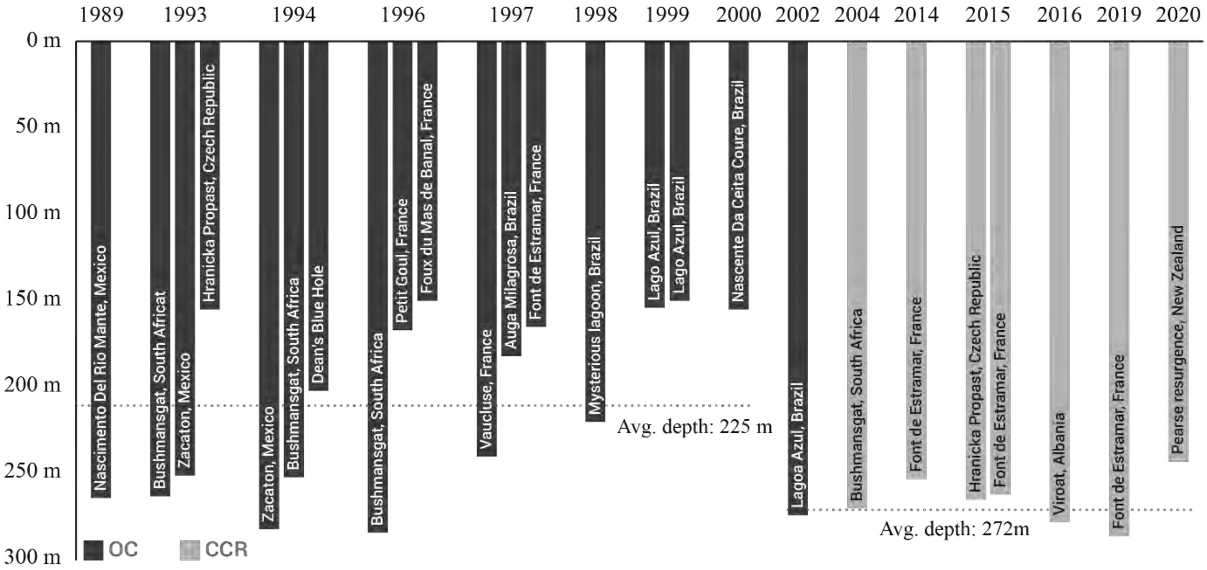
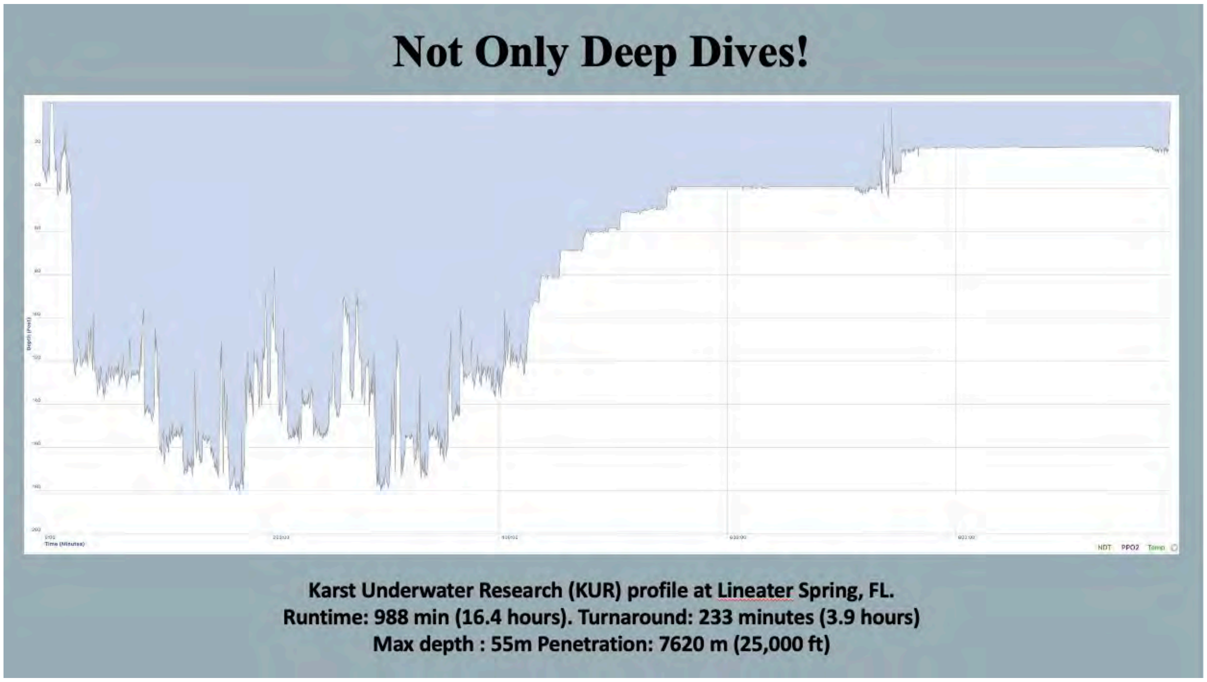


Figure 19. Rebreathers have extended the underwater envelope: deep caves.

The 10 deepest cave dives today average 272 m (895 ft) in depth (adjusting for altitude and freshwater), compared to an average depth of 225 m (739 ft) for the 10 deepest dives in the 1990s, or approximately 47 m (155 ft) deeper. As expected, these extremely deep cave dives exceeded the average 176 m (577 ft) depth of the deepest wreck dives by 97 m (318 ft).

The advantages of rebreathers are not limited only to deep dives, but to long dives as well, where the logistics of open-circuit gas can become unmanageable. Figure 20 shows the profile of a recent 16.4 h cave dive using an eCCR with SCR bailout representing a 7620 m (25,099 ft) penetration to a maximum depth of 55 m (180 ft). This dive would be extremely difficult, if not impossible, to conduct with open-circuit scuba alone.



Not Only Deep Dives!

Karst Underwater Research (KUR) profile at Lineater Spring, FL.
Runtime: 988 min (16.4 hours). Turnaround: 233 minutes (3.9 hours)
Max depth : 55m Penetration: 7620 m (25,000 ft)

Figure 20. Karst Underwater Research (KUR) dive profile at Lineater Spring, FL.

The combination of improved gas logistics and decompression efficiency (constant PO_2), can also improve diving productivity on shallow dives. According to David Conlin, chief, Submerged Resources Center, US National Park Service (NPS) (Menduno 2012b), "*The real value of rebreathers is not deep diving at all, but staying longer at 20-30 m (66-98 ft) You can work at those depths nearly all day long when the conditions are good.*" Conlin reported that rebreathers improved NPS divers' productivity by 40%. "*We gain nearly one day for every three days we're in the field*," he said.

Rebreather Diving Safety: The Elephant in the Loop

While rebreathers have enabled tech divers to significantly extend their operational range, rebreather diving safety is arguably still a work in progress. Rebreather safety was a primary focus of RF3 (Menduno 2012). At that time there were approximately 20 rebreather fatalities identified per year compared to about 100-120 scuba fatalities.

Andrew Fock, Chair of Hyperbaric Medicine at the Albert Hospital, Melbourne Australia, analyzed available global rebreather accident data from 1998-2011 at RF3, representing 181 fatalities, and concluded that the risk of dying while diving a rebreather was 5-10 times greater than the risk of dying on open-circuit scuba (Fock 2013). He asked for a show of hands of how many people thought the current safety record was acceptable. No one raised their hand. Much of RF3 was spent discussing how safety could be improved, for example, through the use of checklists, pre-breathes, and engineering solutions.

Based on interviews prior to RF4, it is fair to say that attendees' expectations were that rebreather diving safety had improved over the last decade. When asked for a show of hands during the opening session, as to how many people thought that the community was doing a good job with regards to rebreather diving safety, nearly half of attendees in the room raised a hand.

Even so, in the pre-RF4 survey conducted among attendees, 85% of respondents identified rebreather diving safety as 'very important' or 'critical' to be discussed at the meeting. In fact, the five critical issues cited were all safety related, including quality control in training, complacency regarding checklists and prebreathing, and carrying adequate bailout.

Based on an analysis of all available databases, Frauke Tillmans, director of research at Divers Alert Network (DAN) reported that at least 241 rebreather divers have died since RF3 (2012), which she noted was likely an incomplete tally, particularly in Asia. For reference, there were four rebreather fatalities identified in the two weeks following RF4. Tillmans estimated CCR fatality rates to be 1.8 to 3.8 deaths per 100,000 dives or 1.2-2.5 deaths per 100,000 CCR hours (Tillmans 2024).

For comparison, skydiving deaths ranged from 0.28-0.45 deaths per 100,000 jumps for the period 2018-2021 according to the United States Parachute Association. While underreporting is also possible in this community, the data suggest that rebreather diving may be 10 times riskier than skydiving, although about one-tenth the risk of base jumping (https://www.uspa.org/Discover/FAQs/Safety).

According to Tillmans, the results were not substantially different from the analysis made by Andrew Fock in 2012. "*I struggle to accept that CCR divers are still dying at a concerning rate and although some promising technology development is underway to mitigate at least the big Hs (hyperoxia, hypoxia, hypercapnia), we are still not there yet.*" (Stewart 2023b).

Practically, more needs to be done to better identify and mitigate the factors leading to rebreather accidents and fatalities in the tech community. If the community does not take action, they are accepting the consequences.

Trends and Initiatives

The Recreational Rebreather

One of the initiatives presented at RF3 was developed largely by PADI working with rebreather manufacturers. Their proposal was to create a simplified, standard rebreather for recreational divers, designated Type R, as mentioned above.

Table 6 lists the specific design elements that a Type R rebreather would include. The idea was, by standardizing on a Type R rebreather, training course could also be standardized across manufacturers, thus eliminating model-specific training that was, and remains the standard for training courses. At the time of RF3, Poseidon was the only manufacturer offering a Type R, eCCR. The following year, Hollis launched its Explorer rebreather, a smart eSCR, designed by Kevin Gurr, VR Technologies.

Table 6. The recreational rebreather - type R specifications

Cannot be assembled incorrectly
Will not operate without scrubber
Prompts for checklist
Self-calibrates O_2 sensors
Checks that gas is turned on
Turns on with immersion
Integrated bailout valve
Multiple warnings re: hazards
PCO_2 or scrubber duration warning
Functions to 40 m (130 ft)
Unit attempts to sustain life despite operator actions
And more....

Not surprising, given the high fatality rate associated with rebreather diving at the time, the initiative was controversial. In fact, Andrew Fock raised the question to the assembled participants (Menduno 2012) during a wrap up session at RF3. "*Given that rebreather fatality rates are 5-10 times that of open-circuit scuba*," postulated Fock, "*should we morally offer this technology to the recreational diving community before putting our house in order?*" There was silence as if no one wanted to tackle the question, then another participant took the stand and changed the topic. Eventually, Mark Caney, then PADI vice president of rebreather technologies, worked his way to the microphone and addressed his comments to Fock. "*Yes, we should*," he said. "*Within certain parameters.*"

However, over the ensuing years, the demand for recreational rebreathers did not materialize as predicted, and Type R initiative quietly faded from view. Evidently, the recreational diving community was not ready to make the move to rebreathers to any appreciable degree.

Perhaps the time for recreational rebreathers has finally come. Hollis reportedly sold approximately 1500 Explorer SCR rebreather before closing down the line in 2017 after being acquired by Huish Outdoors. Mares launched its own smart eSCR in 2019, aimed at recreational divers, offering training courses through its sister company Scuba Schools International (SSI).

Rebreather Bailout

While Stone first tested the efficacy of his redundant rebreather protype at his Wakulla Springs 1987 project, Swiss cave explorer Olivier Isler was the first to make a major push using a redundant rebreather bailout system in August 1990 (Figure 21). He used a triple RI2000 SCR in his crossing of the Emergence du Ressel (Doux de Coly, France), covering a distance of 1850 m (6070 ft) at a maximum depth of 81 m (266 ft). The following year, Isler went on to push through the 4000 m (2.5 mi) penetration barrier for the first time.

Figure 21. Olivier Isler at Doux de Coly 1990. Photo courtesy Olivier Isler.

Other explorers have also considered the concept. Welsh cave explorer and author Martyn Farr reported in his book, "The Darkness Beckons," that his German colleague, pioneering cave diver Jochen Hasenmayer, had experimented with a homemade dual unit he dubbed the Speleo-twin rebreather (STR-80) as early as 1981. However, it seems that Hasenmayer never used his system on any big dives.

There was little if any focus on rebreather bailout during the first 15 years of tech rebreather growth (1997-2012), rebreather divers relied almost exclusively on open-circuit bailout. But as explorers extended their range, they began to bump up against open-circuit bailout limitations. At RF3, Richard Harris explained to delegates why he and teammate Craig Challen were giving up on open-circuit bailout at Pearse Resurgence—it required some 28 cylinders each to bailout from a 220 m (718 ft) dive with 30 min bottom time. Instead, the pair planned to dive dual backmounted Megalodon rebreathers connected at the bailout valve—a configuration they still use today.

The introduction of sidemount rebreathers, beginning with the SF2 eCCR, and the KISS Sidekick in 2012, helped accelerate the move to rebreather bailouts. However, there was no simple, straightforward approach on how best to create and implement it. The Rebreathers and Scientific Diving workshop held in 2015 offered these observations in its workshop priorities, "W3 - Bailout strategies are complex and are specific to individual circumstances and available equipment" (Pollock et al. 2016).

Today, numerous exploration groups and individuals are using bailout rebreather configurations. These can be characterized (Pitkin 2023), as "symmetric" (eg, twin rebreathers of the same type), or "asymmetric" (eg, a backmount CCR with sidemount bailout CCR). In the pre-RF4 survey, 20% of respondents said that they had used or were using a bailout rebreather. An additional 15% or so (40-50 people), said that they planned to use a bailout rebreather in the future, when asked during the RF4 rebreather bailout session.

Note that RF4 participants were not unfamiliar with having to bailout from a rebreather. In a show of hands during the RF4 rebreather bailout session, approximately 70% of attendees indicated that they had bailed out at least once for real, and more than 50% indicated that they had had one or more caustic cocktails as a result of a loop flood.

Even so, a bailout rebreather is not a panacea (Covington et al. 2022). They add complexity, which has a cost, that must be balanced against the potential benefits/increased capacity. Nevertheless, the use of bailout rebreathers has grown significantly, and will likely continue to grow in the future (Pitkin 2023).

RF4 delegates recognized the importance of this trend and the need for further development, and accordingly, added it to the RF4 consensus statements as follows: "*Bailout Rebreathers: The forum identifies as a priority/goal the development and documentation of practices and/or monitoring for optimizing bailout rebreather use*" (Mitchell and Pollock 2023).

The Cutting Edge of Tech Diving

While Stone's 24 h dive at Wakulla Springs represented the inception of technical rebreather diving, Harris' 230 m (755 ft) hydreliox test dive arguably represents its cutting edge. The 13-h dive was the latest in an estimated 54 experimental hydrogen dives, the majority of which were saturation dives that have been conducted over the last 80 years by military, commercial, and technical divers. It was the first reported hydrogen dive made on a rebreather, in this case, dual Megalodons connected by the bailout valve—one charged with trimix diluent, the other with hydreliox (O_2, H_2, He). It was also the first known hydrogen dive conducted in a cave (Menduno 2023).

It has long been hypothesized that hydrogen might improve diving safety and performance on extremely deep technical dives. First, and most importantly, hydrogen can reduce the WOB, which is a major risk factor on deep dives (Figure 22).

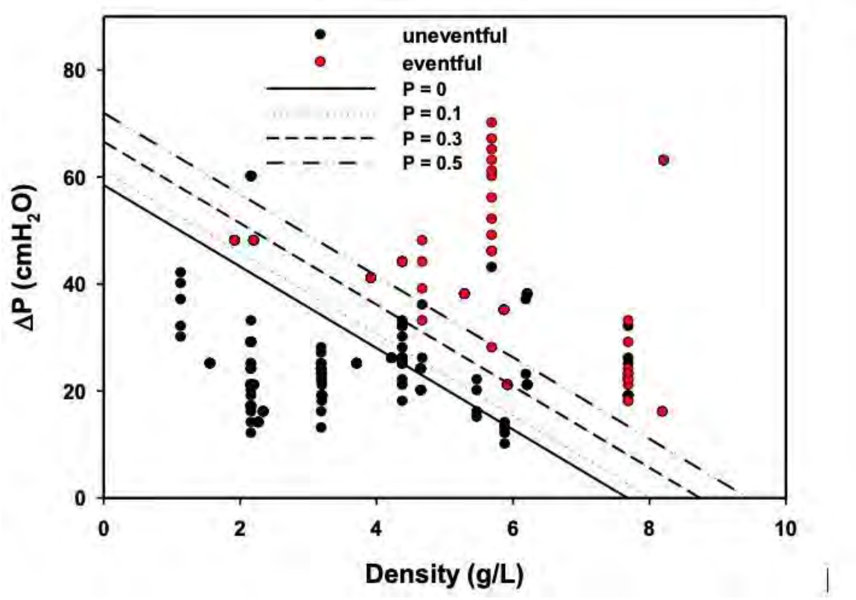


Figure 22. Peak-to-peak mouth pressure and gas density conspire to increase a diver's risk of an "event" during a dive (Clarke 2019).

At 250 m (820 ft), the gas density of trimix 4/90 (4% O_2, 90% He, 6% N_2) is 7.6 g·L^{-1}, significantly above the recommended maximum threshold of 6.2 g·L^{-1} (Anthony and Mitchell 2015). At 300 m (984 ft) the density soars to 9.1 g·L^{-1}, clearly in the danger zone in terms of WOB. Note, experts concluded that high WOB killed David Shaw, who suffered respiratory insufficiency during a 270 m (880 ft) dive at Bushmansgat (Mitchell et al. 2007).

Unfortunately, if you replace the nitrogen with helium to reduce gas density, the risk of high-pressure nervous syndrome (HPNS) increases, in part resulting from tech divers' rapid descent rates. It was likely HPNS that led to the death legendary cave explorer Sheck Exley at Zacatón (Hamilton et al. 1995).

With one-quarter the molecular weight of helium, hydrogen can reduce gas density to safe levels resulting in lowered WOB. For example, the density of hydreliox 4/30 (4% O_2, 30% H_2, 66% He) at 250 m is 4.6 g·L^{-1}, equivalent to breathing normoxic trimix 21/35 at 40 m. Hydrogen, which is narcotic at deep depths (PH_2 ≥15-20 bar), has also been shown to ameliorate HPNS, which is another major limiting factor at depth (Fogarty 2020).

There are a number of formidable challenges that must be addressed if self-contained hydrogen diving is to be possible, let alone successful. These include the real risk of fire and explosion both above and below the surface, respiratory heat loss—hydrogen has about three times the specific heat of helium and could lead to acute respiratory heat loss; its high specific heat also impacts scrubber efficacy, particularly in cold water. Then there is H_2 to He isobaric counterdiffusion, hydrogen narcosis, and the issue of decompression. It is a formidable list.

According to Harris, his dive demonstrated that hydrogen can be handled and boosted, that hydrogen is compatible with CCR diving, and that their strategy of introducing hydrogen on descent was successful, as was the flushing on ascent and reintroducing a high PO_2. Harris' decompression was successful, and importantly, HPNS and narcotic impacts were subjectively favorable (Stewart 2023; Figure 23).

Figure 23. Richard Harris at the entrance of Pearse Resurgence about to begin his hydrogen CCR dive. Photo courtesy Richard Harris.

However, Harris, who spent nearly two years planning the dive, remains cautious. "*In introducing hydrogen, we have addressed the issue of gas density, but we certainly have not established it is safe to use in terms of explosion risk, decompression, or the thermal hazards,*" Harris said. "*Fortunately, I evaded the nickname, 'Hindenburg Harry,' but it remains an ever-present risk.*" He warned people not to read too much into his successful dive. "*All we have shown is that we got away with it on one occasion. N=1.*"

If proven safe, hydrogen rebreather diving may well be enabling technology that empowers elite tech divers to continue to explore in the 250-350 m (820-1148 ft) range, depths that were almost unimaginable 35 years ago. It would open up new shipwrecks and caves that previously were out of reach.

Interestingly, Exley was once asked what he thought the ultimate tech diving limit would be (Menduno 1994). Not surprising, his response fully reflects tech diving ethos. "*There is no limit. We will always find a way to go deeper and deeper. That's been the pattern all along. Ten years from now, 20 years from now, people will be doing things we have never dreamed of, and I see no reason for it to change.*"

Conclusion

Though it is likely that only one in 10 technical divers currently own a rebreather, rebreathers represent the dominant platform for exploration and deep diving, and have greatly extended the range of technical diving since their introduction to sport divers in the late 1990s. Based on the latest market data, both the number of rebreather divers and manufacturers have doubled in the past 10 years. While most of the units in the field are backmount rebreathers, both sidemount rebreathers, and more recently front-or chest mount rebreathers have experienced a surge in demand. Many innovations have been realized, and patterns of use evolving as the exploration range has expanded, including the use of bailout rebreathers. Rebreather diving safety remains a critical issue, with incident rates similar to those of 10 years ago. Safety remains a work in progress in and for the technical diving community.

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QUESTIONS AND DISCUSSION

MARK CANEY: So at the next Rebreather Forum what would you like to look back on in 10 years and say we have accomplished, i.e., the positive things we have accomplished?

MICHAEL MENDUNO: The thing I go to first is the safety. It is what Sam Huss said. "We make our divers safer, so they can go deeper and stay longer." Clearly, we still have some challenges. I would like to look back and say we were really at an inflection point; rebreather diving has gotten a lot safer.

In: Pollock NW, ed. Rebreather Forum 4. Proceedings of the April 20-22, 2023 workshop. Valletta, Malta. 2024.

Hazards in Rebreather Diving

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Abstract

Closed-circuit rebreathers offer several advantages over open-circuit systems, but at a cost of increased complexity. While manufacturers have made great strides in improving equipment safety, this is enabling technology associated with greater risk than that of basic open-circuit systems. Core hazards include hypoxia, hyperoxia, hypercapnia, respiratory loading, gas supply, caustic ingestion, buoyancy management, decompression stress, and human factors. Rebreathers can expand the diving range, but they are demanding in design, training needs, monitoring requirements, and operation. Some issues cannot be engineered out, and some solutions can create their own problems. Users must accept responsibility for both risks and management demands. Ongoing commitment is required to maintain best practice, considering both collective experience and evolving knowledge to make changes when appropriate.

Keywords: accident, closed-circuit, decompression, health, incident, physiology, safety

Introduction

Closed-circuit rebreathers (CCRs) offer several important advantages over open-circuit systems, including far more economical gas use and the potential to optimize decompression. The cost of these benefits is increased complexity. Manufacturers have made great strides in engineering out failure points, simplifying the user experience, and improving reliability, but the maintenance and operational demands are greater, and the nature of the equipment as enabling technology can entice divers into potentially risky situations. The picture of true risk is still evolving, but a review of 181 deaths associated with rebreather diving estimated that the mortality rate was tenfold higher than that of open-circuit diving (Fock 2013). While not a comfortable finding, the evolution of equipment, training, practice, understanding, and awareness can all change the overall risk of engagement.

Core hazards related to rebreather use are summarized in Figure 1, including hypoxia, hyperoxia, hypercapnia, respiratory loading, gas supply, caustic ingestion, buoyancy management, decompression stress, and human factors. The agents commonly promoting or contributing to each are also depicted. Diving-related issues that can apply similarly to both open-circuit and closed-circuit diving are not included, for example, diver medical and physical fitness issues, barotrauma, narcosis, thermal stress (outside of decompression-related), and high-pressure nervous syndrome. Immersion pulmonary edema is mentioned since some of the risk factors can be augmented by some applications of rebreather diving. Although extreme exploration and extended range diving are now more likely to employ closed-circuit rather than open-circuit, factors such as diver rescue, evacuation, and in-water recompression are also not addressed.

The purpose here is to review the fundamental hazards specifically associated with rebreather diving, considering contributing factors, equipment solutions, knowledge gaps, and related issues that may influence risk and sometimes complicate or confound event analysis. The focus of literature citations is on work published since the Rebreather Forum 3 conference in 2012.

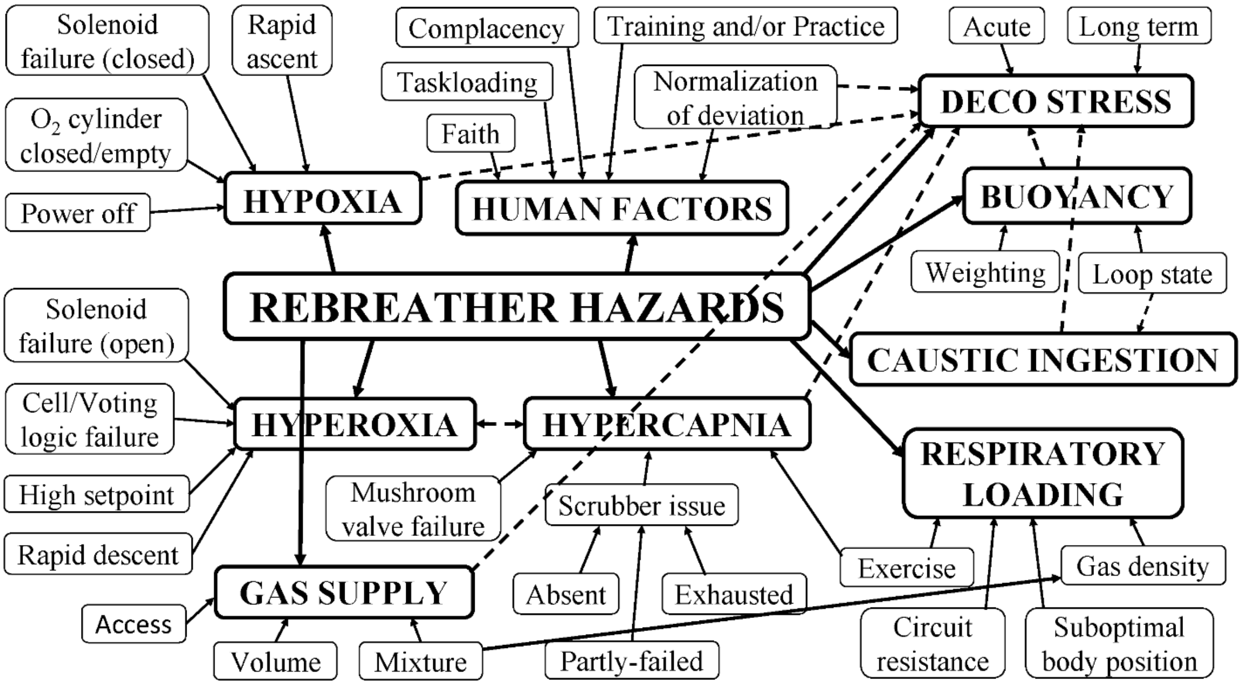

Figure 1. Summary of rebreather hazards and common or contributing factors. Primary relations between factors are indicated by solid lines; secondary relations between factors are indicated by dashed lines.

Hypoxia

Hypoxia is a major concern due to its potential as a life threat. Engineering design and information displays/alerts have made it much easier to avoid with reasonable vigilance, but they have not eliminated all problems. For example, it is possible for hypoxia to develop and be missed if power to a unit is off, if an oxygen cylinder is empty, if a solenoid valve fails in the closed position (in the case of electronic CCRs), or during rapid ascent. Timely recognition and corrective action is important to manage hypoxia (Popa et al. 2022).

The display systems used in current electronic rebreathers provide good information to divers on wrist displays, and increasingly on head-up displays. The industry standard is to provide hypoxia alerts - with a variety of color displays and audible alarms - when the oxygen partial pressure (PO_2) in the loop drops to 0.4 atm. This is a point with approximately twice the oxygen content of surface air conditions, which allows divers at least some time to evaluate and respond before an actual state of hypoxia is reached.

Hyperoxia

Hyperoxia is a major concern primarily due to the risk of incapacitation that accompanies seizures common to central nervous system (CNS) oxygen toxicity. Problematic hyperoxic conditions can develop if a solenoid fails in the open position, if there is a failure in cells and voting logic, if there is an excessively high oxygen setpoint, or if there is a rapid descent (particularly when accompanied by a high oxygen setpoint).

Close monitoring of cell displays provides the best protection. This requires divers to be mindful of normal and deviating patterns. Checks can be completed at appropriate depths with oxygen or diluent loop flushes, and cell voltages can be checked along with PO_2 value displays. A variety of strategies are employed to minimize the risk of multi-cell failures, often related to rotating schedules of cell replacement to avoid the possibility of single batch issues.

PO_2 setpoints are user-selected for most rebreathers. The choice is often made to strike a balance between decompression stress and the risk of oxygen toxicity (Figure 2).

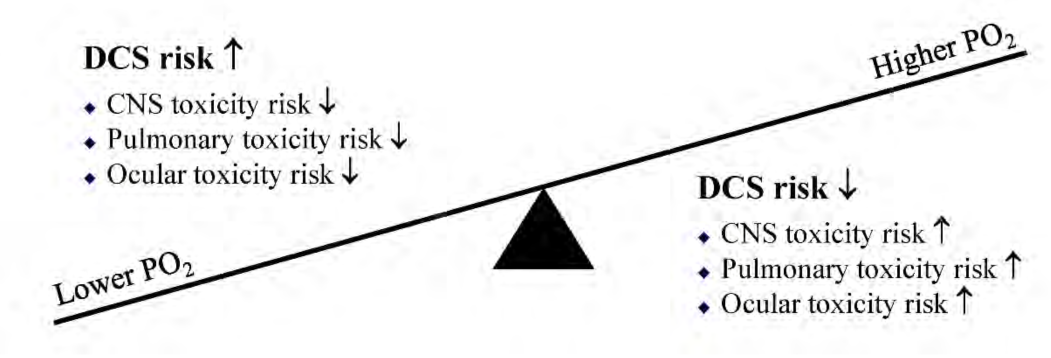

Figure 2. Risk balance schema for oxygen setpoint selection. High PO_2 offers both benefits and risks to divers. A reduction in decompression stress is balanced against an increased risk of oxygen toxicity. Acute oxygen toxicity risk climbs with PO_2 >1.4 atm. Oxygen toxicity risk is reduced by lower PO_2 levels (note that normal "low" PO_2 on a rebreather is still substantially hyperoxic compared to surface air).

Higher PO_2 is a greater concern at deeper depths when surviving a seizure is far less likely. The decompression benefit of high PO_2 is also reduced at deeper depths since the oxygen fraction is dramatically smaller than the inert gas share for any PO_2 setpoint. The greatest utility of high PO_2 is in shallower water when it plays an increased role in accelerating inert gas elimination (eg, increasingly <50 msw [165 fsw] with a PO_2 setpoint of 1.3 atm). Community practices continue to evolve, with a trend towards reducing extreme PO_2 values. As an example, the National Oceanic and Atmospheric Administration (NOAA) lowered the PO_2 limit during the working phase of dives from 1.6 atm to 1.4 atm in 2015. The 1.6 atm limit became an option only during the final shallow, resting phase of dives. The Canadian Standards Association (CSA) had been considering a similar change for several years, and quickly ratified it after the NOAA decision (Pollock 2019).

CNS oxygen toxicity is a chief life threat concern. While mild symptoms might appear initially, including muscle twitching and tunnel vision, it is also possible that no meaningful warning will precede loss of consciousness and/or seizure onset. While the risk of CNS toxicity increases with PO_2 >1.4 atm, the true risk threshold can be influenced by many factors. Absolute PO_2 is almost certainly the single most important factor, but the seizure threshold can be reduced by elevated PCO_2, by a variety of medications and drugs, and by a host of miscellaneous factors (Figure 3). Inter- and intra-individual variability complicate the risk assessment. It is a reality of funding limitations and societal prioritization that little research has been directed at evaluating the impact of medications or miscellaneous factors under the hyperbaric conditions experienced by divers.

Pulmonary oxygen toxicity is less of a concern with diving, but it can develop with multi-hour exposure to PO_2 >0.50 atm. Its symptoms of coughing, chest tightness, inspiratory discomfort, and retrosternal pain can also be confused with symptoms of immersion pulmonary edema, leading to the possibility of misdiagnosis.

The oxygen risk that is frequently not fully appreciated in the diving community is ocular toxicity. While the reversible visual changes are reasonably well known, the potential for irreversible promotion/acceleration of cataract formation is not. The limited data from repeated hyperbaric therapy exposures (Palmquist et al. 1984; Gesell and Trott 2007; Hagan et al. 2019) indicate that this is a potential risk for highly active rebreather divers.

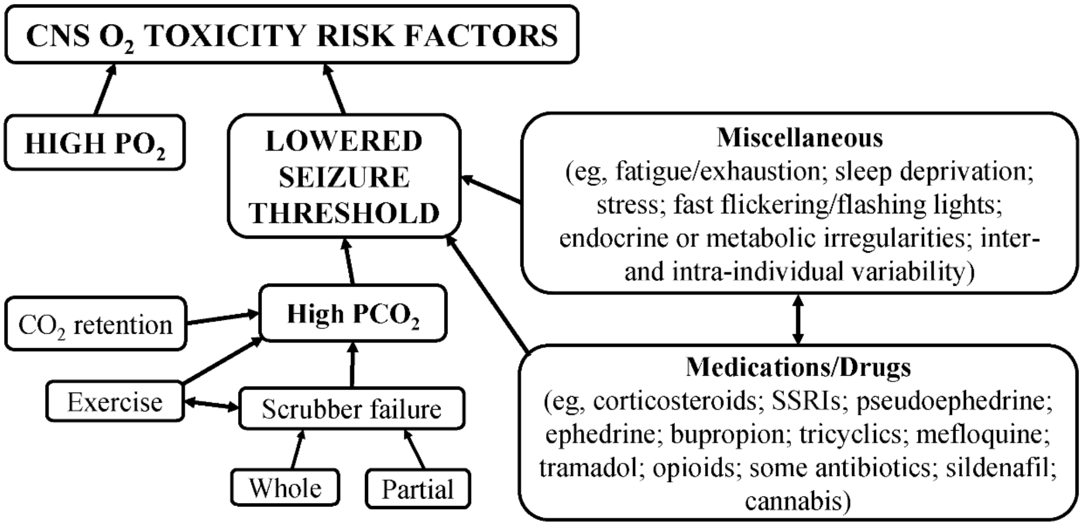

Figure 3. Central nervous system oxygen toxicity is primarily driven by elevated PO_2, but many factors can increase the risk by lowering the seizure threshold. Duration of exposure can also play an important role.

Hypercapnia

Hypercapnia is a core concern given the potential for altered (compromised) mentation and consciousness. Primary causal agents include mushroom valve and scrubber system failures. Mushroom valves are essential to ensure that gas flows in only one direction in the rebreather circuit, thus limiting the inspiration of expired gas before it travels through the scrubber assembly where carbon dioxide (CO_2) is removed. Checking the function of these valves is a simple but critical step in system setup.

Scrubber failures can develop in several ways and to differing degrees of effect. Total failures will occur if no scrubber is loaded or if the loaded scrubber is chemically exhausted. Partial failures can result from scrubber material that is close to being exhausted, particularly during periods of elevated diver workrate. It is also possible with some rebreathers for scrubber assemblies to be put together in an incorrect way that allows some gas to bypass the scrubber bed. An evaluation of a five-minute prebreathe found that 90% of subjects were unaware of CO_2 rebreathing associated with a partial bypass state, and 25% were unaware of CO_2 rebreathing associated with the absence of scrubber material (Deng et al. 2015). Prebreathes are important to check cell readings, solenoid activity, and PO_2 setpoint regulation, but they do not adequately assess scrubber function unless the unit is equipped with a temperature-based "Temp Stick" or similar apparatus (Silvanius et al. 2019) or with a functional CO_2 monitor. Temperature-based systems are proxy devices that do not measure CO_2, but they can confirm that the scrubber bed is present and active, removing at least some CO_2 through an exothermic reaction. Direct measurement of CO_2 is challenging in the humid loop environment since water vapor can be difficult to distinguish from CO_2. Hydrophobic membranes can isolate sensors from water vapor, but these must be periodically replaced and are susceptible to failure and subsequent risk of false positive signaling. New technologies in development will likely improve the reliability of direct CO_2 monitoring, but the release and implementation is slow. The best practice approach is to ensure that scrubber material is replaced at appropriate intervals (Harvey et al. 2016; Pollock et al. 2018; Gant et al. 2019), to take care in packing the scrubber and configuring equipment, and to heed the guidance of warning mechanisms.

Respiratory Loading

The potential for high respired gas density to impair, and possibly incapacitate, divers has recently become clearer (Anthony and Mitchell 2016). The circuit resistance inherent in any breathing system can be optimized through component design (eg, large bore, minimal sharp corners, and minimized resistive elements like scrubber beds), but the breathing gas mixture plays a role that becomes increasingly important with depth. Helium ($0.179\ \mathrm{g \cdot L^{-1}}$) is much less dense than either nitrogen ($1.251\ \mathrm{g \cdot L^{-1}}$) or oxygen ($1.428\ \mathrm{g \cdot L^{-1}}$), making increasing fractions of it desirable for deeper dives beyond just the reduction in narcotic potential. Problematically, gas density is not something adequately perceived by divers. Increasing gas density will compromise diver performance far before it will be recognized. Gas density is now appearing on some technical dive computer displays, and this trend should be encouraged. The best practice approach would be to have a real-time display on the home screen to remind divers of a hazard that could be missed. Gas planning is important, but the real-time reminder can be useful when limits are being approached.

Breathing gas mixture and depth will control respired gas density, but other factors can play a role in the overall work of breathing. Respiratory loading is not only influenced by equipment configuration, but also by diver orientation (trim) in the water. The relative positions of the mouth, lungs, and rebreather counterlungs influence respiratory effort independent of circuit resistance. Optimized trim is reinforced in rebreather training, but the assessment is subjective. Looking forward, the incorporation of an inclinometer into a rebreather head or other point with a stable relation to the diver's body position (not a more mobile handset or head-up display) could help to quantify diver trim. The information could be consolidated into simple scores viewed in real-time or reviewed as part of diver training and skill refinement. Such devices could also play a role in the forensic evaluation of diving accidents. For example, a sudden shift from a well-trimmed position to an upright position could indicate the start of a stressful event, and a sudden absence of change could indicate the point of incapacitation.

Gas Supply

There are several gas supply issues to consider. Gas selection involves balancing the hazards of narcotic potential, respired gas density, decompression stress, oxygen toxicity, and high-pressure nervous syndrome. Consideration must also be given to whether diluent and bailout gases are appropriate for part or all of a dive profile. Gas analysis is important to ensure that all gases are as expected.

The economy of gas use with rebreathers is a known strength, but the limited supplies sufficient for normal operation can quickly be depleted if adverse events develop. Gas use is substantially increased by diluent and oxygen flushes, and even more so by bailout to less economical open-circuit, especially when decompression obligations increase. Multiple bailout options may be necessary to ensure that appropriately breathable mixtures are available at all points of a dive.

Inefficient gas use to control buoyancy will primarily be a problem for novice users, but situations requiring circuit flushing or use of bailout valves (BOV) connected to onboard sources can quickly consume the normally limited supplies. Controlling drysuit buoyancy by plumbing into offboard gas will conserve onboard supplies, but will consume offboard supplies that might be important if bailout is required. The choice of gas plumbed into a BOV can be problematic if a single gas is not breathable throughout the entire dive. Switching the gas source supplying a BOV or using different bailout strategies at different points in a dive adds complexity, which could be problematic in stressful conditions.

BOVs are attractive for the ability to switch between closed- and open-circuit quickly, but planning is required to ensure the gas plumbed into them is both appropriate and sufficient. The dive profile determines when the gas can be used safely, and supply volume determines if it is sufficient solely for "sanity breaths" or as a definitive bailout option.

Bailout gas supply is a major consideration that can be underappreciated. Rebreathers commonly use a high PO_2 setpoint that accelerates inert gas elimination compared to typical open-circuit gases. It is easy to underestimate the gas supply needed to complete a dive on open-circuit, particularly in stressful conditions.

Decisions on how to carry bailout gas can also be challenging. While having an independent supply for each diver would be optimal, there are practical barriers for more extreme dives. The decision to rely on team bailout, where the collective group rather than each individual carries enough gas for a bailout event, may seem like a compelling alternative, but it is not without risk. Problems with team separation or multiple failures could render the available resources inadequate.

There is increasing interest in using bailout rebreathers in cases where adequate open-circuit bailout is difficult to ensure (Covington et al. 2022). While this may address many gas supply issues, there must be a high level of confidence that the bailout rebreather will be ready to function properly when needed. Additionally, it is possible that switching to another rebreather circuit may not address the concerns that prompted the need for bailout in the first place, such as problematically high respired gas density. Engineering solutions are likely to provide tools to monitor and maintain bailout loop integrity and readiness. The question of whether bailing out onto another rebreather circuit is the right choice will be more difficult to address. Training solutions need to be developed to ensure that divers adequately consider the positives, negatives, obligations, and implications of bailout rebreather use for different applications.

Ensuring reliable access to the right breathing gas at all points is critical. While BOVs typically offer the quickest switching, manual switching of mouthpieces may also be necessary. Manual switching requires easy removal of a current mouthpiece and reliable location, ease of deployment, and proper function of alternate mouthpieces. Seemingly simple steps can become less simple, such as in cold water when handwear can dramatically compromise dexterity.

There is growing awareness that mouthpiece retaining straps (MRS) can improve the chance of survival if a diver loses consciousness (Gempp et al. 2011; Haynes 2016). Water infiltration is still possible with an MRS, particularly if it is not appropriately secured, but a properly deployed MRS can help protect the airway for at least some time. Airway protection is also provided by full-face masks, but the MRS is less obtrusive and more easily overridden if required by the diver (eg, to manage vomiting). The rate of adoption of either system seems to be modest in the technical diving community. Some manufacturers are incorporating MRSs into units being sold, but broader adoption will likely require instructors and other leaders in the community to serve as advocates for and role models of their use.

Caustic Ingestion

Rebreather systems rely on scrubber material to extract CO_2 from the breathing loop. While effective, the material also poses a risk to divers due to its reactivity with water. If substantial water volumes reach the scrubber, a fulminant reaction can occur that will propel a caustic soda mixture (ie, a "caustic cocktail") into the inspiratory limb that leads directly to the diver. The priority action should this occur is for the diver to bail off the loop, either with a BOV or by switching to a different mouthpiece attached to a bailout gas. Modern rebreathers are constructed with a variety of water traps to minimize both the likelihood for and the volume of water reaching the scrubber material. Experience with caustic cocktails has been captured in a recent survey (Buzzacott et al. 2022), but little is known about the frequency or severity of events or the degree to which engineering solutions have reduced the risk. Best practice includes care in unit assembly, active leak checks, and readiness to bailout immediately when needed. An immediate flush with freshwater remains the best first aid for a caustic cocktail. Cases involving substantial exposure or any airway compromise should be evaluated medically.

Buoyancy Management

Buoyancy control is a well-known obligation in diving, but its complexities can be overlooked. Many divers focus on optimizing trim and minimizing the risk of inadvertent ballast loss and may ignore scenarios where ditching ballast would be desirable. Maintaining minimum ballast weight and optimized trim reduces physical effort and work of breathing issues, and retaining ballast is important for normal activities. There are situations, however, where jettisoning ballast may be appropriate, such as in shallow water when positive buoyancy is lost due to loop flooding or critical buoyancy system failure.

Divers should consider the need for minimum workload, good trim, ballast retention, rapid ballast removal, and buoyancy compensation redundancy. Ballast weight distribution can aid in trim and retention, but it will impede rapid removal. In the case of ankle weights, an unnecessary workload burden is also added that could become problematic in emergencies.

Unnecessary weighting should be avoided where feasible to minimize loading. The positive buoyancy that can reliably be provided by drysuits is quite modest (Covington et al. 2022), particularly if a diver moves into a vertical position when neck seals will release gas more easily. Planning to rely on surface marker buoys as a backup is also problematic. Even if they could provide sufficient buoyancy, the additional demands of deployment and management can pose challenges. Practically, having sufficient ditchable weight to compensate for the buoyancy that might be lost with a flooded loop is probably a reasonable minimum. Avoiding overweighting reduces the likelihood of having to simultaneously manage multiple buoyancy systems, and having at least some easily ditchable ballast could help in some emergent events.

Decompression Stress

Decompression stress is a core concern for diving, and certainly for technical diving. True safe physiological depth/time exposure limits may or may not equate to the guidance provided by any table or computer algorithm. Rebreather divers are likely to rely on dive computer-based algorithms, but it is critical to remember that they provide only a first-order approximation of risk; they get you in the ballpark with no guarantee of safety.

Dive computers excel at measuring pressure and time and making pre-programmed computations. While human testing has partially validated some algorithms, this typically covers only the shallow end of exposures. In most cases, the computations for deeper exposures rely on mathematical extrapolation with little or no human testing. Practically, while they assess important factors, a much wider array of variables can influence decompression stress (Figure 4; Pollock 2016).

The dive profile is the single greatest factor in decompression stress, but definitely not the only important one. The timing and intensity of both exercise and thermal stress can play dramatic roles in affecting safety. The best demonstration of the impact of thermal status was provided by work conducted at the US Navy Experimental Diving Unit in which 73 subjects completed a total of 484 decompression dives to 37 msw (120 fsw) with controlled exercise in a wet hyperbaric chamber (Gerth et al. 2007). The water temperature was manipulated separately in the descent/bottom and ascent/decompression stop phases of the dives. The two water temperatures were 36°C (97°F - "hot") and 27°C (80°F - called "cold" but more appropriately described as "cool"). The divers wore no thermal protection, so their skin temperature was effectively maintained ("clamped") at the water temperature. Tissue warming increased inert gas uptake and tissue cooling decreased uptake during the descent/bottom phase, while tissue warming increased elimination and tissue cooling decreased elimination during the ascent/decompression phase. It is the magnitude of the effect that is most impressive (Figure 5). The "warm/cool" combination yielded a 22% rate of symptomatic decompression sickness (DCS) with a 30-min bottom time. In stark contrast, the "cool/warm" combination allowed the bottom time to be increased to 70 min with only a 1% DCS rate. The "cool/cool" and "warm/warm" combinations were less problematic than "warm/cool," but still produced increased DCS rates compared to "cool/warm."

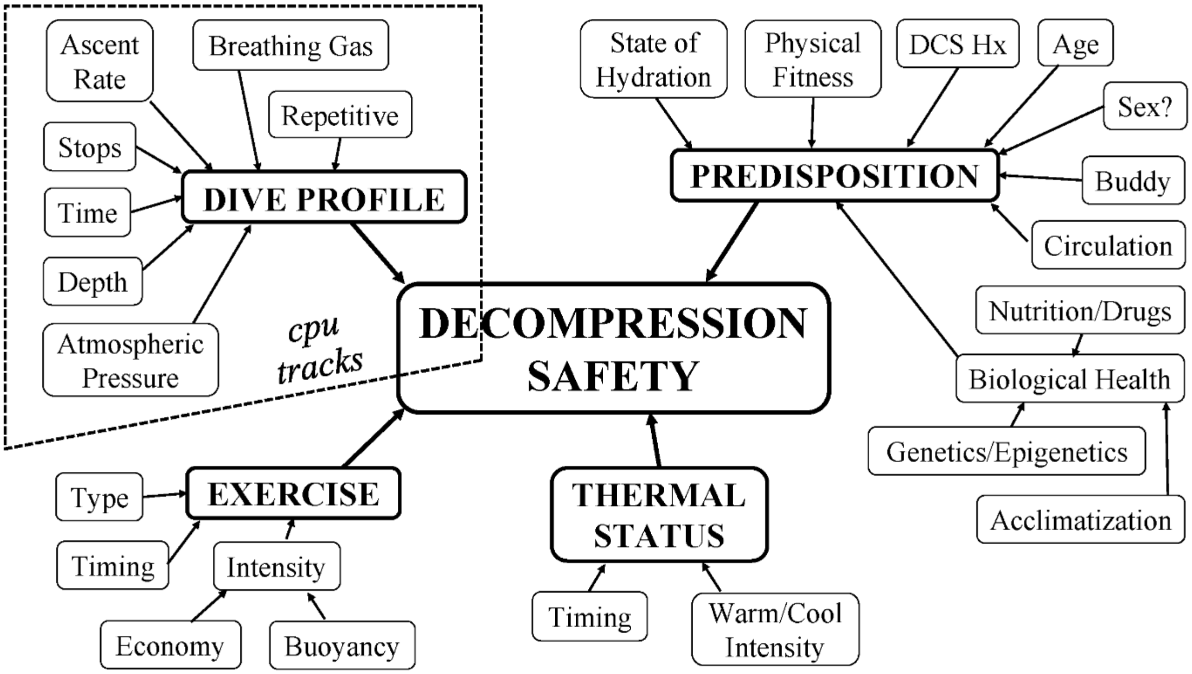

Figure 4. Factors in decompression safety. The dashed line indicates the factors tracked by dive computer algorithms. The remaining factors are not effectively captured or considered in any decompression models (Pollock 2016).

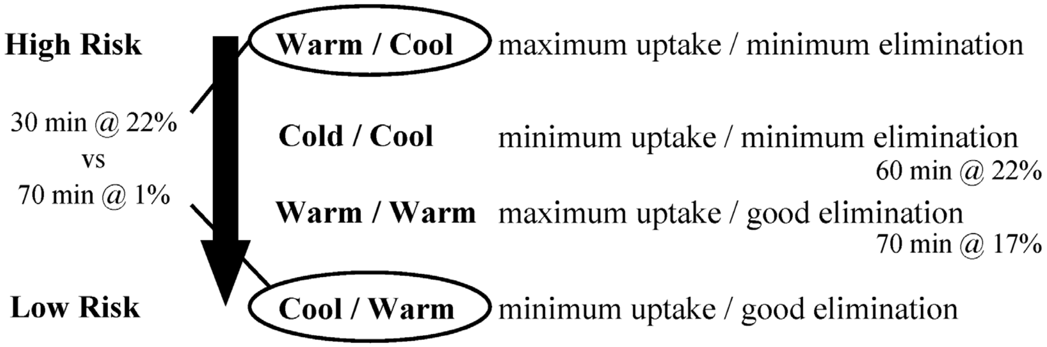

Figure 5. Thermal status and decompression stress in exercising dives to 37 msw (120 fsw) conducted in a controlled wet hyperbaric chamber. The maximum bottom times and percentage of subjects developing symptomatic DCS are presented for each of the four thermal combinations of descent/bottom and ascent/decompression phases (extracted from Gerth et al. 2007).

No current decompression algorithm incorporates the impact of thermal status or exercise in a meaningful way. Misleadingly, the water temperature displayed by many dive computers may have little relationship to the thermal stress or status of the diver and does not inform algorithms (Pollock 2024). Similarly, no "predisposition" factors (Figure 4) are integrated into decompression models as validated parameters. This could change in the future, but not the near future since it will require the development of new tools and the collection of a staggering amount of data to learn how to interpret highly nuanced regional thermal data in a valid way to produce effective personalized decompression models.

Decompression stress generates both acute and long-term risks, with the latter far less understood and appreciated than the former. For example, a diver who develops mild symptoms that resolve overnight may have dodged the immediate problem, but perhaps not the long-term consequences. The formation of white matter hyperintensities has been associated with a history of repeated decompression stress (Erdem et al. 2009; Jersey et al. 2013). While there is no direct link to symptoms and no diagnostic utility, this should encourage erring on the side of conservative practice.

The formation of lesions primarily found in long bones was observed in early caisson workers and in commercial divers (Uguen et al. 2014). The problem tends to develop slowly, sometimes decades after exposure. A surveillance program initiated with North Sea commercial divers identified three primary predisposing factors: a history of dive depths >50 msw (165 fsw), a history of inadequate or experimental decompression, and a history of DCS. While changes in practice have reduced the risk for commercial divers, the predisposing risk factors suggest that this is likely a real hazard for deep technical divers. A single case report involving a technical diver has been published (Coleman and Davis 2020), and it is possible that patterns of imprudent diving will result in many more cases in the future.

A prospective longitudinal study of professional diving students found that a history of DCS was associated with more neuropsychiatric symptoms at 12-year follow up (Bast-Pettersen et al. 2015). Similarly, a retrospective study of retired Norwegian commercial saturation divers found that those with a history of DCS had more neurological findings when tested years later (Sundal et al. 2022). The first study had a small sample size and the second was subject to recall bias, so more work is required to confirm if a history of DCS can reliably be associated with measurable deficits later in life, but the possibility does encourage a cautious approach to diving.

Computer models can be informative, but they should not be confused with truth. It is a reality that current mathematical models do not equal or fully explain physiology. Given the uncertainties discussed here, it is important that divers build in reasonable buffers to avoid both acute symptoms and insults that can develop over time. Many dive computers, certainly those intended for technical diving, allow some degree of user-selectable conservatism settings. Problematically, the impact of "conservatism settings" is not consistent and some may act in ways that do not increase safety.

The "M-value" was developed as a theoretical limit representing the maximal supersaturation that a "compartment" (a mathematical representation of a tissue) could tolerate before bad things happen. Different M-values can be assigned to different compartments. "Bad things" include the formation of decompression-induced bubbles and symptoms of DCS. Ultrasound data and additional research experience have made it clear that the bad things can still happen within the M-value limits. While M-values have been adjusted in some algorithms, they remain theoretical constructs, not true safety limits.

The most common decompression algorithms employed for technical diving computers are the Bühlmann model, the varying permeability model (VPM), and the reduced gradient bubble model (RGBM). The Bühlmann gas content model was derived mathematically and revised through substantial human testing. The VPM and RGBM bubble models were mathematically derived with minimal human testing, and in some cases adjusted over time to address observations of weak points.

User-selected conservatism settings are allowed by many dive computers. Gradient factors (GF) were developed to be applied to the Bühlmann decompression algorithm, effectively allowing for percentage-based mathematical reductions from the defined M-value limits. Conceptually simple, they allow divers to have their computers display altered limits to match their risk tolerance and understanding. Gradient factors are defined by two numbers. The first (GF_{low}) determines the percentage of the M-value that drives the first decompression stop during ascent. The second (GF_{high}) determines the percentage of the M-value not to be exceeded at any point during the subsequent surfacing (Pollock 2015). GF_{low} is only relevant during decompression dives, while GF_{high} will adjust limits during both decompression and no-decompression dives.

The conservatism settings created for bubble models are less straightforward to interpret. Bubble models favor the addition of deeper stops with a goal of controlling bubble formation. While higher conservatism settings do require longer shallow stop time, they are paired with increasingly deeper initial stops, where any unsaturated tissue will continue to uptake inert gas that must subsequently be eliminated. The pressure gradient at depth can be sufficient to result in substantial loading that may not be sufficiently offset by the time spent at shallower stop depths. The deep stop approach has been shown to worsen decompression outcomes (Blatteau et al. 2005; Gerth et al. 2009; Doolette et al. 2011). Table 1 displays the decompression profiles for a cross-section of GF and VPM-B conservatism settings following an arbitrarily selected 20 min bottom time at 70 msw (230 fsw).

Table 1. Comparison of decompression stop depths and times required by the VPM-B algorithm across six conservatism levels and by the Bühlmann algorithm across six gradient factor combinations. The dive was to 70 msw (230 fsw) with a 20 min bottom time, using an electronic closed-circuit rebreather with a PO_2 setpoint of 1.3 atm and diluent gas of trimix 15/60. The decompression schedules were produced by a Shearwater (Vancouver, BC) dive planner implementation of the models.

Stop depth	**VPM-B levels of conservatism**						**Buhlmann gradient factor samples**					
m (ft)	**0**	**+1**	**+2**	**+3**	**+4**	**+5**	**20/85**	**30/85**	**30/70**	**40/70**	**50/70**	**70/70**
6 (20)	20	21	22	25	28	29	30	30	36	35	35	35
9 (30)	5	6	6	6	7	7	6	6	8	8	8	8
12 (39)	4	4	5	5	4	5	5	5	6	6	6	5
15 (49)	3	3	3	4	5	5	4	4	4	5	4	4
18 (59)	3	3	3	3	3	3	3	2	4	3	3	3
21 (69)	2	2	2	2	2	3	2	3	2	2	2	2
24 (79)	2	2	2	2	2	2	2	1	2	2	2	2
27 (89)	1	2	2	2	2	2	1	2	2	2	2	1
30 (98)	1	1	1	2	2	2	2	1	2	1	1	
33 (108)	2	1	1	1	1	1	1	1	1	1		
36 (118)	1	1	1	1	1	1	1	1	1			
39 (128)		1	1	1	1	1						
42 (138)					1	1						
Total time	**48**	**51**	**53**	**58**	**62**	**65**	**61**	**60**	**72**	**69**	**67**	**65**

Divers Alert Network conducted a multi-year observational study effort named "Field Dive Monitoring" using two-dimensional echocardiographic imaging to identify decompression-induced bubble formation patterns in technical diving, for which few data were available. Monitoring was typically conducted on liveaboard technical diving trips to minimize external influences more prevalent with shore-based activities. Divers were able to see each bubble scan and were free to adjust their conservatism settings and profiles as desired on any or every dive. The lack of control over subject conservatism selections and dive profiles made the data difficult to use for hypothesis testing, but many insights emerged (Pollock 2016). Marked differences in bubble formation were seen between divers on similar dives, with some appearing to be relatively bubble-resistant and others more bubble-prone. The effect of adjusting conservatism settings also varied between divers but was usually more consistent with GF changes. While the range of absolute GF settings used was limited, a decrease in GF_{high} from 85 to 70 tended to reliably decrease peak bubble grades for divers prone to bubbling. Similarly, $GF_{low} <30$ was associated with higher bubble scores (unpublished data). The impact of changes in bubble model conservatism settings were much more difficult to predict, with higher levels of "conservatism" not consistently associated with lower bubble scores.

Human Factors

Human factors represent an important core concern for diving safety. Task loading is a particular problem in rebreather diving, with much to monitor and manage during dives. Additional tasks or distractions can compromise critical attention. It is common for people to anthropomorphize and say that rebreathers are trying to kill divers (or protect them), but the reality is that rebreathers do not care one way or another. It is up to the diver and team to make sure that equipment is set up and used properly and that operational decisions are smart ones.

The reliance on equipment and practice is intrinsic to rebreather diving. Consistency and best practices can be protective, but unquestioned faith or complacency regarding equipment performance or practice efficacy can also create substantial risks. Drifts in practice, usually away from the optimal, can also be problematic. Normalization of deviation is an ongoing concern. The first time a diver violates a rule can be stressful, but the second and third time will most likely be less so, and at some point the violation practice can become the new normal. It is common for divers to think about their best behavior ("best self") as the "normal" case, even if they have drifted far away from best practice. Drift or mission creep can develop as comfort grows, over both short and long terms, often resulting in a host of more aggressive decisions and actions, either conscious or unconscious.

Training and vigilance to ensure a rigorous focus on best practice is important to minimize drift and manage risk. Human factors can include many efforts to reduce risk and the errors, omissions, miscalculations, and poor decision-making that can increase hazard. Small problems are inevitable, and they are sometimes helpful as reminders of the need for greater care, additional training, or modifications of practice. An honest and ongoing self-evaluation of performance and an openness to meaningful improvement are critical. Success requires objectivity and a resistance to ignoring or hiding issues for convenience or because of a sense of embarrassment or bruised ego.

One of the labels that is rarely warranted in describing decompression-related injuries is "undeserved." Water is an unforgiving environment for air-breathing organisms, and increasing depth makes DCS and other hazards clear possibilities. Events may be unexpected, but that is more a reflection of the failure in foresight and planning than anything close to being undeserved. A critical component of objective evaluation is the diligent rejection of efforts to shift blame from where it should rest. This can start with a simple question of "What would I think if I heard the same details relating to someone else?"

Equipment problems are often blamed on manufacturers, but in most cases diver maintenance of equipment plays a pivotal role. The most obvious issue with rebreathers is oxygen cell replacement. The cost is sufficiently high that divers want to get as much time out of them as possible. The problem is that all cells will fail, and timely replacement is the best way to avoid it happening. This is very much a "best self" human factors issue, struggling between what is right and what is wanted. The old saw is that anyone wanting to dive rebreathers should be asked if they have ever run out of gas while driving and, if they answer in the affirmative, they should be disqualified. This is a harsh position, but gets to the importance of monitoring vigilance. Another question for the potential rebreather diver is whether they are willing to commit to manufacturer-scheduled replacement of all cells as long as they operate the unit. It is a fundamental problem if this commitment cannot be made.

Rebreathers require more effort and attention in setup, operation, breakdown, and maintenance. Divers must be sure that they are willing to commit to all to use the equipment. If not or when not, open-circuit offers a great option to continue diving with fewer demands. Knowing when not to transition to and when to transition away from rebreathers is important. Thoughtful divers will hopefully guide their own evolution appropriately, but these are issues for which partners and teammates may have to encourage honest reflection.

Interactive and Potentially Conflicting Effects

Risk factors can act independently, but many accidents are fueled by a cascade of events. Single issues that would typically be easily managed can reach a breaking point when combined with other complications. Planning is often focused on individual points of failure, but consideration must be given to potential event chains. Practice is important to maintain and improve physical readiness, with additional "what if" planning to help prepare for more complicated scenarios.

Problems should be considered from the points of view of the agents causing them, the impact of them, the solutions for them, and the consequences of the solutions (positive and negative; intended and unintended). Consideration should be given to any knowledge-, practice-, or equipment-based gaps that might be eliminated to better address issues. Caution is required to ensure that any perception of hazard or solution is well grounded in reality.

One of the things often espoused as a risk factor for DCS is dehydration. It is certainly possible that a state of dehydration could impair circulation and the orderly elimination of inert gas, but dehydration has become a scapegoat that can detract from a more objective evaluation of events. It is important to understand that fluid shifts that appear as "dehydration" may result from DCS rather than cause it. Ultimately, reasonable levels of hydration should be maintained for both general health and decompression safety, but excessive hydration should be avoided since it is one of the risk factors for immersion pulmonary edema.

Deep stops are another example of a well-intended "solution" going awry. As discussed earlier, deep stops were intended to control bubble formation, but the concept moved into counterproductive extremes. Stops are too deep when they are conducted at depths where bubble formation is unlikely to occur but substantial uptake of inert gas by any unsaturated tissue will continue. Without sufficient additional shallow stop time to compensate for the greater uptake, the decompression risk increases.

The warning of "hypoxia" at a PO_2 of 0.4 atm is intended to give a diver time to react before a state of hypoxia is reached (PO_2 <0.2 atm). The warning is extremely important, but so is the reminder that it is designed to provide a period of grace for smart decisions to be made. A moment of thought can help to maintain calm and avoid precipitous responses that could create other hazards.

Many problems are addressed by engineering solutions, but it is essential that divers understand both the purpose and limitations of solutions to avoid compromising their safety. Added complexity may introduce new protections but possibly also new failure points and new demands on divers. Careful consideration is required before making changes, with ongoing review an important part of any implementation. While an unbridled acceptance of every new thing should be avoided, an unjustified resistance to making well-founded changes to enhance safety should also be a cause for concern.

Risk Management

The risks of underwater diving, and particularly rebreather diving, will never be eliminated, only managed with acceptable margins of safety. There will often be more than one solution to a problem, and there can be differences in impact, efficacy, and related or created risks that will vary situationally. Both consistent practice and well-informed flexibility can be useful in real-time situations. Many events will differ in varying degrees from those planned for. Incremental changes in practice are often best for advancement, with the ultimate risk:reward matrix constantly being re-evaluated. Small safety buffers applied to a variety of parameters can substantially increase overall safety, and a true commitment to safe practice is necessary to avoid compromise by very normal human failings. Critical, objective evaluation of both knowns and unknowns and a healthy respect for limitations are important to prepare for and minimize hazards. An inability to quantify risks should not be equated with a lack of knowledge, nor as a justification to ignore risks. Conceptual hazards and relative risks should be considered as part of risk management, with as few lies as possible folded into the process.

Adverse events should be acknowledged and shared so both the local and the broader community can learn from them. Some may serve as a simple reminder to pay attention to established standards, but others may prompt modifications to equipment, training, practice, or drive additional research. Continuing education and community engagement can help divers ensure best practice and awareness.

Conclusion

Rebreathers can expand the diving range, but they are demanding in design, training requirements, operation, and maintenance. Users must accept responsibility for both risks and management demands. Engineering solutions have addressed many shortcomings and reduced some challenges, but not all. Some issues cannot be engineered out, and some solutions can create other problems. Ongoing commitment to safety is required to maintain best and appropriate practice, considering both collective experience and evolving knowledge to make measured changes when appropriate.

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QUESTIONS AND DISCUSSION

KENNETH BLAKELY: Can you describe how you induced partial failure of scrubbing in your prebreathe assessment study?

NEAL POLLOCK: The partial failure was achieved with an AP Evolution rebreather by leaving the spacer and the O-ring out of the scrubber canister assembly. This allowed some gas to travel on the outside of the scrubber, thus bypassing scrubbing. The results are in the Deng et al. (2015) paper.

KENNETH BLAKELY: One more question. When you say the term central nervous system O_2 toxicity, are you referring exclusively to seizures?

NEAL POLLOCK: Not exclusively, but seizure is the most powerful outcome and the primary focus. You can have a mild movement towards toxicity that may be perceived, such as some tingling or muscle twitching, but the primary concern is seizure. It can be a short path between high levels of inspired O_2 and the start of a seizure.

DAVID DOOLETTE: I have a follow-on question from that. Getting back to the oxygen toxicity slide that you showed from Arieli's work, I am not that familiar with the later paper, but I know that data for the 2006 paper came from self-reported, often non-specific, symptoms. I think, for instance, headache was much more common than any of the more specific symptoms. I was struck by the short amount of time for the 2.5% risk isopleth at 1.3 atm and wanted you to comment.

> [Arieli R, Shochat T, Adir Y. CNS toxicity in closed-circuit oxygen diving: symptoms reported from 2527 dives. Aviat Space Environ Med. 2006; 77(5): 526-32. PMID: 16708533]

NEAL POLLOCK: That is a good point. Both of the most common symptoms - headache and difficulty in equalizing - were non-specific, as were several others. As an added weakness, the 2020 paper appeared to include repackaging of some of the same data. It is not particularly compelling.

> [Arieli R, Aviner B. Acclimatization and deacclimatization to oxygen: determining exposure limits to avoid CNS O_2 toxicity in active diving. Front Physiol. 2020; 11:1105. DOI: 10.3389/fphys.2020.01105.]

DAVID DOOLETTE: I agree with your point. It is something to be considered, but I just thought those times were really short.

NEAL POLLOCK: Yes, we are probably looking at the margins of effect. There is no single consistent threshold. The key concept is that rising PO_2 will likely be associated with an earlier onset. I would not have much confidence in specific times since associated factors can alter the risk. The data must be interpreted cautiously.

DAVID DOOLETTE: I agree with you, we are not going to get to exercise or thermal inputs to decompression models by Rebreather Forum 5. The US Navy has some pretty good data and probably better than we will ever get in the field, and I cannot make much of it.

NEAL POLLOCK: Indeed. Thanks.

CHRIS PRESS: I spent a fair bit of time picking up British divers in the acute phase, in the first 15 or 30 min of injury; British recreational divers who, as you say, are often of a certain age and well naturally insulated against a cold environment. It makes it very difficult to pull apart the cause-effect medical immersion pulmonary edema, pulmonary edema as a result of pressure shifts and panic, and things like that. The answer to this may not be quantifiable. Do you have a sense of incidence of causes of critical illness in technical divers? How would you rank them? Because once I put people in a helicopter, there is a limited amount that I can do. Being able to predict the cause is very helpful to me. What are the incidences of the various causes? Do you have a sense of that at all?

NEAL POLLOCK: Meaningful incidence data are difficult to come by. We know there are a lot of causal agents and/or contributing factors, but the clustering of factors makes it difficult to separate them. It is clear that the likelihood of medical compromise goes up with age, decreased physical fitness, and suboptimal body habitus. Quantification, however, is very difficult.

JARED HIRES: I had a question about hypoxia from the beginning of the presentation. You said that there was a knowledge gap around the 0.4 atm buffer. What do you think that knowledge gap is and are you advocating for people to maybe stay on the loop and troubleshoot?

NEAL POLLOCK: I am advocating that people do not overreact without thinking. The 0.4 atm threshold for hypoxia warning comes in advance of hypoxia. I am not saying you should stay on the loop if there is a reason to get off it, but the move may not have to be rushed if the warning signal is your only concern. My concern is that an excessive drive to respond to warnings could lead to rash action. We have some people who take training with little understanding of physiology. I am concerned about a hyperfocus on a threshold that is still in a very safe, breathable, hyperoxic range. The rate of decline is important, but a PO_2 of 0.4 atm is not a threshold for an instant life threat. It is important to make sure that all divers have sufficient understanding to make good decisions.

RACHEL LANCE: I have a question, but first I am going to make a follow-up comment to that. I have intentionally put divers on failed rebreathers. And from 0.4 atm, at least on an Innerspace Megalodon with a 3.6 kg (8 lb) scrubber, which provides a larger than usual gas volume, you have about 2 min to risk of loss of consciousness. So, no, you do not have to get off the loop immediately at 0.4 atm, but if it is still falling you should plan to get off within about 2 min. My question regards a comment you made about some asking why a PO_2 of 2.8 atm can be handled in a hyperbaric chamber but not for in-water activity. I understand you are not advocating for it, but I wondered if you have a sense for how strong that push is.

NEAL POLLOCK: I did not say there was a push, just a point of question. Some divers have asked questions along the lines of "If they are doing that in chamber treatments, why are lower PO_2s of concern for us?" This may come from discussions over the general shift away from the 1.6 atm PO_2 limit. The increased conservatism concerning oxygen limits may not be felt to be necessary by those who have not had problems with it.

RACHEL LANCE: I was just wondering how strong the question of the divers was.

NEAL POLLOCK: It varies. My point was that PO_2 limits and guidelines should be discussed to ensure that hazards and best practices are fully understood. We need perspective in addressing both hypoxic and hyperoxic ends of the extreme. The goal is to ensure thoughtful practice and to avoid excessive or potentially panicked responses.

ALEJANDRO GARBINO: You talked about hyperoxia and addressed physiological monitoring. On the decompression side, venous gas emboli are a proxy to assess decompression stress. Do you know of any measures or tools that can be used to explore hyperoxic limits without actually inducing seizures underwater?

NEAL POLLOCK: That is a tough one. There have been a lot of studies of oxygen toxicity, but few with simple results. It is also difficult work to do with humans because of the ethics of potentially inducing seizures so, no, I do not have a good solution. I think that chamber data cannot easily be matched to the more complex natural diving environment. We need to collect the data we can from both chamber and open water diving to get a better handle on thresholds, patterns, and potential contributing factors.

ALEJANDRO GARBINO: Agreed.

NEAL POLLOCK: I think we need to do a better job of capturing reports on when people do have oxygen-related problems. I think our best source of data is going to be a more comprehensive capture from the community. We can do a better job of capturing cases and documenting details to gain insight. It is a curse that most diving-related case data tends to be incomplete, especially in fatal events.

DAN REYNOLDS: My colleagues and I have spent a substantial chunk of our lives trying to engineer out problems like hyperoxia and to improve sensors for detecting hypoxia and hypercapnia. I wonder what proportion of mishaps is due to equipment failure or despite equipment failure.

NEAL POLLOCK: Our data are, unfortunately, incomplete. We often cannot fully tease apart complex situations in fatal events. Similarly, if people have failures that do not end up with really problematic outcomes, we will rarely hear of them. We can gain important insights from global numbers and single events for which comprehensive information is available, but proportion questions are more challenging.

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Closed-Circuit Rebreather Accident Review – The Safety Situation

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Abstract

Recent data suggest that most closed-circuit rebreather (CCR) divers are male (84–95%), 42–46 years of age, and have been certified for six years, with a median of 200 CCR dives. Assessing the number of active rebreather divers is difficult. DAN's fatalities database relies on DAN resources, public resources, and individual reports. Over the past 10 years, the number of certified CCR divers has increased from an estimated 2000 in 2013 to 3000 in 2022. There has been an increase in growth in the CCR sales market over a five-year period from 2018, with around 25,000 to 35,000 units on the market today; rebreather divers are a growing community. There were 241 confirmed CCR fatalities from 2013–2022, 24±6 (mean±SD) per year. Most fatal accidents reported involved dives made between 40–80 m (130–260 ft) depth. Cause of death is difficult to establish due to lack of detail and dive-specific training for the medical examiner. The estimated death rate is 1.8–3.8 deaths per 100,000 CCR dives and appears to have fallen in recent years. DAN continues to collect CCR data, aiming to increase the amount of information collected and to improve its quality to allow more accurate reporting.

Keywords: accident, death rate, demographics, fatality, global use, rebreather

Introduction

This paper presents an overview of the global use and safety of closed-circuit rebreather (CCR) diving equipment. The topics covered included CCR diver demographics, a review of fatalities since Rebreather Forum 3 (RF3) took place in 2012 (Vann et al. 2014), and a description of the state of the CCR market. The challenges of incident and accident investigation were discussed, then leading on to the future of rebreather safety.

Diver Demographics

Data sourced from the DAN hotline, the RF4 participants' survey, and the caustic cocktail survey (Buzzacott et al. 2022) show that the reported age of rebreather divers was 46±10 years (mean±SD), with 84–95% of participants being male. The length of time that a CCR diver had been certified was 6 (3,12) years (median [interquartile range]), with 40% being certified for less than five years, and 10% for more than 20 years. The median self-reported dive experience was 200 (100, 500) CCR dives, with 300 (120, 750) hours clocked on CCR equipment. The certification time and experience for RF4 participants was almost twice as high, which is not surprising given the specialization of the audience.

CCR Divers Contacting DAN

Divers contact DAN to ask for information on diving with a CCR and to log accident cases, which entail emergencies. Figure 1 details the types of calls made to DAN from January 2013 through December 2022.

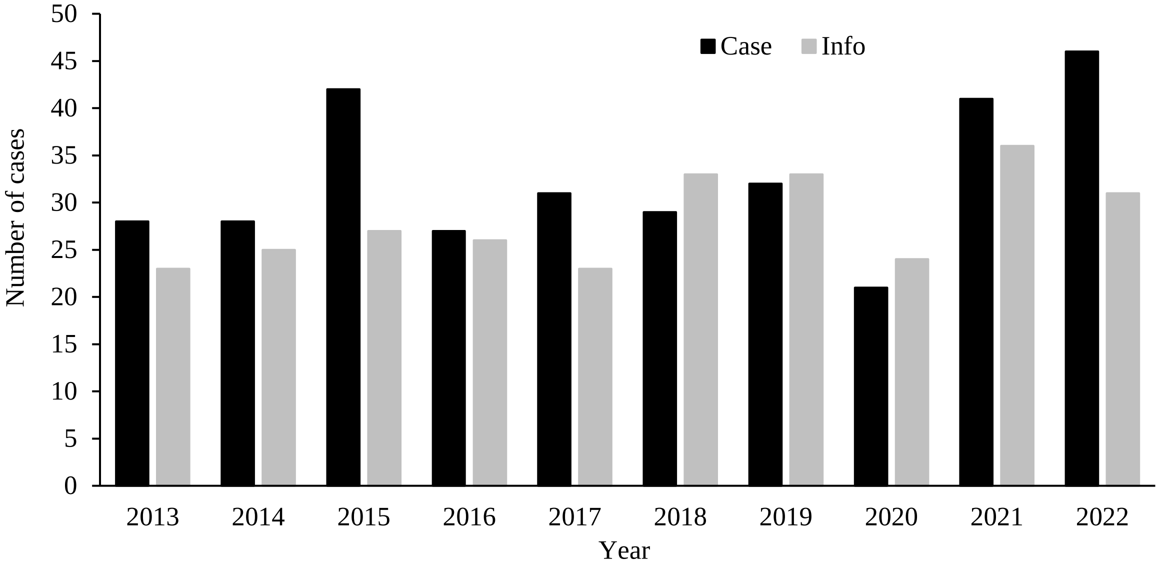

Figure 1. CCR divers contacting DAN (n=325 emergency cases, n=281 information requests).

Little had changed since RF3 with regards to the sex and age distribution of CCR divers contacting DAN. The majority of the 319 phone calls and email inquiries for which sex and age was reported were made by men, with only 48 female inquirers (Figure 2). The age distribution of the callers was centered around those 50–59 years of age.

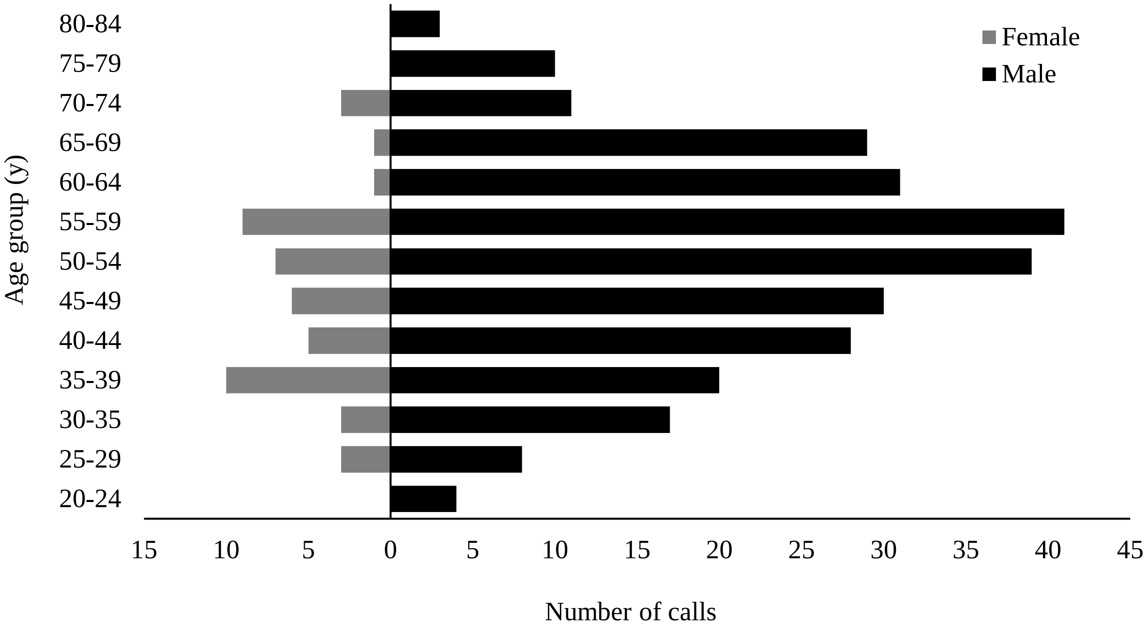

Figure 2. Distribution of emergency calls and information inquiries by age and sex where disclosed; calls made between January 2013 through December 2022 (n=319).

The differential diagnoses obtained from the emergencies are often of greater interest. DCS involving pain comprised ~27% of the cases reported, while more severe neurological DCS made up ~19%, and anxiety caused by the worry of DCS and later diagnosed as such (rather than the originally attributed

DCS) accounted for around 17% of cases (Figure 3). Barotrauma of varying types formed several differential diagnoses, the frequency of CCR-derived barotrauma being relatively comparable with other forms of diving (Figure 3). Trauma, loss of consciousness, and neurological complications made up the rest of the categories reported (Figure 3).

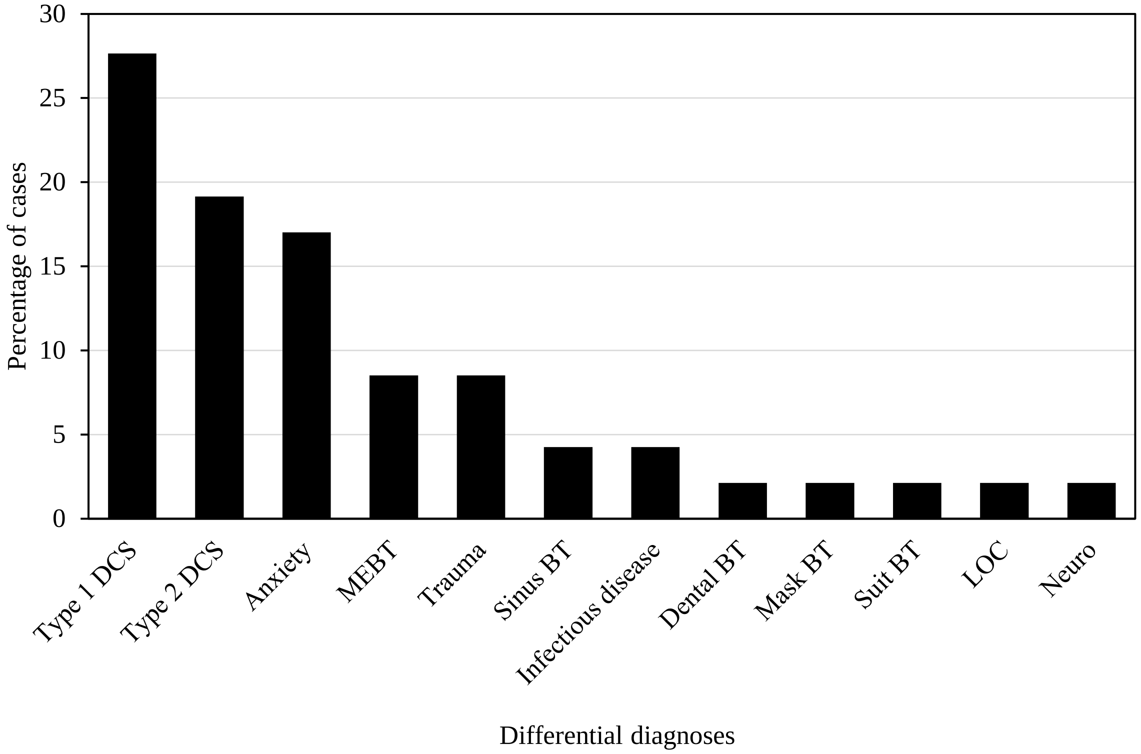

Figure 3. Differential diagnoses of DAN CCR emergency calls taken from a sample November 2021 through March 2023 (n=47). BT, barotrauma; DCS, decompression sickness; LOC, loss of consciousness; MEBT, middle-ear barotrauma; Neuro, neurological manifestation.

Fatality Review

What Data are Available?

Although it might be expected otherwise, there is a paucity of fatality data available, with most collected from insurance claims and the emergency calls received by DAN America and DAN Europe. DAN conducts a fatality surveillance project, scanning media and news outlets for possible fatalities, then following up the primary information to collect further data from medical reports, investigation reports, and witness statements, when available. Equipment experts who examine rebreathers used in accidents may also forward information. Internet databases, such as 'The deep life list' are useful to compare with the DAN fatality database to check for any cases that might have been missed. Finally, individuals who have expertise in CCR, for example, manufacturers, training agencies, diving physicians, and pathologists occasionally call with information that they feel would be useful to share. Once all of these data were collated and merged, duplicates were identified and removed. Verification of the incident followed. Once the database was consolidated (Figure 4) a final tally was obtained; from 2013–2022 there were 241 verified CCR fatality records captured.

Limitations to collecting and verifying the data include a hesitancy to share information by family or friends, language barriers, legal restrictions (for example, in Australia case data is released only 5 years post-accident), the time and effort needed for follow-up, data reliability, incomplete information, third-hand information, and conflicting information.

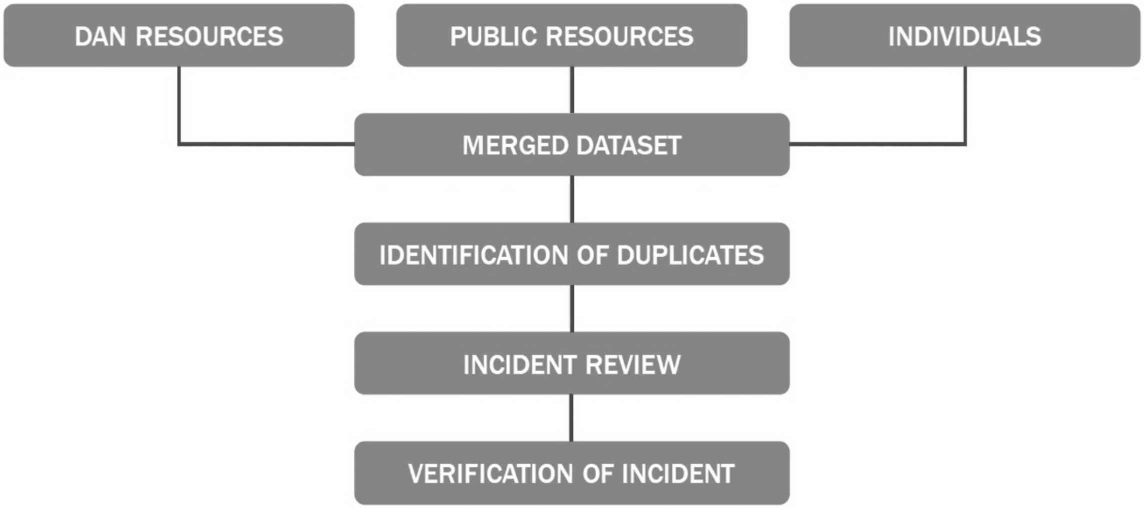

Figure 4. Fatality database consolidation.

CCR Fatality 25-Year Review

A report on CCR fatalities for the period of 1998–2010 showed a peak at around 26 fatalities per year in 2005, having risen from 5 to 10 fatalities per year from 1998–2004 (Fock 2013). Figure 5 displays these data plus additional numbers through 2022, showing that in the years 2013–2017, an even larger spike in the number of CCR fatalities was seen, rising to around 35 cases per year at its zenith. In the years 2018–2022, the number of fatalities varied enormously but did not dip below 20 per year. A 5-year rolling average trend line reveals that in 2022, the typical number of fatalities was still around 25–30 deaths per year.

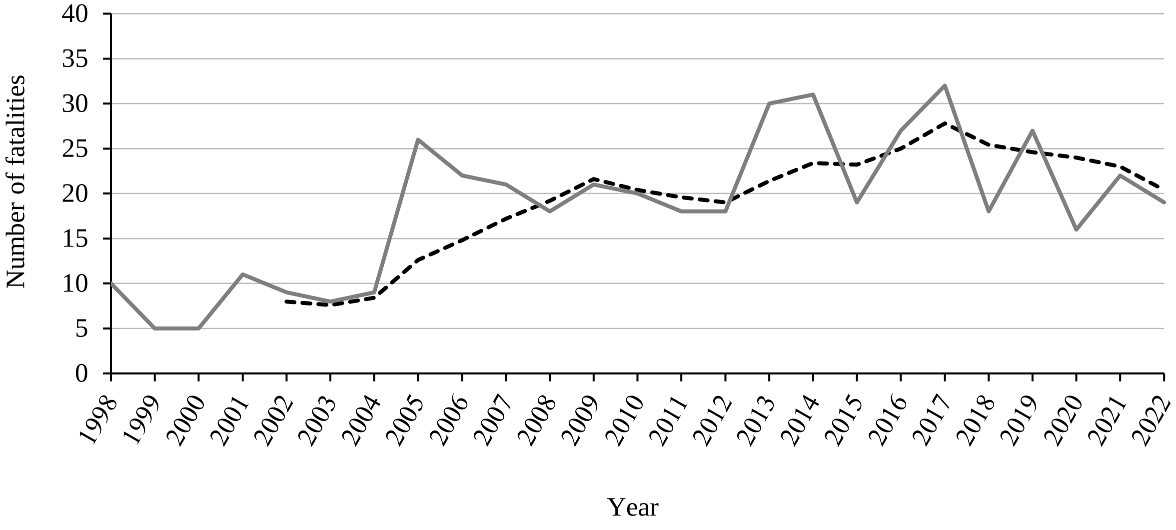

Figure 5. CCR fatality 25-year review 1998–2022; counts per year (solid line) with 5-year rolling average trend line (dashed line).

On further examination of the data from the last 10 years, it was possible to derive 241 confirmed CCR fatalities (Figure 6) with a trend towards fewer deaths in the second half of those 10 years. This count excludes military and commercial accidents.

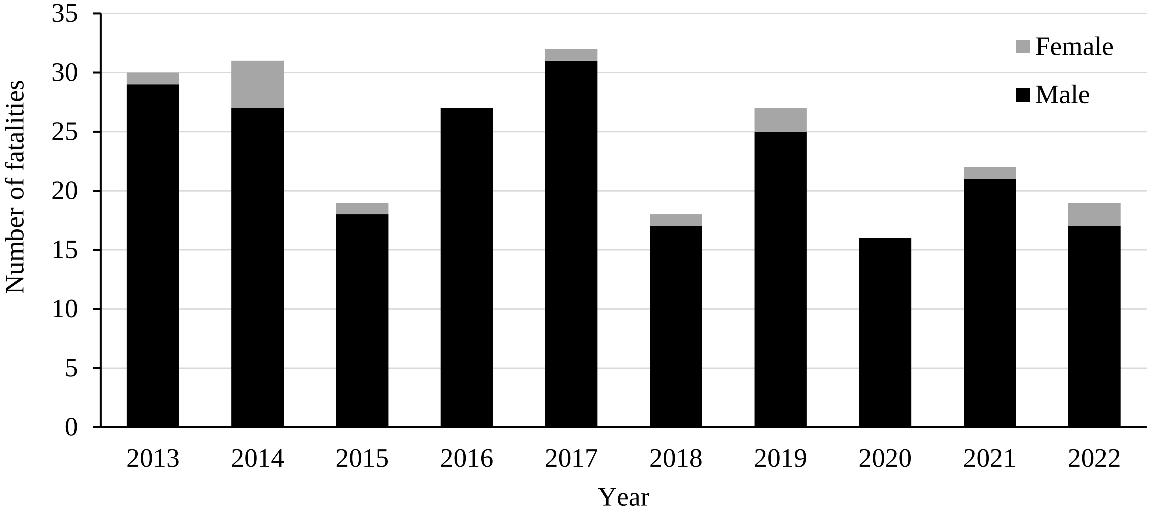

Figure 6. Confirmed CCR fatalities in the 10-year period 2013–2022 (n=241).

What is Known About These Accidents?

As previously noted, the majority of CCR divers who had fatal accidents were in their 40s and 50s, and only 12 of the 241 (5%) confirmed cases were women (Figure 7).

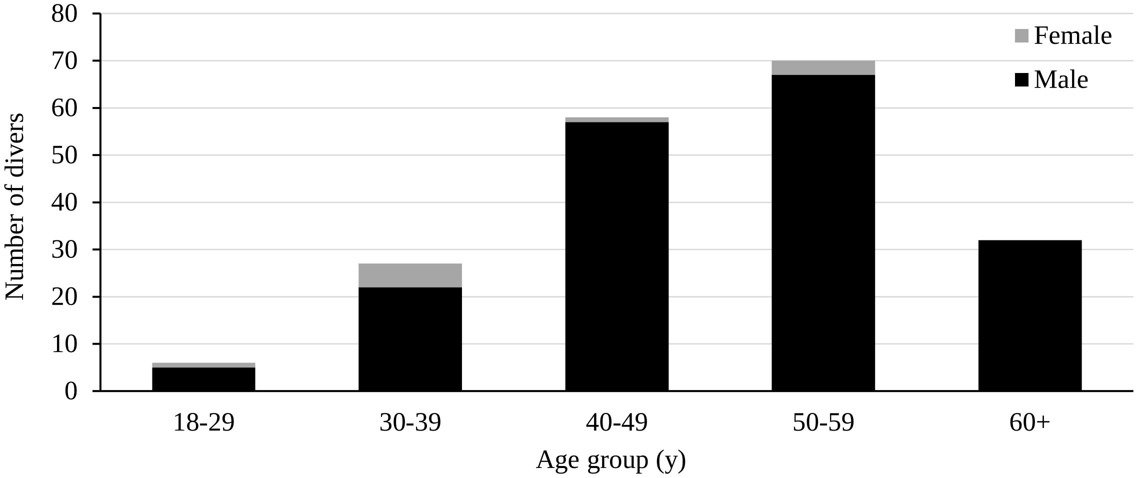

Figure 7. Age and sex of deceased rebreather divers (n=193; 20% of ages unknown).

Fatalities are reviewed at DAN using an adaptation of Vann et al. (2007), classifying each fatality in possible predisposing factors, trigger events, disabling/harmful agents, nature and mechanism of the disabling injury, and cause of death (COD). Frequently in diving-related incidents, the COD is difficult to establish and is most often ruled a drowning in the medical examiner reports submitted to DAN.

For the analysis of the current dataset, we established the disabling injury that most likely contributed to the chain of events of the fatal outcome/drowning. Of the 241 confirmed cases, 124 fatal accidents had insufficient information to draw any conclusions, classified as unknown. Cardiac incidents or questionable cardiac health of the diver were involved in 29 of these cases and provided the largest category in the 117 deaths where data analysis was possible. Given the distribution in age of the fatalities, with most occurring in the over-40 year age groups and the risk of cardiac-related illness increasing with age, this finding was not surprising. Hypoxia was likely responsible for 21 deaths and the remaining confirmed causes are illustrated in Figure 8. The category 'other' included less than 3 occurrences of suicide, gas contamination, venomous marine life encounters, or poor gas management.

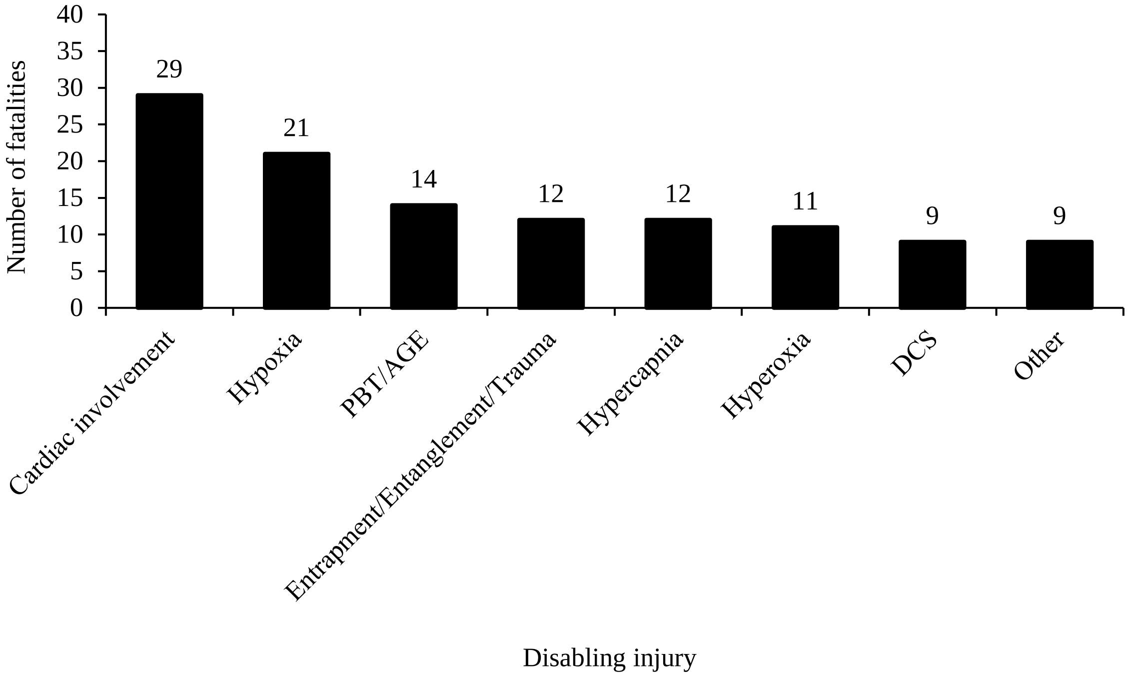

Figure 8. Disabling injuries that contribute to COD (n=117, 52% unknown). PBT, pulmonary barotrauma; AGE, arterial gas embolism; DCS, decompression sickness; Note that cardiac involvement, hypoxia, hypercapnia, and hyperoxia all contribute considerably to COD and remain issues that should be addressed.

A primary concern related to CCR diving relates to the depth of the dives made; given rebreathers may allow divers to go deeper for longer is it depth that kills them? Figure 9 illustrates the depths at which the issue that led to the fatality most likely occurred, showing that most were in the relatively deep 40–80 m (130–260 ft) range. There is a fairly even spread at depths shallower than this, some events having occurred during entry-level CCR training, as well as the occasional exceptionally deep dives >200 m (656 ft), for example, exploratory dives or record attempts.

In summary, not enough information is made available to address accident analysis in full. This lack of detail may stem from family/friends not wanting to talk about the accident, other priorities, fear of litigation, and/or lack of diving knowledge or familiarity with the subject matter reducing the amount of useful information that can be provided.

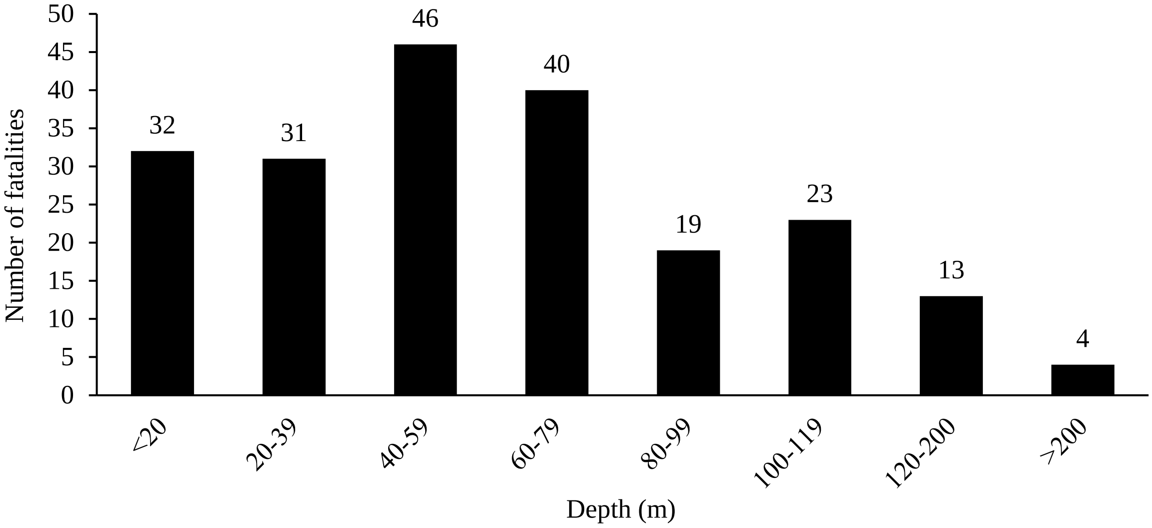

Figure 9. Diving depth at which the problem that led to the fatal outcome first occurred (n=208; 17% unknown dive depth).

CCR Industry Statistics: How Big is the Industry and is it Growing?

We were able to gather information from eight CCR training agencies on how many certifications are issued each year over 10 years (Figure 10). Certifications are classified as basic, intermediate, and advanced (60 m plus) qualifications. Although the number of certificates for the advanced group remains similar across the 10-year period, a trend towards an increase in the numbers qualified for the basic and intermediate qualifications can be seen. Overall, over 5000 certificates were awarded in the last year that were related to rebreather diving. However, this may not allow us to determine how many CCR divers are actively diving, as people can start to dive CCR on either basic or intermediate certification, and many divers will have more than one certification, resulting in duplication within the total number of divers.

With regards to duplication, following a personal communication (B. Carney, March 2023) who received data from another party, it was estimated that around 44% of certifications were duplicated. Removing this percentage of the total (Figure 10) means that an estimated 2000 certifications were issued in 2013, increasing to around 3000 in 2022. Given a quick poll of the participants of RF4, it may be fair to assume that each CCR diver has at least two certifications, which would suggest that around 50% of the total could be deducted and this is illustrated in Figure 10. Overall, these ranges provide an educated estimate, which suggests that post-2020, there was an increase in training certifications awarded.

Drawing on these data, we could start to address the question of how large the CCR industry is. The training survey suggested a minimum growth of 1400–2800 new CCR divers per year over the past 10 years. We included 22 manufacturers of rebreather equipment to ask how many units they sold per year (estimated or calculated), and how many sales they made per year since RF3 in 2012.

Twenty manufacturers agreed to share data anonymously (two opted for a data use agreement before supplying this information), and from this, it was estimated that around 23,000 units had been sold in total over the past 10 years. The data provided were limited since 36% of the manufacturers provided an estimate of their sales only without specific figures. Of the remainder, 55% provided actual sales numbers, and 9% did not provide data. If we assume that the companies forming this 9% could be representative of anywhere between 10–40% of the rebreather market, an estimate of 25,000 and 35,000 units would be on the market today.

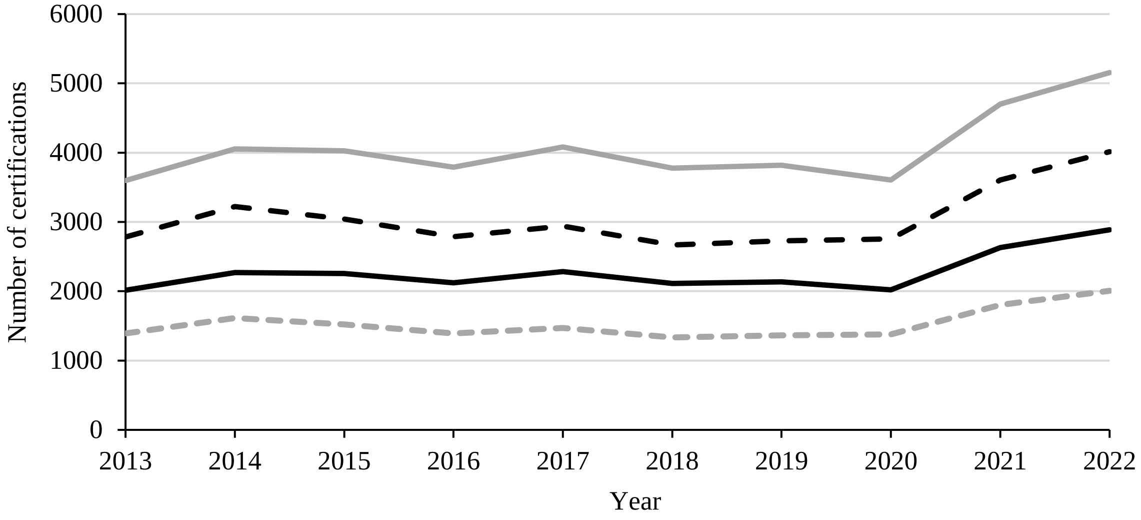

Figure 10. Training survey 2013-2022: total and corrected certifications issued each year. gray solid line, all certifications incl. basic, intermediate, and advanced; black dashed line, basic & intermediate certifications; black solid line, total certifications minus ~44% duplicates; grey dashed line, basic and intermediate certifications minus 50%.

The growth of the rebreather market is illustrated in Figure 11. Overall, there has been an increase in growth of the market over a 5-y period starting in 2018. Although we cannot be sure what has driven this, potential explanations include a rise in the choice of CCR units coming to market from a range of manufacturers, or the high price of helium making recirculation of gas more attractive. It is noteworthy that the increase in CCR diving certifications shown in Figure 10 is reflective of the expansion of the rebreather manufacturing market (Figure 11).

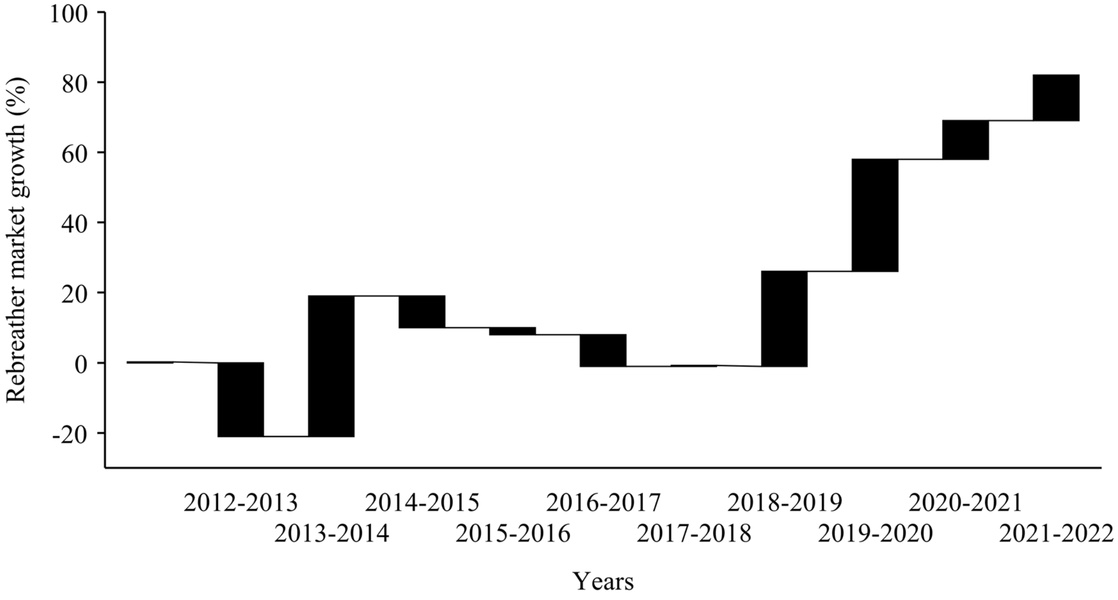

Figure 11. Growth of the rebreather market (%) since 2012 derived from submitted sales data from CCR manufacturers.

Safety Status

DAN data suggest that there are around 180–220 diving fatalities per year that are attributed to scuba diving. Of these, 10–15% (n=20–25 per year) are thought to be rebreather divers. The number of deaths is likely underreported for both CCR and open-circuit. Overall, CCR diving is a flourishing market and there is a growing community of these divers across the world. We cannot account for how many divers own multiple units, how many divers buy units secondhand, and how many sell units when they leave the sport.

CCR Death Rates

We have previously published an estimate of the demographics of CCR divers, the number of dives conducted, and the hours spent underwater by rebreather divers (Buzzacott et al. 2022). From these data, a rough estimate of death rates can be made. If the estimate of 20,000 active CCR divers is used alongside 20–25 deaths per year, then the CCR death rate would be 1.8–3.8 deaths per 100,000 dives or 1.2–2.5 deaths per 100,000 h of CCR dive time. In previous presentations on the topic, this estimated rate reached 4–5 deaths per 100,000. If the present estimate is correct, the rate is slightly reduced and it would be tempting to attribute this to positive safety implications, but it is not possible to verify this, and all data presented are estimates from the best available data at any given time.

All of this points to the fact that accident and incident surveillance needs to be improved in the future, which will be aided by the industry (training agencies, CCR manufacturers, and computer manufacturers) continuing, or in some cases starting to provide anonymized data to produce a common denominator to report against the fatality numbers. Incident reporting would be encouraged by a safe space for individuals to report their close calls to experts without any peer judgment. Country-specific information needs to be streamlined and standardized to facilitate easier collation of data.

DAN continues to produce its annual diving report, which monitors diving incidents and fatalities, and relies in part on people accessing the DAN website and filing a report on the diving incident reporting system (https://dan.org/safety-prevention/incident-reporting). Data quality and usefulness can be improved by better reporting. Thus, divers and their families should be encouraged to provide information as soon as possible after an incident to help them provide accurate information, and follow-up should be made. Continuing medical education efforts could help to aid clinicians in identifying not only the obvious COD of drowning in a watery environment, but also to look for triggers and existing medical conditions that may have pre-empted the drowning. Expert handling of the diving equipment following an accident is also necessary to extract the maximum amount of information available. This could include returning units to the manufacturer or knowledgeable independent third parties for examination. In the US, DAN America tries to work with law enforcement with some success in areas where diving is common, although in the states and counties where diving accidents are infrequent, the information is often not passed on or reported in detail. Again, education is key. Another important link is being able to provide people who have training to talk to family members and witnesses, which aids in collection of pertinent information.

Conclusion

Although attempts are made to collect as much data as possible on global provision and use of CCRs, increased collaboration between the providers of equipment and training, and education of those involved in reporting on incidents and accidents, will help to allow collection of the best quality data. This is key to improving our knowledge and in turn to disseminate potentially life-saving information to the CCR community as a whole.

Acknowledgments

The author thanks all equipment manufacturers and training agencies who willingly contributed sales and training data to this report, as well as Marta Marocco, Catherine Harris, Dr. Camilo Saraiva, and Martin Parker for their invaluable support in accident data collection and interpretation and Dr. Lesley Blogg for assistance in editing this manuscript.

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QUESTIONS AND DISCUSSION

MARK CANEY: One thing which struck me is the number of divers being trained each year is about 2500, you say. Yet, the number of rebreathers being sold each year is about 25,000.

FRAUKE TILLMANS: It is 25,000 total units on the market. I did not go into the actual sales numbers per year because there was too much data missing. I only looked at the growth and not at the actual sales.

DAVID DOOLETTE: You were talking about accident investigation of underwater breathing apparatus, and saying they should be expertly handled, chain of custody. But where would they go? Who would do the accident investigation? Are you thinking about sending them back to the manufacturer? Do you have a proposal for that?

FRAUKE TILLMANS: I am leaving this up for discussion because I do not have a proposal - in the United States it is probably an issue to get it back to the manufacturer, especially if there is a lawsuit at hand. In general, I would like a transparent industry where the manufacturer who gets back the unit can say, "Yes, that was definitely hypoxia," or "Yes, they stopped moving at that time." In most cases that we have seen it is not the piece of equipment that is killing the person. It is the human component connected to it, and here we need to work on culture. We need to work on not blaming people and/or companies for undesired outcomes. I would encourage a system where the unit goes back to the manufacturer that knows it best and then reports that information without fear of litigation. How feasible that is is completely in the stars.

DAVID DOOLETTE: That is something that probably should be discussed in this forum. In the United States at least, I do not think there is a civilian authority that would do that. The military does not do it. If someone like DAN might be in a position to coordinate these efforts. It is a difficult thing to establish in the civilian market.

SIMON MITCHELL: Congratulations on a terrific effort to derive some meaningful data. That is a huge challenge and that is an amazing contribution and I look forward to the manuscript being submitted to diving and hyperbaric medicine in the near future. Just wanted to point out, Frauke, a few years ago DAN, did a really clever thing trying to derive the same kind of numbers for the general scuba diving population. Because all your data is dogged by the fact you do not have such an accurate numerator and a really difficult-to-capture denominator. What they did is they used insured DAN members as the denominator because why would you insure yourself for diving if you were not actually diving. So, it is a pretty strongly accurate denominator. Could you not do the same thing with a rebreather diver cohort who have insured themselves for diving activity, they have identified themselves as rebreather divers. And then you follow that cohort for incidents and fatalities and calculate accurately a fatality rate from that sort of diver set? Because you probably have that right? Do you know who insures themselves and who are rebreather divers? I guess that is the important part of my question.

> [Denoble PJ, Pollock NW, Vaithiyanathan P, Caruso JL, Dovenbarger JA, Vann RD. Scuba injury death rate among insured DAN members. Diving Hyperb Med. 2008;38(4):182-8. PMID: 22692749.]

FRAUKE TILLMANS: I am not sure. I do not believe that we distinguish in our insurance plans between technical and sport diving so I would not know if we can get that information. We can ask members to give us additional information, that would certainly be something to look at. Only about a quarter of the rebreather fatalities are in the US. DAN America can do this. In Europe it looks different because DAN has a lot of competitors in Europe in various countries.

SIMON MITCHELL: Completeness does not matter. It just matters that you have an identified cohort.

FRAUKE TILLMANS: Right. From the data we have right now, we cannot. But we could initiate that kind of survey.

DOMINIC HOUSIAUX: Does DAN have any plans to build near-miss reporting into its app?

FRAUKE TILLMANS: The plans are there, and I am going to keep it at that. I cannot say that it is going to launch. We would also really like to integrate that in dive computers because not everyone is using the DAN app, but everyone is using a dive computer and the computer-associated app so that would be a different way to go about that.

ALEJANDRO GARBINO: I think you have shown the infrastructure exists there on how to report. I really want to emphasize the idea of reporting near misses because for every fatality there is probably at least on order of magnitude more near misses that we can learn from. On the aviation side, back in 1975 there was the aviation safety reporting system, it is managed by NASA. It basically provides pilots a not quite get-out-of-jail-free card, but consideration with any adverse action on anything they have done. When the FAA reviews the incident, they may or may not pull their license. Nobody is pulling dive certificates, which I think is a separate discussion altogether, but what is a carrot that you can use for either individual divers, dive operations, or certifying agencies to actually report not only fatalities but near misses because there is no carrot here. I think you have the infrastructure, just not the motivation.

FRAUKE TILLMANS: We do not have a stick and we do not have a carrot. And I am at a loss for what we could offer divers to start reporting. In general, as you said, we cannot pull certifications of divers and there is no governing body for the diving world. There is not one overarching industry standard for this and I do not believe that we as an industry will get there.

EDMUND YIU: I am based in Hong Kong. I would like to make some comments about data coming from Asia because it is really underrepresented, especially in the Chinese community. I know that all of the manufacturers are really pushing for the Asian market and instructor training and certainly there has been a lot of incidents and a number of deaths reported. I mean, just in the past month I am aware of two deaths of Chinese divers on CCRs. I would like to know if there is any way that we, through the training agency or through the instructor network, that there is a way we can report something that we hear. Because we definitely hear about it from the community, from the peer groups, from social media, from friends. We know events happen, but we never get real information. We kind of think what happened, but we cannot prove it. But I think that is really good information to share so we get a much higher representation from Asian and Chinese divers. And I think the numbers are very much underreported. We can see the growth of instructors and rebreather diver buying units in China or Asia. It is growing quite rapidly. And the demographic is actually getting younger as well because I think they are more like in their 30s and 40s. For all of us here, we all belong to kind of the older generation, but for the new market and everyone is much younger as well. It would be nice if there is a way we can go through all the agency, through the instructors and from the regional office that we can anonymously report something that happened and you cans can also try to get more information.

FRAUKE TILLMANS: That would be much appreciated. I would certainly welcome that input.

OSKAR FRÅNBERG: I spoke on post-accident investigations in Rebreather Forum 3. In Sweden the Navy performs the investigation if there is one. We use the manufacturers quite a lot. But when we do that, we have independent experts in accident investigation participating. I think that in countries where you do not have the facilities to do these investigations, this could be a very good way of conducting them. Maybe DAN could have these kind of experts on hand to accompany in these investigations.

FRAUKE TILLMANS: Good comment. Yes.

ANDREW PITKIN: I wanted to pick up on Simon's comment about the difficulty of getting data and your comment, Frauke, about the difficulty of getting data for the whole population of rebreather divers. There are some analogues of this in healthcare, particularly in epidemiological studies where the way you get around the inability to get data from the whole population is you choose a sample that is hopefully representative of the whole population and then track that sample. It occurs to me there may be an opportunity here for us to do a similar thing in rebreather diving where it would take some funding, but we could potentially identify a representative sample of rebreather divers and follow them and hopefully collect near misses, and incidents and potentially deaths and get some pretty good data that could be extrapolated to the whole population.

FRAUKE TILLMANS: Fantastic idea. I am on board.

MICHAEL MENDUNO: In your numbers you had 1.8 to 3.8 deaths for 100,000 dives. What is general scuba? How does that compare to general scuba?

FRAUKE TILLMANS: There are no new estimates since RF3 met 12 years ago so it still stands at 1 in 100,000.

MICHAEL MENDUNO: Andrew asked about comparing the risk of one versus the other. We do not have the other to compare it to. Understood.

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Human Factors and Rebreather Diving

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Abstract

The role of human factors in human performance has been recognized in many high-risk domains including nuclear power, aviation, healthcare, oil and gas, and military operations. Although some studies have taken place in the past that have examined the need to include human factors training in rebreather diving, nothing formal has been included in training materials from the training agencies or the manufacturers. The application of human factors in rebreather diving means to takes a systems-view perspective from training agency materials to instructor development, to dive team operations, to post-dive debriefs, and incident/accident investigation and does not just focus on the cognitive aspects of rebreather operations. The evidence that shows human factors should be embedded in a more structured manner within the rebreather diving community, dive operations, and incident/accident investigation processes if diving safety is to be improved. Neither equipment certification nor training agency programs explicitly cover the topic.

Keywords: just culture, non-technical skills, psychological safety, systems thinking

Introduction

Rebreather diving takes place in an inherently hazardous environment. There are multiple physical and physiological hazards including hypoxia, hyperoxia, hypercapnia, drowning, and entanglement – some of these are present even when not in the submerged environment. These outcomes are often the focus of research and incident reports because of their obvious and tangible nature (Denoble et al. 2008). Training materials provided by diver training agencies and equipment manufacturers cover these topics at differing levels of detail, focusing on how to control the associated risk, and how to mitigate them if they materialize.

In addition to these more obvious hazards, there are other psychological hazards that are faced, including peer pressure, bullying, blaming and shaming, and financial and reputational pressures that impact the safety of rebreather divers and/or rebreather instructors. Additionally, latent factors (Reason 1990) within a system, such as errors in training materials, inherent individual and organizational drift, and changes in the science associated with safe diving practices, can lead to situations where failures emerge from what appears to be a 'safe' system. Woods et al. (2010) stated that *"safety is an emergent property of systems, not of their components."*

Taking a systems view of rebreather safety is critical if diver safety is to be improved. A system is defined as "*a regularly interacting or interdependent group of items forming a unified whole. A basic principle of a system is that it is something more than a collection of its parts*" (Arnold and Wade 2015). The boundary of the system is defined by those examining the system, for example, a regulator, a rebreather unit, a training program, and the diving industry are all systems, but for system safety, a holistic approach should be taken (Rasmussen 1997). Systems can be simple, complicated, or complex based on the interaction of the elements within it (Cilliers 1998). A systems view of a complex system examines the relationships and interactions between components within the system (Dekker at al. 2011), not just the actions of the errant operator, for example, pilot error or diver error, because error is a symptom of the system, not an outcome (Dekker 2014). Consequently, we should be designing systems that have the capacity to fail safely and promote resilient performance. Human factors is a design-focused science where the prime objective should be to make it easier to do the right thing and harder to do the wrong thing – where the 'thing' could be rebreather operations, teamwork, effective communication, developed situation awareness, or learning from unintended outcomes (incidents/accidents).

The challenge for the rebreather community is breaking down the silos that exist between manufacturers, training agencies, dive centers, and divers, to create an environment where failures at organizational, instructor/instructor trainer, dive center operations, and divers can be explored without fear of punitive action, that is, the development of a '*just culture*' (Dekker 2016). This is not a small task, particularly given the litigious culture of the United States of America where many major dive training agencies have their base location. The fear of punitive action does not just apply to serious injuries, but also minor incidents and accidents, especially if they have involved instructors or dive professionals. The ability to make mistakes, contribute to safe diving operations, and challenge the status quo are key aspects of psychological safety (Clark 2020) where there is shared belief that it is safe to take an interpersonal risk (Edmondson 1999).

Safety and Risk

Rebreather diving takes place in an inherently hazardous environment. Consequently, there is an irreducible level of risk that needs to be accepted by participants. Given this, rebreather diving cannot be considered safe, where safe has been defined as 'not in danger or free from harm.' In high-risk operations like aviation, healthcare, and oil and gas exploration, prospective and reactive data are available to decision-makers showing the quantitative value of a failure occurring which allows controls and mitigations to be developed. In addition, formalized and detailed incident investigations in these fields highlight that many failures have their genesis much further back in time and space. These data allow quantitative risk values to be determined and an 'as low as reasonably practicable' (ALARP) approach can be taken wherein the controls and mitigations are compared against potential losses and only when disproportionate costs for control/mitigation are present can the risk be tolerated (Jones-Lee and Aven 2011).

Problematically, the quality of incident data are poor in rebreather diving. There are insufficient data on how many dives are conducted, what the risk exposure period is, and on how many dives incidents or adverse events occur. Even more fundamentally, there is no universally accepted definition of an incident. The most obvious definition of an accident in diving is a fatality, and how the diving industry tends to measure safety, but even that number is not complete (Tillmans 2023)**.** Given the lack of quantitative data, divers are not so much dealing with risk as they are working with uncertainty. Uncertainty is managed differently and relies more on cognitive biases and heuristics (Gigerenzer 2014). Consequently, because of the lack of comprehensive reporting, the likelihood of an adverse event can be misjudged as we rely on biases/heuristics to make this determination. This can be summarized as "If we don’t hear about events, do they occur?" As such, divers should be looking to reduce uncertainties by focusing on the processes which lead to successful outcomes rather than managing 'risk' which is often based around a social construct of a 'negative' outcome (Adams 1995).

What does Human Factors Mean?

Human factors is defined by the International Ergonomics Association as *"…the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance."* (Casali et al. 2019). This broad definition can lead to many different areas of research and practice, covering the interactions between people and people, people and technology (hardware), people and organizational systems (paperwork and processes), and people within their environment (social and physical) – this framework has been defined as the SHELL model (software, hardware, environment, and liveware - Hawkins 2017). Shorrock (2017) describes four key areas which can be interpreted as describing what academics and practitioners believe human factors is:

- 'The human factor' – relating to the psychology of humans, agency, and intention.
- 'Factors of humans' – focusing primarily on human characteristics.
- 'Factors affecting humans' – referring to internal and external factors which impact human performance.
- 'Socio-technical system interaction' – addressing how people interact within and with the systems and operational/social/technical environments.

As described above, human factors has a broad definition, and this means it can be misinterpreted. Given the diversity of understanding, we should also consider what human factors is not. Again, Shorrock (2019) expands on this, and a summary is provided below:

- Common sense – common sense is a shared understanding of a certain process, task, or outcome between a certain group or community and is developed over time, often through trial and error. In of itself, common sense does not exist as a tangible asset that can be transferred.
- Courtesy and civility at work – being civil is a 'decent' human activity.
- Crew resource management (CRM)/Non-technical skills (NTS) – these tools and concepts were developed in the aviation sector in the 1970s and 1980s following a number of seminal events, including Tenerife, UA173, and the Kegworth crash. They initially related to communication and assertion in the cockpit but have evolved into creating a shared mental model between operators in a complex adaptive system. A substantial body of research surrounding the implementation of CRM/NTS in high-risk industries is available (Flin et al. 2002; IOGP 2014; ICAO 2018; Casali et al. 2019; Roberts et al. 2022).
- Cause of accident – it is easy to attribute 'human factors' as the cause of an accident if we take a linear approach to the assessment, for example, lack of situation awareness, miscommunication, or fatigue. However, modern safety science has identified that we construct the causes of accidents based on our perspective (Gherardi et al. 1998; Blazsin and Guldenmund 2015; Pupulidy 2015). Healthcare, in the past, has conflated human factors with CRM but has now recognized the need to take a systems view (Hignett et al. 2013; Waterson and Catchpole 2016; Casali et al. 2019).
- Checklists – checklists are an effective tool to reduce the likelihood of a human error. However, the most effective checklists are those designed with human factors principles in mind (Degani 1990; Jones 2020) rather than through trial and error, and deployed in a social environment that has been developed based on the acceptance of human fallibility (Thomassen et al. 2010; Catchpole and Russ 2015).

Healthcare has significant evidence to show the value of human factors, but there are many socio-technical and organizational barriers to implementation. Implementing human factors in diving is likely to be harder for many more reasons, not least the lack of organizational frameworks to mandate and monitor the application and development.

Existing Literature Relating to Human Factors in Rebreather Diving

The world of rebreather diving is small, and as such, the literature directly relating to human factors in rebreather diving is limited. Tetlow and Jenkins (2005) conducted a truncated fault tree analysis of a theoretical closed-circuit rebreather (CCR) to examine the role of human factors in safe diving practices. Given the potential failure modes within the system, and the scale of effort needed, their research paper only focused on the failure mode 'unconsciousness following hypoxia.' Despite focusing on only one failure mode, they stated that, *"It can be clearly seen from the above that consideration of human factors are vital to the design and operation of a rebreather in a safe manner."* They described the need for the diver to understand what the rebreather system was doing and the challenges faced by the limitation of human cognition in relation to monitoring. This is known to be a problem when things start to go wrong, as the mental model of what has happened in the immediate past needs to be rapidly constructed so the problem can be resolved. Seminal work by Bainbridge (1987) highlighted that elements of the technical systems that are 'easy' to automate are automated, but the 'difficult' activities are left to the human to solve. She went on to say that humans are not effective monitors, and so the attention paid to automated systems drops, and when surprises happen because the system has unexpectedly failed, it can be difficult to quickly regain awareness of the situation and control the system to achieve a safe outcome. Consequently, the training burden for automated systems goes up, not down, because of the need to practice contingent operations. In the context of rebreather diving, this relates to failures on a dive and the need to bail out. It is known that some rebreather divers only undertake live bailout drills from depth when their cylinders need testing and some do not undertake any live bailout training from depth; both of these increase the risk of injury or fatality during a real emergency when the requirement to bailout is needed. A difficulty faced by the rebreather diving community to solve this problem during training scenarios is the inability to induce simulated system failures that develop over time, rather than using flashcards to prompt failure and initiate an associated recovery action. This difficulty is primarily caused by the need to maintain life support via the correct PO_2 and PCO_2 in the breathing loop, along with a limited change in loop volume which would impact buoyancy control. Electromechanical or electronic solutions would add considerable time and expense to the safety certification of each rebreather to ensure inadvertent operations did not occur leading to unsafe conditions.

A study to assess manual operations and emergency procedures for closed-circuit rebreather operations included a recommendation that *"[human factors] should be mandated for inclusion in all CCR courses"* (Fletcher 2011). This recommendation was made because of the inherent hazards within rebreather diving, the latent nature of systems failures compared to open-circuit diving, and the importance of checklists and attention to detail when assembling the CCR units due to the cognitive failure modes of divers. This recommendation has not been broadly implemented although one training agency has included a 30-min video 'Human Factors Basics for Divers' on their GUE.tv platform which provides an overview of the topic. A 'Human Factors and Team Selection' module has also been created as part of their Level 3 core program.

Rebreather Forum 3 considered a number of ways in which rebreather diving safety could be improved with the goal *"to improve human factors in rebreather diving"* (Vann et al. 2012). The key areas included the use of checklists (but not the human factors principles behind their effective use) and the need for more robust accident/incident investigations. The conference was primarily focused on 'the errant diver' and equipment design, with very little time spent looking at the wider systems view, for example, competency (not currency), quality control, and developing a just culture. Bruce Partridge, from Shearwater Research, highlighted a critical factor during the discussion on accident analysis, *"The primary reason good accident analyses are not conducted is because there is no industry initiative to collect and analyze root-cause data."* Divers Alert Network has a diving incident reporting system in place, but there are not the social conditions, that is, a just culture, nor technical resources to optimize this capability. Accident analysis is a complex system in of itself and is not as simple as providing a technical data collection and report-producing capability; it needs to address the social and cultural aspects of reporting and learning too.

Scientific diving is an area that appears to be ideal to develop human factors-focused interventions given the structured nature of diving. While the 2015 Rebreathers and Scientific Diving conference (Pollock et al. 2015) discussed a number of human factors topics including checklists and alarm design and implementation, it missed a golden opportunity to examine the organizational and individual human factors surrounding a hyperoxic incident during a National Park Service Submerged Resources Center rebreather dive in 2012. Unfortunately, the report from this event has never been released, but a presentation by Dr David Conlin at the 2021 Human Factors in Diving conference explores numerous socio-technical factors behind the event.

As cave and open water exploration expands to greater ranges and depths, the ability to carry enough bailout in the event of a rebreather failure is becoming logistically limiting. As such, the potential to use a second or third rebreather as the bailout is now becoming more commonplace. Aspects of, and the challenges involved in the use of dual rebreathers are described by Covington et al. (2022) including the point that "*Divers and explorers need to consider not just the technical aspects of operating the dual CCR as an equipment-based system, but also the socio-technical aspects and error-producing conditions that adding additional complicated equipment has to the wider system.*"

Human Factors in Rebreather Diving – A Systems View vs An Individual View

A framework was developed through which accidents and incidents could be examined by taking a systems view (Rasmussen 1997). The framework was based on control and direction coming from above, for example, government and regulators, to organizations, through to the leadership and management, and down to the operators at the front-line who have to complete the 'work.' The higher levels within the organization would receive feedback from subordinate groups/systems that shows how things are working. Figure 1 shows how this could be applied in the diving domain. To understand how accidents occur, Rasmussen expanded the framework further to create the AcciMap (pronounced 'Acci' as in accident, Map) which showed the relationships and interactions within a system, shown on the right of Figure 1.

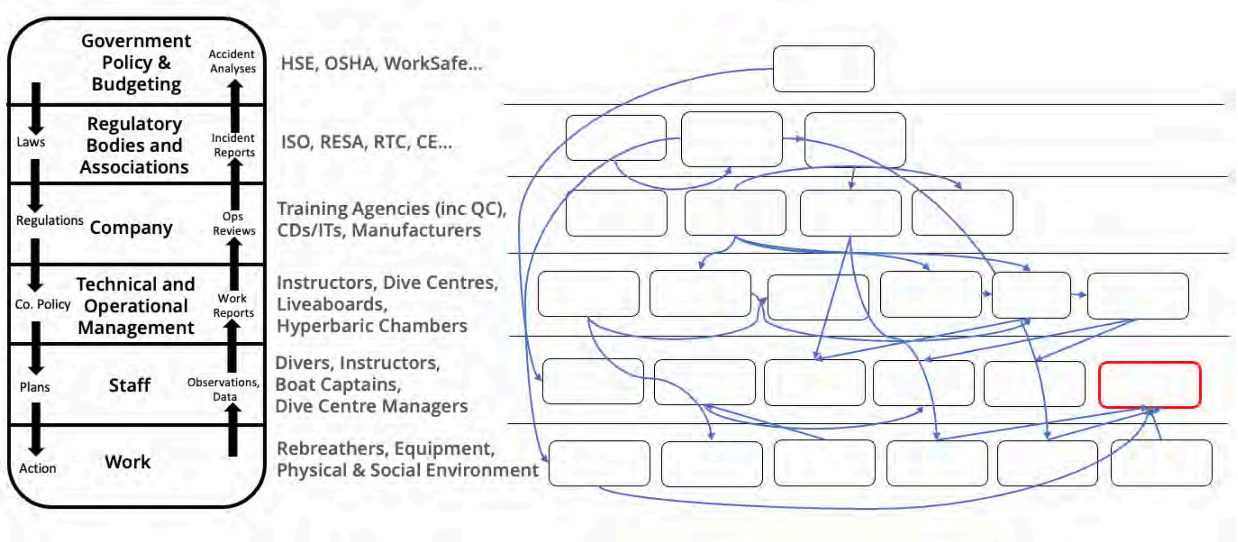

Figure 1. Example AcciMap with Rasmussen's risk model (based on Rasmussen 1997).

An online training program developed by the current author uses a real CCR diving fatality as the case study to serve as a common thread throughout the course. The first module shows the following and asks students to provide feedback on the 'cause' of the accident:

> *"A student diver entered the water from a dive boat while on a CCR training class. An instructor and three other students were present. While waiting to have their stage passed down to them, they appear to have lost consciousness and sank to 40 m where their body was recovered."*

Analysis of the answers from the 1000+ students who have completed the course have elicited the following seven causal themes: instructor supervision, buoyancy, weighting, medical issue, checklists, equipment malfunction, and camera. The statement was purposely limited in detail to align with those normally seen on social media following an incident/accident and to generate a simple, potentially judgmental, response. Along with three hours of course material focusing on non-technical skills, psychological safety, and a just culture, students review the documentary 'If Only…' (https://www.thehumandiver.com/ifonly) which is a mixture of interviews with the widow and the dive team, and the author of this paper. During this review process, students are again asked to explore the cause of the accident, and the answers are much richer, recognizing the interdependent nature of the factors that lead to the fatality, spreading back days, months, and years. Figure 2, an AcciMap of the event, shows many of the factors present and their interdependence. This context-rich perspective helps understand the local rationality of those involved (Dekker 2019), thereby leading to a better understanding of how it made sense for those involved to do what they did, even if it appears to be irrational to post-event observers and analysts.

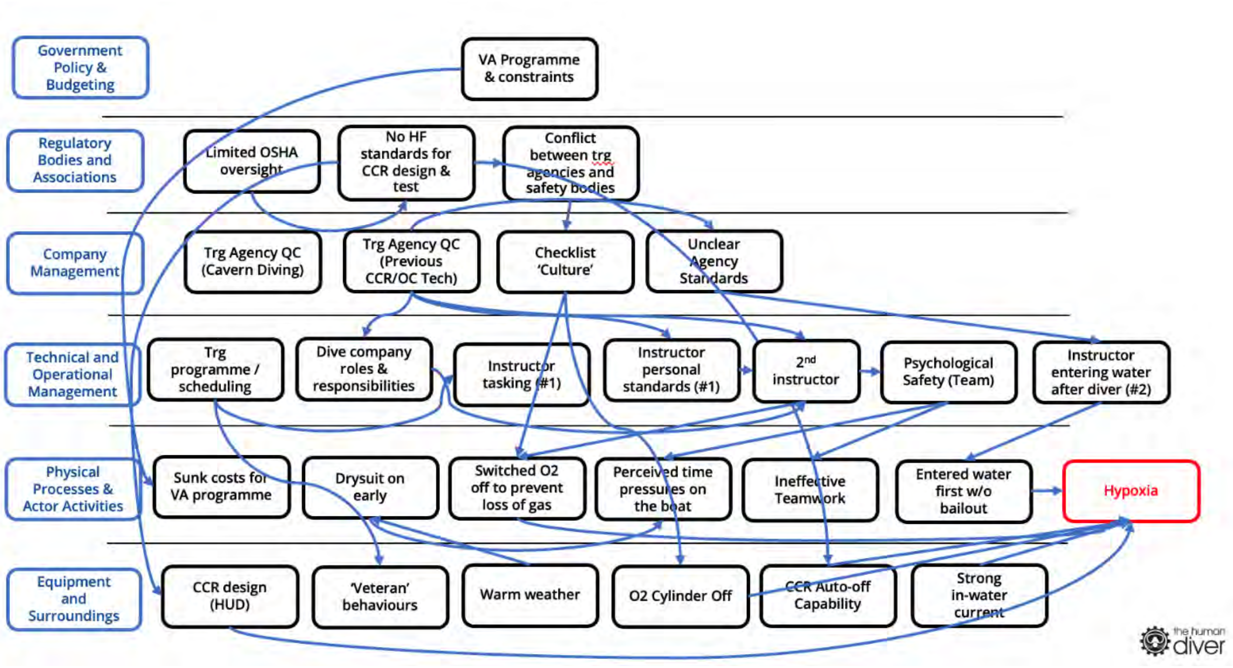

Figure 2. A systems view of a CCR diving fatality using AcciMap.

During the production of the 'If Only…' documentary, the human factors and analysis classification system (HFACS) framework (Shappell and Wiegmann 1997) was used to categorize the individual and latent factors within the system. Table 1 shows the distribution of these factors within the 33-min documentary. Without an understanding of the systemic nature of accidents or the role that human factors plays in both success and failure, it is easy to focus on the proximal causes which have limited value when it comes to learning and improving. Aviation learned this in the 1970s as they moved from 'pilot error' to a wider systems perspective, recognizing that the pilots were doing the best they could with the resources and skills they had.

Table 1. HFACS high-level category attribution from 'A Field Guide to 'If Only…''

HFACS category	Count
Organizational factors	13
Supervisory factors	24
Latent factors	18
Active factors	10

Safety Culture in Diving

Successful outcomes are a combination of technical skills, non-technical skills, the context in which the operation is taking place, and sometimes an element of chance (Casali et al. 2019). When looking at the context, there is a need to consider the culture of those involved. A positive safety culture has been proposed as a way of improving the likelihood that positive outcomes will occur in high-risk industries (Hudson 2003) with significant sums invested to create it. A safety culture has been defined as being made up of five component parts: just culture, reporting culture, learning culture, informed culture, and a flexible culture (Reason 2016). Figure 3 shows the interdependence of these components, and the importance of a just culture to facilitate the reporting.

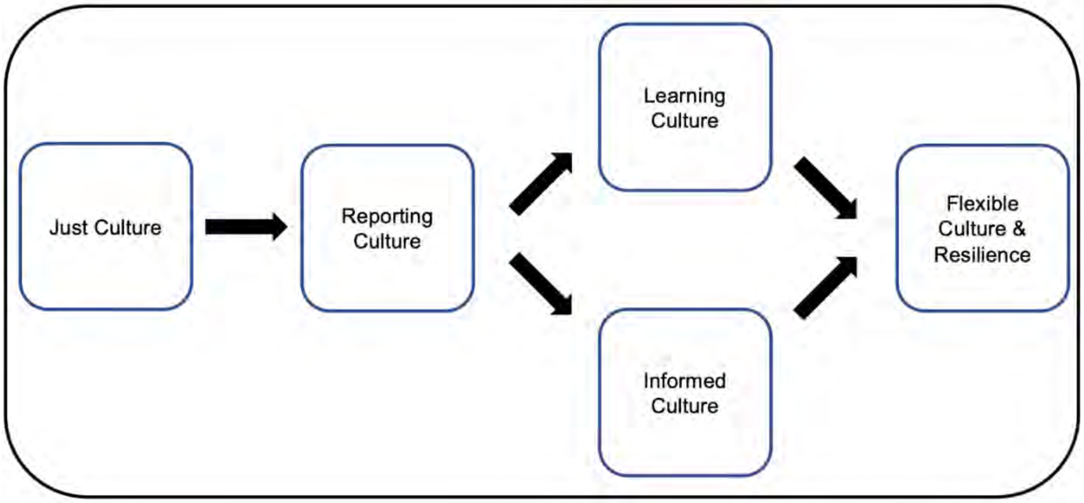

Figure 3. Subsets of a safety culture (based on Reason 2016).

While it might appear that the development and maintenance of a homogenous safety culture within the diving community is a desired outcome, culture is based on the interactions and relationships of those within the 'system,' and what we see are the demonstrated behaviors rather than hidden artifacts, attitudes, and values. It would be extremely difficult to develop a homogenous culture given the diverse definitions of 'safe' and 'risk,' different regional cultures, and the multiple 'tribes' that exist within the diving community. Guiding principles can help bring the community together because they provide a direction rather than an absolute, in the same way that a compass provides direction to the sailor or mountaineer. The human and organizational performance community, with roots in the nuclear power sector, has five principles that could be more widely adopted to move from a blame-focused culture to one of learning:

- Principle 1. Human error is normal
- Principle 2. Blame adds no value to learning
- Principle 3. Context drives behavior
- Principle 4. How leaders respond matters
- Principle 5. Learning and improvement are vital for success

These principles will likely cause dissonance with those who are used to compliance and the belief that we make 'unsafe choices' and these lead to accidents/incidents. The narrative provided through agency training materials, diver training courses, and the discussion of incidents and failures infers that accidents happen because of non-compliance, and if the standards, rules or plans ('work as imagined') were followed, adverse events would not occur. However, there are always gaps between 'work as imagined,' that is, International Standards Organization (ISO) standards, agency materials, dive center protocols, and dive plans, and what happens in the real world, 'work as done.' Standards are a useful baseline to ensure a common agreement on what 'good' can look like. However, standards in and of themselves do not create safety - they must be combined with an effective quality management system, including context-rich feedback, to ensure that the performance delivered is what should be delivered, and deviations are identified and corrected. Feedback, based on performance at each level of the system, is what helps the system be resilient and maintain safe outcomes – this is shown in the right part of Rasmussen's model in Figure 1. The lack of a just culture and psychological safety within diving organizations and the diving community at large limit the ability to find out the 'truth' and where these gaps are.

Organizational drift is normal, even for high-risk, high-reliability organizations like the National Aeronautics and Space Administration (NASA). The normalization of deviance (Vaughan 1996) or more accurately described, the normalization of risk, is a normal human behavior in that we will always look for the more efficient/cost effective way of achieving the goals we are rewarded for (Hollnagel 2009). The term 'normalization of deviance' emerged from the work of Vaughan following the loss of the Challenger Shuttle and relates to the social acceptance within an organization or team of rule-breaking rather than the actual rule-breaking that takes place. Figure 4 shows how this creeping determinism develops, and the perception that without an adverse event, things remain safe.

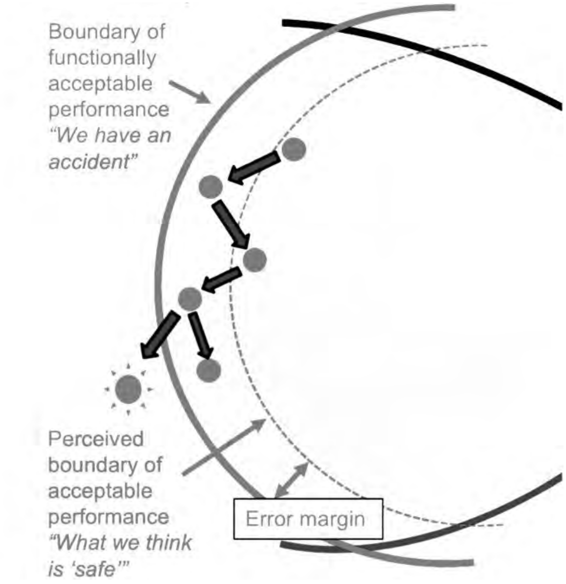

Figure 4. Normalization of deviance or normalization of risk (adapted from Cook and Rasmussen 2005).

Closing the Gap – Human Factors and Incident/Accident Investigations

There have been numerous calls to improve the quality of incident and accident reporting and the associated investigations in diving. This call is not unique to the diving industry, and mature safety industries frequently struggle with delivering quality outputs when they are better resourced than the organizations involved in diving. Notwithstanding the lack of a formal investigation process, nor well-resourced organizations within the rebreather diving community, there are a number of biases that prevent learning from near misses: hindsight bias (Fischhoff 1975), outcome bias (Baron and Hershey 1988), and the fundamental attribution bias/error (Shaver 1985; Roese and Olson 1996). These biases make it easy to focus on the individuals involved and the proximal causes, rather than look further back in time and space and learn from the situational factors or context. When an incident or accident involves a deviation from a standard or process, it is easy to judge the outcome because of these deviations and workarounds, when in fact they are 'normal.' Often, workarounds in a professional setting are executed because the conditions surrounding 'work as imagined' do not match the real conditions of 'work as done,' and rather than deviations or violations, we should consider them as adaptations and try to understand what limits the execution of 'work as imagined.' Research in the healthcare sector has shown that short-term successes (getting the job done) mean the worker does not perceive it to be worthwhile to report the issue and just fix it themselves (Tucker et al. 2002), but in the process of doing so, they hide deeper, systemic issues that are only obvious when a major incident or fatality occurs (Amalbert and Vincent 2020).

Formal investigation processes, eg, HFACS, ICAM, TOPSET, or TAPROOT, are not used by recreational or technical diver training agencies for incident or accident investigations. One exception is the American Academy of Underwater Sciences (AAUS), which has promoted use of a modification of the serious accident investigation guide (SAIG) from the United States Department of the Interior. The original SAIG came under criticism from Pupulidy (2015; 2017) and since 2015, the US Forest Service has used learning reviews as a way of generating learning within the wildland firefighting community, even when it comes to multiple fatalities. These reviews focus on the local rationality of those involved, and specific learning products are developed for different stakeholders within the system. The learning products are not just written accident reports, but could be videos, role-playing scenarios, or infographics depending on the educational needs of the stakeholders.

There appears to be some reticence to undertake such training to complete context-rich investigations – conversations the author has had with training agency staff who have stated that, where possible, nothing is written down regarding adverse events in the training system, and that which is written down, is based on the premise it can be called upon during legal proceedings.

Creating Change – Top Down or Bottom Up?

Creating positive change is hard. While there is significant evidence that the embodiment of human factors knowledge and practice in rebreather training and rebreather design could improve diving safety, there are cognitive biases and practical reasons that are likely to prevent this from happening in a 'top down' manner.

Change costs. It costs time and resources. With the exception of a few organizations, the majority of the diving industry works on a semi-volunteer basis with materials developed by instructors and instructor trainers with little compensation provided for their efforts. As such, there needs to be a commercial or regulatory imperative for change to happen. This is no different to other domains, even high-risk domains. There often needs to be a "politically relevant event" before change happens (Henriqson et al. 2014). Politically relevant events in high-risk domains which led to the development of human factors or systems thinking interventions include the Tenerife disaster and the Kegworth crash (aviation), Chernobyl, and Three-Mile Island (nuclear power), and Piper Alpha and Deep Water Horizon (oil and gas).

Change needs a reason. In one model of change, the first step is to create a sense of urgency (Pollack and Pollack 2015). The events in aviation, oil and gas exploration, and the nuclear sector which led to the adoption of human factors involved the loss of, or potential loss of, significant numbers of lives, and often in a very public way. Consequently, the sense of urgency either came from a regulator mandating change, or public opinion generating a discourse towards change and not accepting the status quo.

There is not a sufficiently perceived sense of urgency in the diving domain. Tillmans (2023) described between 180-210 diver fatalities per year, of which approximately 30 were rebreather divers. Fundamentally, there is not a strong enough public emotional argument to be made to create change top down. Therefore, change becomes an ethical argument rather than a safety one. Change may be forced upon the industry if the insurance underwriters decide the number and type of insurance claims are deemed to be no longer commercially viable, causing premiums to rise to a level that is not affordable for instructors, and the financial model for agency revenue collapses as a consequence.

While change can happen top down through organizational direction and guidance, it can also occur bottom up. 'Join the Club' details numerous examples where change has happened because those at the grass roots level have instigated change when organizational or government interventions failed (Rosenberg 2011). The 'bottom' of the system is where changes in attitudes towards human factors in diving are starting to grow by making use of multiple resources provided outside the training agency programs.

Conclusion

There is substantial evidence that human factors influence the performance and safety of rebreather divers within a socio-technical system because rebreather divers are broadly wired the same way as other humans who operate within high-risk industries. Humans are humans, it is only the stories that change. Human factors, as it applies to rebreather diving, is not just about the cognitive elements of human performance, the use of checklists, or the attribution of 'human error' or 'human factors' as a cause of an incident or accident, but rather requires a much wider systems view of how rebreather divers, rebreather instructors, equipment manufacturers, training agencies, and dive centers manage safety and performance in the presence of multiple competing goals. The lack of a structured incident/accident investigation process, scant organizational resources, and the absence of a just culture all limit the discovery of the role of human factors in diving incidents and accidents, and importantly their prevalence. Unfortunately, given the way the rebreather diving 'system' operates, until there is a "politically relevant event," change is likely to happen bottom up rather than top down.

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QUESTIONS AND DISCUSSION

DOMINIC HOUSIAUX: One of the things you did not touch on is one of the kind of secrets I think is hidden in plain sight that nobody talks about is fatigue. The industry is basically set up to maximize fatigue and people really do not factor that into their thinking.

GARETH LOCK: Fatigue is an issue. Traveling instructors, long-haul instructors pitch up. A number of instructors I speak to admit to falling asleep during deco while I was doing this or that class. That is not a good thing. Stress and fatigue are performance shaping factors within the nontechnical skills framework. Even in established industries like aviation, healthcare, and oil and gas, fatigue is poorly understood other than it really impacts your performance. Is there anything out there? No? Will people talk about it? No. In healthcare, surgeons, yes, I worked a 40-h day to get stuff down and I did not make a mistake. How many catches were made by the rest of the team? So fatigue is a genuine issue. How you capture it, I do not know. I think there are bigger issues than fatigue, but I think it is a genuine problem.

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Rebreathers for Military Diving

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Abstract

Rebreathers, extensively used in military diving, control a diver's inspired oxygen and eliminate carbon dioxide. They can be part of various systems, including shore-based chambers, sea-going saturation systems, and atmospheric deep submergence vehicles, or defined by functionality as closed-circuit or semi-closed-circuit. Their use is determined by military mission requirements such as extended duration or deep saturation diving, clandestine operations, and acoustic and magnetic signature minimization. Ancillary equipment, including in-water propulsion devices, saturation habitats, underwater navigation, and sonar systems, may also be used by divers to enhance efficiency and safety. The potential use of electronic CCRs in combat diving is recognized, but they need to be ruggedized. A software-based algorithm is proposed to validate sensor accuracy, potentially improving oxygen measurement technologies. Deep rebreather diving may be conducted with reasonable bubble loads post-dive, and a short reduction in minutes at depth can significantly reduce the risk of decompression sickness. Continued research and development aim to improve rebreather capability and performance for deeper depths and extended durations in extreme environments.

Keywords: carbon dioxide, closed-circuit, diving, military, oxygen, rebreather

General Introduction to Rebreather Systems as Used by Naval Forces

Functionally, at a minimum, a rebreather must replace metabolized oxygen (O_2) and effectively remove exhaled carbon dioxide (CO_2) before re-inspiration of the circulating gas. Ideally, a rebreather will present a low work of breathing (WOB) and appropriate O_2 levels at all ambient pressures of exposure. Military use of rebreathers is dependent upon mission requirements and operational environments such as clandestine special operations forces and combat diving operations, extended duration saturation operations and minimized acoustic and magnetic signatures for explosive ordnance disposal. Depending upon where and how they are used, rebreathers may be categorized as being part of the life support subsystems of shore-based, sea-going or diver-worn underwater breathing apparatus (UBA). Rebreathers used for diving operations can be further categorized as semi-closed or closed-circuit systems using 100% O_2 or in combination with inert gases to reduce the partial pressure of O_2.

Rebreather Platforms and Ancillary Equipment

Shore-based facilities incorporating rebreathers are typically used for diving-related research, development, testing, and evaluation or for medical evaluations and therapy. They incorporate multiple interlocking hyperbaric chambers allowing for transfer of personnel and supplies and may provide for both dry and wet conditions to simulate various environments. These facilities are normally manned by personnel outside the pressure boundary of the chambers who control the environment inside the chambers. Chambers designed for extended exposure have habitation capability providing berthing and bathing spaces and allowing for the transfer of waste products. Chambers operating at elevated partial pressures of O_2 may have fire suppression systems. CO_2 is eliminated with scrubbers external to the chambers using either an expendable product, like soda lime or lithium hydroxide, or through reversible or regenerative processes.

Sea-going systems incorporating rebreathers include submarine rescue systems, saturation diving systems, dry submersibles, deep submergence vehicles, and ship/submarine damage control systems. They are typically launched and recovered using winches from specially designed vessels or vessels of opportunity outfitted to support the diving operations. Saturation and rescue systems are capable of transferring personnel under pressure to and from minimal volume dry chambers (bells) to larger topside dry chambers for berthing and controlled decompression procedures. As with shore-based systems, fire suppression and CO_2 scrubbers external to the chamber may be incorporated.

Submarine rescue systems are pressurized vessels which have hatches or seats designed to mate to submarine hatches providing under-pressure transfer of entrapped personnel. These systems are cabled to the surface support vessel or designed to be launched and under their own propulsion, They provide life support to onboard rescue personnel and can provide medical assistance and life support stores directly to the disabled submarine. They may incorporate the use of remotely piloted vehicles during rescue operations.

Saturation diving systems with diving bells are cabled to surface platforms directly over the mission area and lowered to operational depth. Diving operations take place outside the diving bell through a hatch or moon pool at the bottom of the bell. During diving excursions outside the bell, the bell is pressurized to ambient water pressure providing a dry (and heated in some systems) environment allowing for water entry and exit through the hatch. Divers may be free-swimming, or more likely, tethered to the bell with an umbilical providing breathing gas, electronic voice communication wires and electricity for heaters or hoses for liquid circulation for thermal protection. During vertical transit to and from operational depth, the hatch is normally closed allowing for adjustment of internal pressure and breathing medium.

Dry submersibles are midget submarines capable of locking divers on self-contained breathing apparatus in and out at depth through a moon pool. These submersibles incorporate one or more closed-circuit rebreather systems and decompression can be completed within the submersible with the pilot and navigator isolated from the decompression compartment.

Deep submergence vehicles are typically one-atmosphere dry chambers capable of extreme depth, launched from a host surface vessel. They have propulsion and life support systems independent of the host vessel. They incorporate rebreather systems, typically of limited duration for shorter missions as long distance horizontal transit is rare and decompression is not required.

Large submarines of the attack, guided missile, and ballistic missile classes operate as closed-circuit rebreathers. They may support diving operations or provide transit of diving personnel and equipment for off board missions. Specially designed and outfitted submarines have internal floodable volume lock in/out trunks and external deck-mounted hyperbaric dry-floodable spaces (dry deck shelters) to transfer divers and equipment between the water column and decompression space upon mission completion. With divers breathing pressurized air in these spaces special consideration is given to the higher concentrations of potential toxins off-gassing from equipment carried for missions.

Shipboard damage control self-contained breathing apparatus use non-submersible rebreathers providing the ability to safely breathe in contaminated spaces. Unlike in most underwater applications, where the exothermic action of the CO_2 scrubber can produce heat useful to the diver, shipboard closed-circuit apparatus may produce excessive heat and require methods to cool the inspired gas or limit the duration of exposure.

Diver-Worn Rebreathers

Diver-worn rebreathers offer potential benefits over open-circuit breathing apparatus, including:

- Extended mission duration
- Reduced magnetic and acoustic signature
- Reduced respiratory heat loss
- Reduced resistive effort and WOB
- Control and real-time status of the partial pressure of oxygen (PO_2)

These benefits must be compared to the increased level of training, support, and maintenance required over comparable open-circuit systems.

<u>Configurations</u> - Similar to systems used by the technical diving community, military rebreathers may be configured in chestmount or backmount form depending on the mission requirements and equipment capability. In an effort to standardize equipment configurations, maintenance and training methods, most military units will limit the rebreather models and configurations available for use to systems thoroughly tested and evaluated for use in the intended environments while meeting mission requirements. Sidemount rebreather configurations as used in the technical diving community have not generally found application in military diving.

<u>Usage</u> - Diver-worn rebreathers can be classified by function:

Primary: The most widely used are self-contained backmount- or chestmount-configured underwater breathing apparatus as required for free-swimming or untethered operations. Unlike in the technical diving community, military divers rarely employ bailout gas cylinders with their primary rebreathers but instead rely on alternate gas sources available in the immediate operational area. This protocol is considered acceptable as open-circuit bailout scuba would potentially compromise the safety of explosive ordnance disposal operations or expose special operations forces to detection. Recently, there has been interest in redundant or bailout diver-worn rebreathers for specialized diving applications.

Bailout ("come-home" system): Used in the event of loss of surface-supplied breathing gas during saturation diving operations. The breathing loop hoses are typically incorporated into the diver's helmet and the scrubber and gas supplies are back-mounted. The useful duration of operation is intended to allow a diver to safely return to a diving bell to complete decompression and not necessarily directly to the surface.

Surface-supplied or diving-bell-supplied: Although operationally rare, these systems utilize a push-pull method where the exhaled diving gas is mechanically pulled from the diver through an umbilical to a location off-board of the diver where it is scrubbed of CO_2, heated, the metabolized O_2 replenished, and then returned (pushed) to the diver.

Gas recovery/reclamation: Surface-supplied with surface-exhaust systems are typically used in applications or locations where limited resources of diving gas are available or in contaminated water diving where the diver must be isolated from possible water intrusion through the breathing apparatus. Although not considered rebreathers in the usual sense, these systems still incorporate many features of typical rebreathers. In operation, the exhaled gas is vented from the diver to the surface where the gas is exhausted to the atmosphere (in the case of contaminated water diving) or captured for scrubbing, temporary storage, and reutilization (when gas supply is limited or cost is considerable). These systems rely on the expansion of the exhaled gas to transport the gas to the surface. When the system is used at shallower depths an inline ancillary pumping mechanism is required to force the gas to the surface. When operating in contaminated water, the exhaust from both the diver's helmet and drysuit are captured to minimize the potential for water intrusion into the breathing gas or skin exposure.

Atmospheric diving systems: Specialized rebreathers are incorporated into one-atmosphere diving suits which eliminate the need for diver decompression. These systems are typically tethered to dedicated support vessels, permitting only minimal horizontal movement of the diver in the water column yet are capable of depths in excess of normal non-saturation diving operations.

Rebreather systems with integrated helmets, including saturation, come-home systems, and gas recovery/reclamation require special considerations in design, testing, and evaluation for hydrostatic imbalance, non-compliant helmet volume, re-inspired CO_2, CO_2 washout, and loop-oral nasal helmet pressure differentials. Further, atmospheric diving systems, deep submergence vehicles, and dry submersibles require gas circulation systems to ensure homogenous breathing gas and CO_2 elimination.

Ancillary equipment - Depending upon operational requirements, military rebreather divers may employ various specialized equipment such as:

- Hand-held sonar to detect objects of interest and for collision avoidance
- Navigation equipment and through-water communications
- Remote operated vehicles (ROVs)
- Video and lighting systems
- Non-magnetic tools for mine neutralization
- Individual diver propulsion devices (tow-behind or semi-enclosed vehicles or diver-attached motors)
- Multi-diver propulsion devices (wet SEAL delivery vehicles or dry combat submersibles)
- Active and passive, diver thermal heating systems
- Full-face masks and helmets
- Respiratory gas heaters
- Heads-up and through-helmet displays
- Dry deck shelters and lock-out/in trunks onboard submarines

Discussion

There exists potential interest in future research and development initiatives to increase rebreather diving safety and capabilities for military divers to include technologies, practices, and equipment:

- Diver-machine interaction expanding operational capabilities by maximizing man and unmanned underwater vehicle (UUV)/ROV presence in the water together.
- Hydrogen gas in the breathing mix for deep excursions
- Reduction of insensible respiratory heat loss through passive and active gas heating
- Integration of decompression computers and physiological studies to minimize or accelerate decompression
- Real-time diver physiological data collection and assimilation (eg, core temperature)
- Real-time solid-state gas sensors for O_2 and CO_2
- O_2 generators to extend mission capability and duration
- Regenerative or reversible CO_2 scrubbers through the use of membranes, zeolites, or electronically-driven processes
- Diver-deployed decompression habitats with underwater mobility having both vertical and horizontal transit capability in the water column and requiring minimal surface support
- Untethered and swimmable atmospheric diving systems which do not require specialized surface support

General Military Diving Conclusions

Divers will continue to be used for the foreseeable future to meet military mission requirements, and rebreathers are important tools, used in their different configurations, to provide life support. The military, technical, and recreational diving communities should continue to advance their capabilities and safety through the sharing of developments in equipment and technology.

Introduction to Rebreathers as Used by Swedish Armed Forces

This provides an overview of the use of rebreathers in the Swedish armed forces. Diving in Sweden is directed by the supervisor of diving in the Navy staff. There is also a competence center the Swedish Diving and Naval Medicine Centre (DNC). DNC is organized with a diving school a naval medicine unit and a development section. The development section also runs a state-of-the-art facility purpose-built in 2007 for dive trials and testing. The facility is equipped with a swim flume for drag testing on dive equipment, an unmanned breathing and metabolic testing apparatus rated for 200 meters of seawater (msw) (656 feet of seawater [fsw]), and an 18 m (60 ft) free ascent training tower with a submarine hatch for testing submarine escape and diving. The Centre also boasts an indoor pool and a pressure chamber rated to 160 msw (525 fsw) with both a dry chamber and a test chamber with a Lanphier barrier that can be filled with water for various equipment and manned testing.

The center employs a multidisciplinary research group spanning specialties from engineering and modeling through physiology and nutrition to medicine. The team strives to keep the research practical and relevant by involving everyone in the diver unit's practice.

One aspect that often separates the military from other forms of diving is the focus on the logistics of military diving operations, especially in preparation for wartime when resources may be limited. This consideration influences the choice of equipment used, often different from conventional diving gear. For example, many units opt to dive deeper using nitrogen than is common despite the increased risk of nitrogen narcosis to avoid the extra logistical burden associated with a helium supply. Another common aspect is the need for stealth, staying undetected from underwater sensors or enemies, which also influences equipment choices. This focus on logistics and signatures has likely delayed the transition to electronic closed-circuit rebreathers (eCCRs).

Contrary to popular belief, most military operations are not intentionally high-risk ventures. Still, any complex mission involves a large number of elements that can lead to a substantial risk profile. Many military organizations are constantly considering risk mitigation strategies to reduce the cumulative hazard.

In terms of decompression tables, lower risk tables are sometimes used to ensure diver safety, even if it means longer stays in the water.

Combat and Special Forces Diving

Classical combat or special forces diving often involves reconnaissance missions to gather intelligence or push forward. This type of diving typically employs oxygen mechanical, closed-circuit rebreathers and semi-closed, constant flow nitrox units, often in a combined setup. Special operators frequently deploy from high-speed boats or helicopters. Upon approach, the unit is either left submerged or buried ashore to conceal it. Thus, the unit may endure cycles of freezing and thawing and other forms of abuse and will still have to function when the operator returns. The possibility of operations with a high level of autonomy and long duration places a high demand on durability and reliability.

The test results in Figure 1 were conducted using the Shadow Exertion from Divex Aberdeen, Scotland and the LAR VII from Dräger Lübeck, Germany. This could represent a typical profile beginning at the surface, starting with a purge to vent the system of nitrogen. The divers then descend to 5 msw (16 fsw) for about 10 min before performing another purge and switching over to the constant flow nitrox. Care is required to manage O_2 levels when switching over to nitrox from O_2. The divers then descend to 21 msw (69 fsw) and continues on constant mass flow injection nitrox in a semi-closed mode for about 30 min. Bypass is performed before leaving the bottom to increase the O_2 content prior to ascent.

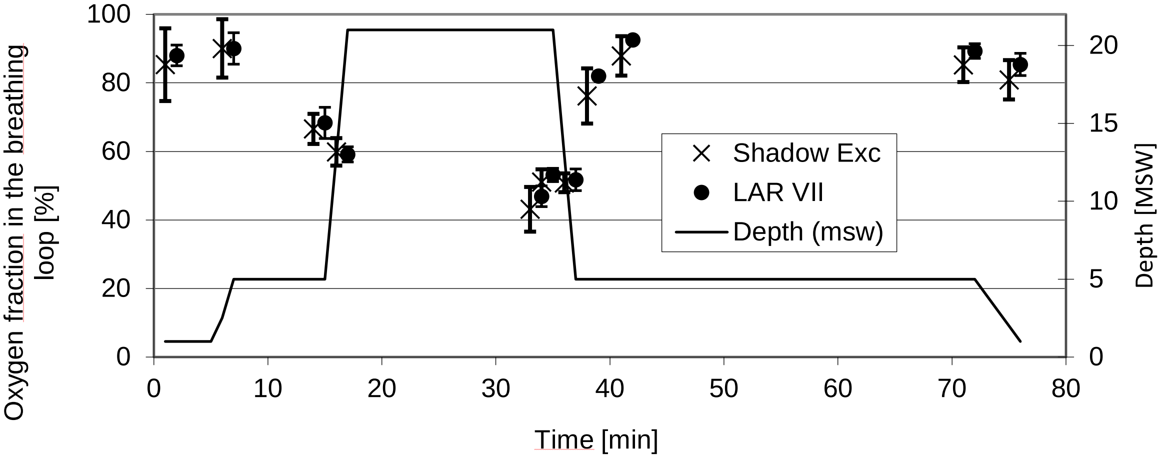

Figure 1. Oxygen content in the Shadow Exertion from Divex Aberdeen, Scotland and the LAR VII from Dräger Lübeck, Germany during a profile starting at the surface through a 21 msw (69 fsw) nitrox switch ending with a tactical ascent. Evaluating a simplified purge procedure for oxygen/nitrox switch rebreathers (unpublished data).

Upon ascending to 5 msw (16 fsw), an O_2 purge is performed again, resulting in about 80% O_2. Another purge is performed 5 min into this stage to vent the nitrogen decompressed from the body. There is not much drop in the O_2 content throughout the dive. The dive ends with a tactical ascent. During a tactical ascent, divers shut off the O_2 supply tank and decrease the O_2 through metabolic consumption. This reduces their positive buoyancy and thus the risk of an inadvertent surfacing, thereby allowing a slow exit onto the beach. This is the most dangerous part of the dive due to the high risk of hypoxia (unpublished data).

According to Swedish regulations, typical dives range from 0 to 6 msw (20 fsw) for 240 min. Excursions are allowed for either 15 min at 12 msw (39 fsw) or 5 min at 15 msw (49 fsw). For dives deeper than 7.5 msw (25 fsw) excursions are not allowed (RMS-Dyk, 2013). It is worth noting that these dives are seldom performed on pure O_2, so the O_2 pressure is typically less than the absolute pressure, often only 80%.

There is a great potential for electronic closed-circuit rebreathers (eCCRs) to increase dive times. However, the importance of having very rugged units that can handle the demands placed on the equipment has to be emphasized. It is possible that the first successful unit with electronic control will also be fully functioning in mechanical mode.

Explosive Ordinance Disposal Diving

Much like the potential role of eCCRs in combat diving there is a role for electronic rebreathers in explosive ordnance disposal (EOD) and mine clearance diving. The first and obvious requirement is for the acoustic and electromagnetic signature emitted from units to remain within specified limits. Logistical aspects such as spare parts, sensors, and batteries are also a consideration. Another issue is buoyancy control in shallow water mine clearance. The PO_2 setpoint drives O_2 injection, and this makes maintaining neutral buoyancy a greater challenge in shallow water. One possible way to address this would be to use a constant fraction from surface to a certain depth, for instance 46% O_2 from the surface to 18 msw (60 fsw), with a switch to a fixed setpoint, for example, 1.3 atm for deeper depths. For this example it would mean that as long as the diver stays shallower than 18 msw the setpoint would be a fixed fraction and thus reduce the buoyancy issues, as the diver descends deeper than 18 msw the setpoint would switch to a fixed partial pressure setpoint and stay at a constant PO_2 throughout the dive, even when ascending shallower than 18 msw to optimize decompression. This could potentially reduce the problem of buoyancy for shallow only dives while still optimizing PO_2 for deeper dives.

EOD recruits start with eight weeks of basic military training at the amphibious regiment. After this is another eight weeks of physically demanding water confidence training. Recruits then continue on to 20 weeks of rebreather dive training. Our EOD divers dive a ventilation-keyed mechanical rebreather, Ismix, by Interspiro AB, Stockholm, Sweden. This unit utilizes nitrox to depths of 60 msw (197 fsw). Diving to 60 msw on nitrox might seem controversial, but it has a long history within the Swedish Navy. One rationale behind this approach is to simplify supply and logistics for wartime shortages. This practice, however, results in both the challenge of nitrogen narcosis and a high work of breathing (WOB).

A high WOB creates a concern with CO_2 retention. It has been reported that divers tend to retain more CO_2 (ie, ventilate less for a given CO_2 challenge) than their peers (Florio et al. 1979). To explore this, our group conducted an experiment where EOD diver recruits and amphibious rangers (non-divers) were tested on their ventilatory response, ie, measuring the ventilation rate per minute of the subjects as the CO_2 gradually increased in the circuit, before dive training began. The diver recruits responded less than their non-diving peers (unpublished data). This was consistent with previous findings of divers breathing less than their peers (Lanphier 1963; Lally et al.1974; Florio et al. 1979). A speculation could be that those who consider diving as an activity might not be as disturbed by elevated CO_2 as their peers.

Naturally, our interest was also in how the dive training affected this, ie, would the dive training further acclimatize the divers to retention or would training the respiratory muscles increase the ventilation? The EOD diver recruits were tested again after the water confidence training, which is primarily apneic training involving swimming, not breathing apparatus diving, and other forms of physical exercise. The recruits were tested again after 20 weeks of rebreather dive training, with about two dives per day. It was observed that they responded more to the CO_2, that is they started to breathe more, with a significant difference between the first and the last test occasion (unpublished data).

These observations do not exclude a pattern of CO_2 retention at elevated WOB, but it was encouraging that they did not seem to develop more of a non-retaining pattern. From a diving perspective, if one is diving with high WOB it could be important to train oneself so that the lungs are strong enough to handle the demand and maybe gradually approach deeper diving, which also has other merits.

Deep Rebreather Diving and the Evolution of eCCRs

Deep diving, defined as diving deeper than 60 msw (197 fsw), has been a focus of experimentation, particularly with eCCRs, within the Swedish navy. This practice, which began in 2012, utilizes heliox and trimix and draws substantial inspiration from technical diving. Civilian technical dive instructors were even brought in to facilitate this process.

From an organizational perspective, the approach to deep diving differs significantly from traditional navy diving. Typically, a large dive organization is accustomed to diving under the guidance of a dive supervisor who directs operations and monitors decompression obligations. However, this was not feasible for free-swimming deep diving with rebreathers. As a result, a self-supervising model was adopted. No diver is permitted to become a deep diver without prior training as a dive supervisor. In effect, the team supervises itself, marking a significant departure from conventional Navy diving practices.

Another adaptation involves the use of standard operating procedures (SOPs) and checklists. A joint check system was implemented where divers go through the checklist collectively, each confirming the completion of their part. This joint communication ensures that everyone has completed the checklist and confidence in the team.

The engineering aspect of deep diving, particularly the handling of O_2 sensors, was a topic of discussion at Rebreather Forum 3 in the consensus statement 4 of design and testing:

> "*The forum strongly endorses industry initiatives to improve oxygen measurement technologies, and advocates consideration of potentially beneficial emerging strategies such as dynamic validation of cell readings and alternatives to galvanic fuel cells*" (Vann et al. 2013).

One approach to this could be through sensor validation software. We have proposed that prediction of how the sensor response could be made through mathematical modeling of the breathing system and comparing this prediction against the measured outputs. Our simulations show that an error of about 0.1 atm could be detected through the analysis of the amplitudes of the O_2 injections alone. A further test was developed using two succeeding setpoint changes, one to a setpoint 0.1 atm lower followed by a setpoint change to 0.1 atm above. The time taken to complete this cycle could predict the sensor status (unpublished data). This approach could potentially lead to the creation of a safety algorithm that if incorporated into a rebreather could potentially warn divers of erroneous sensor outputs.

Decompression Stress and the Development of the SWEN21 Algorithm

The armed forces are an employer and as such have a safety responsibility for divers. An important aspect of this is the choice of decompression algorithms and tables. A diver is mandated to dive according to the tables and algorithms supplied by the navy and thus the navy must ensure that these are reasonably safe. Some algorithms available on the market today for deep heliox and trimix diving are not validated to the extent that our navy staff require. Part of our effort to find a way forward for deeper rebreather diving has focused on finding suitable algorithms and quantifying the risk.

Bubbles as measured in the heart post-dive have been seen as a way of estimating the risk of decompression sickness (DCS) following dives (Sawatzky 1991). In a collaboration with the Danish Navy, a series of trimix dives were conducted on the ventilatory-keyed Ismix rebreather (Interspiro, Stockholm, Sweden). The loop gas for these dives consisted of approximately 21% O_2 and 35% helium, with dives ranging from 30 to 60 msw (98-197 fsw). The decompression was calculated using the DCAP (TOWANDA II) decompression model. Out of the 92 dives conducted, 16% had a bubble grade above 3 on the KM bubble grade scale (ranging from 0 to 4) (unpublished data).

In another series of deeper eCCR dives using Inspiration (AP-diving, Cornwall UK) and JJ (JJ CCR, Presto, Denmark) dives ranging from 20 m to 100 m were conducted using trimix most commonly 15% O_2/70% He and a eCCR setpoint of 1.3 atm O_2. The decompression was calculated using the Bühlmann ZHL16B algorithm with gradient factors 15/85 and VPM-B conservatism 2. Out of 133 dives, no dive had a bubble score above Kisman-Masurel grade 3; on 11 repeat dives to 70 msw (230 fsw) the median was Kisman-Masurel grade 2 (unpublished data).

It is in this context important to remember that most decompression models do not calculate fully for O_2 so dives with more O_2 have lower supersaturation for a schedule calculated with high O_2 vs a schedule with constant O_2 fraction throughout the dive. Therefore, these data do not suggest that one model is superior to another, but rather provides insight into typical bubble scores in deeper technical diving and that these can be conducted with reasonable bubble loads.

As previously stated, the navy has an employer safety responsibility for the tables and algorithms used in diving in the Swedish armed forces. Recognizing this, efforts were made to develop a new Swedish Navy decompression algorithm, SWEN 21, which has just recently been implemented in the Swedish armed forces. The development consisted of compiling a data set of about 3000, with data sourced from various databases, including those provided by the US Navy (Hjelte et al. 2023; Silvanius et al. 2023).

In Figure 2, dives are represented by circles, and instances of DCS, by red dots. The size of the circle and dot represent the number of dives. These were later analyzed with a maximum-likelihood model to calculate the risk-curves by the dotted lines for the different risk levels. The Navy staff decided on a table with an estimated 1% risk of DCS (Silvanius et al. 2023).

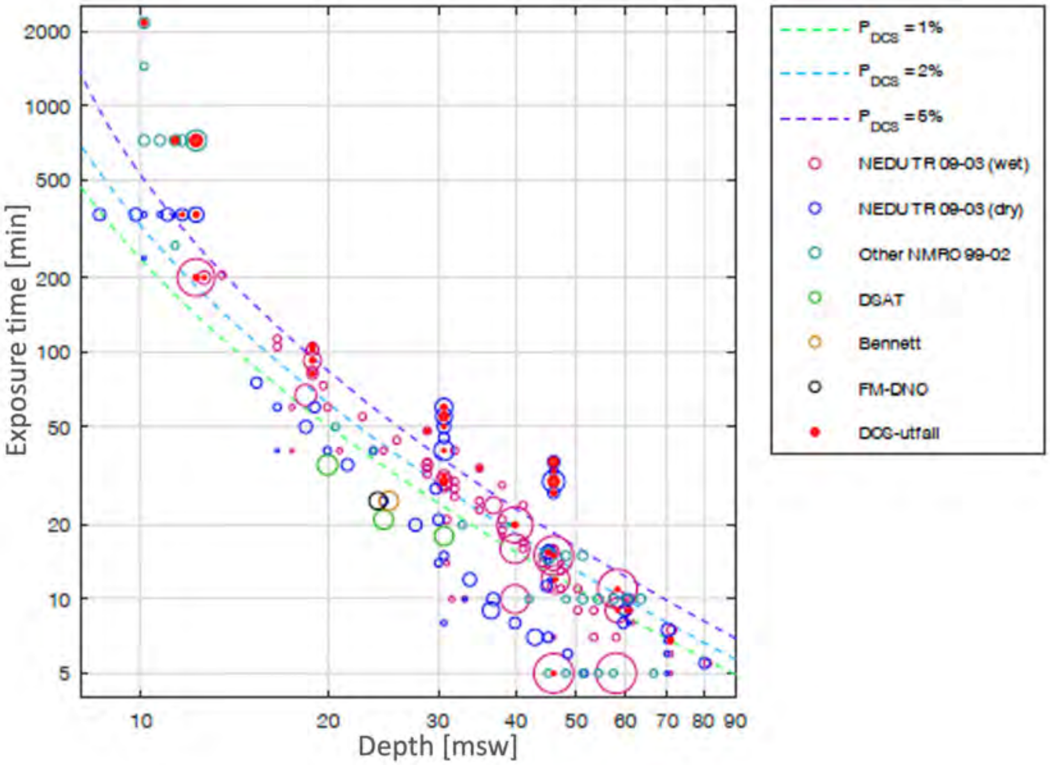

Figure 2. Uneventful and DCS dives database to calculate risk profiles in the development of the SWEN21 decompression tables (Silvanius et al. 2023).

In Figure 3, the maximum permissible tissue tensions of SWEN21 are compared to VVal 79, the basis for US Navy air diving tables (USN 2016). The values were slightly lower due to the Swedish Navy staff's requirement for a table with an estimated 1% risk of DCS. The most significant changes were observed at 10 min and 20 min half-times. (Silvanius et al. 2023).

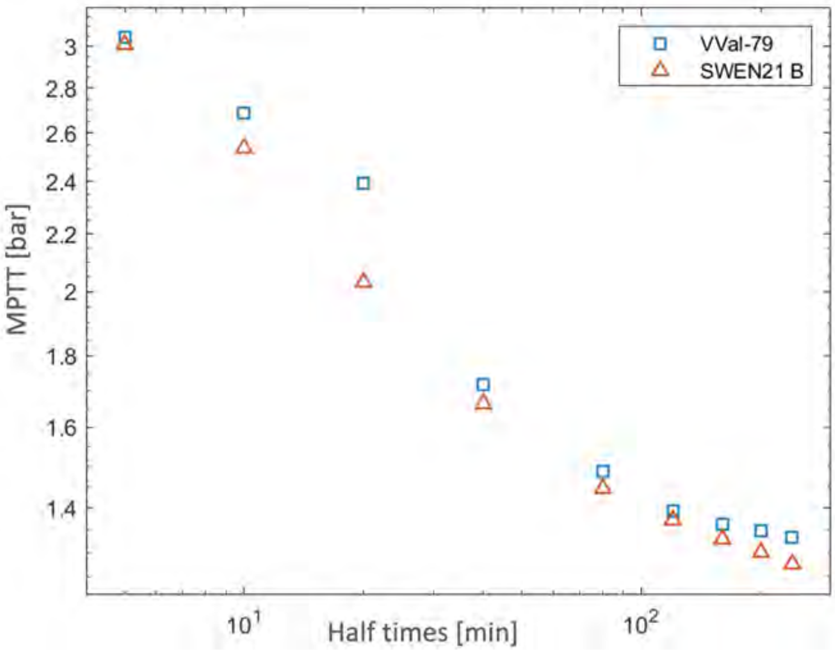

Figure 3. The maximum permissible tissue tensions of SWEN21 B and VVal-79 (Silvanius et al. 2023).

The iso-risk lines in Figure 4 indicate that there is often not more than a couple of minute difference between a doubling of risk of DCS (Silvanius et al. 2023).

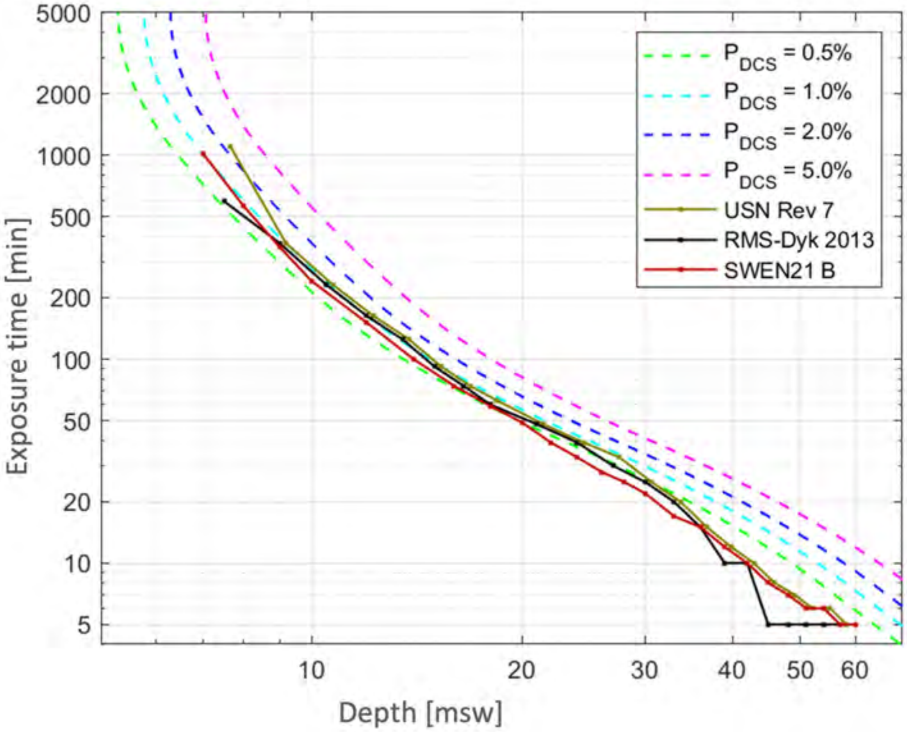

Figure 4. DCS iso-risk curves based on calculations from the SWEN21 database (Silvanius et al. 2023).

A short reduction in time at depth can significantly reduce the risk of DCS. Furthermore, as the first treatment for DCS upon surfacing is normobaric oxygen, staying on the rebreather and on oxygen for a while could be considered good practice in technical type diving. Trials involving the administration of oxygen directly at the surface have shown promising results in reducing bubble formation.

Swedish Military Diving Conclusions

- Sweden has a new purpose-built testing facility for diving research and development.
- There is potential for the use of eCCRs in combat diving, but they need to be ruggedized.
- Buoyancy issues in shallow water mine clearance operations could be reduced with the use of fraction setpoints rather than partial pressure setpoints.
- To reduce the risk of CO_2 retention; building up to deeper diving with frequent diving and gradual increases of dive depth.
- In response to the call for improved O_2 measurement technologies in the consensus statement from Rebreather Forum 3 we propose a software-based algorithm to validate sensor accuracy.
- Deep rebreather diving may be conducted with reasonable bubble loads post-dive.
- A short reduction in minutes at depth can significantly reduce the risk of DCS.
- Staying on oxygen post decompression has shown promise in reducing the number of bubbles.

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QUESTIONS AND DISCUSSION

JOHN CLARKE: Oskar, you spoke about 100% oxygen rigs but you are not using 100% oxygen in the actual gas bottle. Did I understand that correctly?

OSKAR FRÅNBERG: We have medical grade oxygen so 99.5% in the cylinder. It is just that in the loop when you purge it, you do not reach 100%.

MICHAEL MENDUNO: Full-face mask, mouthpiece retaining straps, or not? Is there a requirement in standard military diving that you have something to keep your mouthpiece in?

VINCE FERRIS: For the US military, you are typically diving simple open-circuit, probably with a full-face mask or a helmet so you are going to be covered there. As for technical diving, speaking for myself, I think it is a good idea to have something in place.

MICHAEL MENDUNO: So military divers just use full-face masks, not a mouthpiece retaining strap?

VINCE FERRIS: Both. For the most part, it is going to be full-face.

MICHAEL MENDUNO: Second question. How do they know their bailout is working? We have talked a lot about technical diving dual rebreather switching. How do they know it is going to work when they need it?

VINCE FERRIS: You are referring to the saturation bailout.

MICHAEL MENDUNO: Yes, the bailout rebreathers.

VINCE FERRIS: With the SLS (secondary life support) system, you do not know it is working pre-dive; whereas, the new COBRA (compact bailout rebreathing apparatus) allows you to pre-dive it and test it. Some of the other rigs, like the EX14 and the MK 29, also allow pretesting.

MICHAEL MENDUNO: And very last question, what is a DPV?

VINCE FERRIS: A diver propulsion vehicle.

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Equipment Options for Diving Safety

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Abstract

The use of rebreathers has expanded rapidly through the recreational and professional diving communities over the past 30 years. Experience and accident data gained over this period has led to numerous changes intended to improve diver safety. Some of the innovations that may be considered optional can provide important protections. These include mouthpiece retaining straps to reduce mouthpiece risk during compromised consciousness; bailout valves to facilitate switching from closed-circuit to open-circuit bailout without mouthpiece removal; checklists for both build and pre-entry readiness evaluation; carbon dioxide monitoring through indirect scrubber temperature monitoring and direct carbon dioxide sensing; and critical information signaling through alarm warnings and head-up displays. The value and limitations of all available tools and associated techniques should be considered to promote best practice in gear selection and diving.

Keywords: bailout valves, checklist, head-up display, hypercapnia, hyperoxia, hypoxia, mouthpiece retaining strap

Introduction

The start of the modern era of rebreather diving can probably be linked to the commercial release of the Ambient Pressure Diving Inspiration in 1997. While substantial effort preceded this point, it was a milestone in providing a ready-made platform that has fueled a diverse community of divers, trainers, and manufacturers.

The past 30 years of rebreather diving has brought a wide array of innovations, a marked expansion of the diving range, and many lessons on safety and hazards. A review of diving fatalities presented at Rebreather Forum 3 (RF3) estimated the rate of rebreather deaths to be 10 times the rate seen in open-circuit recreational diving (Fock 2013). Ongoing efforts in equipment design, training, practice, and continuing education have been directed at improving safety. This presentation considers equipment, primarily that which might be considered optional, that can help to promote diving safety.

Mouthpiece Retaining Straps (MRS)

Divers who become unconscious underwater are at high risk of having their regulator or mouthpiece dislodged, leaving their airway vulnerable to water intake. The primary purpose of the MRS is to keep the mouthpiece in place should consciousness be impaired. It has become standard practice not to try to replace a victim's mouthpiece because the effort is typically ineffective. The recommendation is to bring the unconscious diver to the surface as is. If the mouthpiece is kept in place by an MRS the risk of water aspiration is lower, giving the diver a better chance of survival.

Improvements have been made in mouthpiece retention efforts since RF3. The traditional bungee was first adapted but found to be ineffective. An additional flange has been added to keep a seal around the lips to minimize water infiltration. A secondary benefit of an effective MRS can be the reduction of jaw fatigue. When properly attached, a diver does not have to bite down as hard to secure the mouthpiece.

A French study reported that out of the 54 loss of consciousness events involving Navy divers, only three drownings resulted (Gemp et al. 2011). Notable in this series was the fact that all of the divers were using MRSs in addition to being in tethered buddy teams. The outcomes could have been vastly different without MRSs. The safety benefits of MRSs are described further by Haynes (2016).

The Rebreather Training Council (RTC), a body formed to represent the rebreather diving industry, has taken a clear position, "*RTC is now recommending and promoting the use of mouthpiece retaining straps (MRS) to reduce the probability of loss of airway protection following loss of consciousness underwater when using a rebreather*." We know where some of the problems lie, so how can we avoid them? What do we do now? Should MRSs be implemented in all diver training literature? If we have all the information available for rebreather diving customers in the future, this would give them the tools to make informed decisions. This could minimize the personal bias that rebreather instructors may have on MRSs. It is a common observation that people who are not taught to use MRSs are less likely to use them, and instructors that do not use them are less likely to endorse them.

One of the questions in the survey I conducted was, "*Do you own or use a gag strap?*" Approximately 75% of the respondents said they did not. Everyone has the right to choose but the relevant information should be made available for decisions to be informed. Choice can be based on historical data and industry sanctioned information, and not purely on what an instructor may or may not say.

Another question is whether manufacturers should provide MRSs as a standard piece of equipment or as an add-on. If manufacturers sell rebreathers with an MRS included, would more people use them? Maybe. At the very least, it would show customers the stance the manufacturer has on these devices.

Bailout Valves

A bailout valve (BOV) is an integrated open-circuit regulator within the breathing loop mouthpiece of a rebreather that can be activated to switch between closed-circuit and open-circuit with a single motion. The biggest advantage of the BOV is evident when a rebreather fails and the transition from closed- to open-circuit bailout can be done quickly, without removing the mouthpiece. If a diver becomes unconscious with a BOV and MRS the buddy could potentially easily switch the diver's gas supply. This would assist a rebreather diver suffering from hyperoxia, hypoxia, or hypercapnia. There are many equipment configuration options when it comes to the source of gas for the BOV. Some divers may choose to have their BOV plumbed into their onboard gas. The typical plan with this configuration is for a quick switch over to open-circuit bailout to give themselves time to recover their offboard bailout regulator attached to a larger gas supply. This may be appropriate in some circumstances, but problematic if the diver is not able to take further action. If the situation involves hypercapnia, the efficacy of follow-on action can vary greatly depending on the degree of intoxication.

Another option is to plug the BOV into the larger offboard gas source via a quick disconnect system. The advantage with this option is that once a switch is made from the closed loop to open-circuit the typically much larger gas supply is available without further action.

There are disadvantages of using BOVs. While improving, the performance of many BOVs does not match the performance and breathing characteristics of top-quality regulators on the market. Deeper dives can also complicate plumbing choices. For example, what is the best option for hypoxic mix dives? A hypoxic mix appropriate at depth could be unbreathable at or near the surface. Special restrictions or steps would be required to ensure that only appropriately breathable gas is used. The simplest for the case of a

BOV plumbed into hypoxic gas would be to establish a minimum depth for the valve used. This, though, could be a problematic plan in periods of stress.

A BOV could also be plugged into offboard gas with quick disconnect systems. Problems could arise in this situation if the wrong connection was made for a given point in the dive. Additionally, a lot of the quick disconnect systems have gas flow restrictions that must be considered.

One of the configuration options and bailout procedures when using a dive surface valve (DSV) is to plan to close the DSV and switch to an open-circuit regulator "necklaced" in position for quick access. Some divers prefer to avoid clutter around the neck and rely on open-circuit regulators stowed on offboard bailout cylinders. Finding the bailout regulator is somewhat more difficult and possibly less reliable, since stowed second stages might be knocked loose over the course of a dive, but there could be some reassurance in confirming which cylinder was being accessed in a multi-cylinder bailout setup.

One published case study provides a good example of the shortcomings of DSVs (Trytko and Mitchell 2005). The diver was a 34-year-old male (Diver X), a highly experienced technical rebreather diver. He was physically fit with no history of decompression illness. The dive was on a submerged reef varying between 95 and 110 meters of seawater (msw) (312 to 361 feet of seawater [fsw]). There were two teams of two for the dive with adequate surface support. Their plan was to stagger the teams entering the water. Diver X and his buddy were the first team into the water. They made a normal descent down to about 105 msw (344 fsw). At approximately 8 min into the dive, Diver X signaled to his buddy that something was wrong and called for an abort.

They went back to the ascent line and commenced their ascent. Diver X was still on his rebreather. By now, the second team had commenced their descent. The second team met with Diver X and his buddy on the descent line at approximately 80 msw (262 fsw). At this time, Diver X was noticeably distressed and would not respond to any signals from the second team. The second team aborted their descent and focused on helping Diver X. One of the divers on the second team offered Diver X his open-circuit bailout regulator by positioning it very close to Diver X's face. I personally know Diver X and his recall was that, in his mind, even though it would take only a rapid change to the open-circuit regulator, if he took his DSV out he would certainly drown, so he refused to take the DSV out of his mouth.

The situation continued to worsen. Diver X made an uncontrolled buoyant ascent from 24 msw (79 fsw) to the surface. A second team member had tried to slow the ascent, but ultimately had to call off his rescue attempt when he reached his decompression ceiling.

Diver X ended up at the surface, unconscious, but within 20 m of the boat. He was recovered from the water and found to be apneic and apparently pulseless with bloody froth coming from his mouth. Cardiopulmonary resuscitation and positive pressure oxygen were administered. He regained consciousness, and then complained of dyspnea and lower limb paralysis. He was airlifted within 20 min of surfacing and reaching the hospital within 40 min. The fact that the hospital was so close to the dive site almost certainly played a part in Diver X's outcome. After a number of intensive care and hyperbaric treatments, he eventually made a full recovery.

The after-action analysis was that Diver X had a hypercapnic episode. He had assembled his rebreather without putting a rubber flange in the proper position to ensure that all gas passed through the scrubber bed. His incorrect assembly allowed carbon dioxide (CO_2)-rich gas to bypass the scrubber bed and be rebreathed.

Another observation to add is that, if Diver X had been using a BOV, the transition from rebreather to open-circuit would not have required the mouthpiece to be removed. It is unclear if this would have changed the outcome, but it is possible. The reality is that once a state of hypercapnia is sufficiently intense it is difficult to recover. The diver on the second team who was assisting in the rescue might have been able to assist Diver X to switch the rebreather to open-circuit bailout if it only required a valve turn.

If the diver had been wearing an MRS, the mouthpiece would be more likely to remain in place during the ascent and time on the surface. Keeping water out of the airway may have resulted in a quicker recovery with fewer complications. Practically, equipment choice and configuration can be important for survival.

Checklists

Assembly/Function

Could the accident described above have been prevented? Almost certainly. The use of checklists could help to eliminate missed steps in the setup procedure to aid the diver in assembling the unit appropriately.

One of the diver survey questions asked of over 500 people was "Do you use a checklist to assemble your CCR and check for functionality?" The responses are summarized in Figure 1.

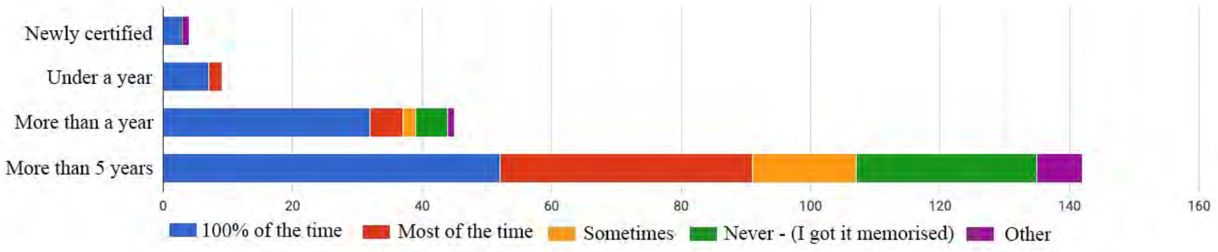

Figure 1. Use of checklists as a function of the number of years certified.

The number of respondents claiming limited experience is small, but the results suggest that complacency grows with rebreather experience, at least regarding the use of checklists. While the majority of rebreather divers describing themselves as being certified for less than one year reported using build/function checklists "100% of the time," the number dropped to just over one-third for respondents claiming more than five years of experience.

There are several ways to complete a checklist. One strategy is to physically check off every component on a written form as it is successfully completed. Another strategy is to simply work through the checklist without physical checks, but by confirming success with each step before advancing. Another approach is to work in pairs or groups in a query-response manner to guide the effort.

Some manufacturers have adopted mobile phone apps with checkbox guidance. Using a grease pencil on a waterproof copy can be similarly effective without needing a functional phone. Practically, the choice of method may be less important than the consistency in execution. The key is to employ a consistent strategy and progression so that steps are done in the same effective way to avoid making mistakes.

Another question on the survey was, "*Have you ever had any near misses?*" Again, the limited number of those claiming less than one year since certification generally did not report such experience, while almost half of those with more than five years since certification answered affirmatively (Figure 2). The survey did not address the circumstances under which these events occurred, but there is certainly cause for concern.

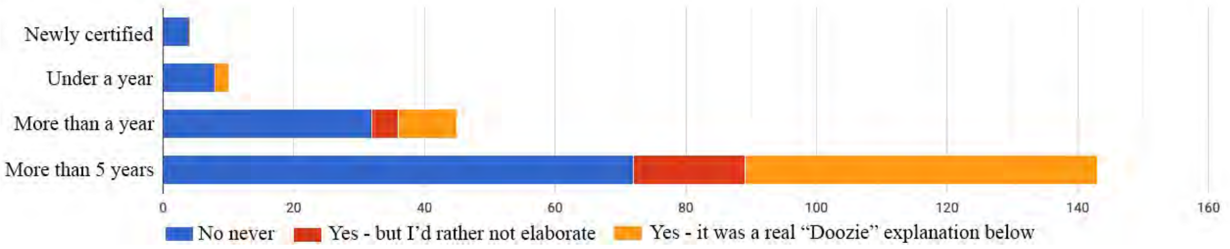

Figure 2. Years since certification and experience with 'near misses.'

The culture dedicated to safety in diving is continually under threat, in large part due to the typical influences of human nature, including complacency that frequently accompanies experience. Engineering can eliminate or moderate a large number of risk factors, but it does not protect against all issues. Checklists can serve as an important tool to further protect safety.

Pre-Entry

Ensuring correct rebreather build and bench function is foundational, but additional checks are warranted. Numerous examples are available documenting dives that have begun in an improper state, including incorrect gases or rebreathers not turned on, insufficient gases, and improper operation. Pre-entry (also known as pre-jump) checklists are intended as a final check of common errors to avoid.

Pre-entry checklists have evolved over time, changing from lengthy tools to more streamlined forms. Figure 3 provides an example of a streamlined form that addresses six key elements. The checklist can be completed with partners or with a dive supervisor.

Question for diver	Verification required to advance
Has Unit Passed All Checks?	"Yes"
Handset On?	Correct diluent and breathable PO_2
Diluent Open and Adequate?	Show pressure gauge while briefly activating MAV
Oxygen Open and Adequate?	Show pressure gauge while briefly activating MAV
Bailout Open and Adequate?	Show pressure gauge while briefly activating MAV
Wing/Drysuit Inflator Function?	Activate each autoinflate valve briefly

Figure 3. Sample of a pre-entry checklist. MAV, manual add valve.

Monitoring CO_2 in the Loop

CO_2, a waste product of metabolism, is a major management challenge in rebreather diving. Scrubbers are designed to eliminate CO_2 from the breathing loop, but this material can be exhausted or bypassed in certain circumstances. While careful unit building and timely replacement of scrubber material offer essential protections, monitoring capability can also substantially increase confidence.

Temp Sticks

Temp(erature) sticks measure the temperature through the column of scrubber material to confirm that the exothermic reaction of CO_2 removal ('scrubbing') is underway. Multiple sensors, commonly up to six located in the scrubber column, can show how the reaction is advancing through the front, initially at the proximal end, then progressing to full engagement, and then progressing to cooling from the proximal end as the scrubber is saturated ('exhausted') and the heat of reaction is lost. While this is not a measure of CO_2 in the loop, it does indicate the process of removing it. Watching the temp stick display during a prebreathe can reassure the diver that the scrubber is present and beginning to function; checking the temp stick display during the dive can show when the reaction is decreasing and scrubbing is less effective.

Scrubber displays typically provide an estimate of scrubber time remaining (Silvanius et al. 2019; Figure 4).

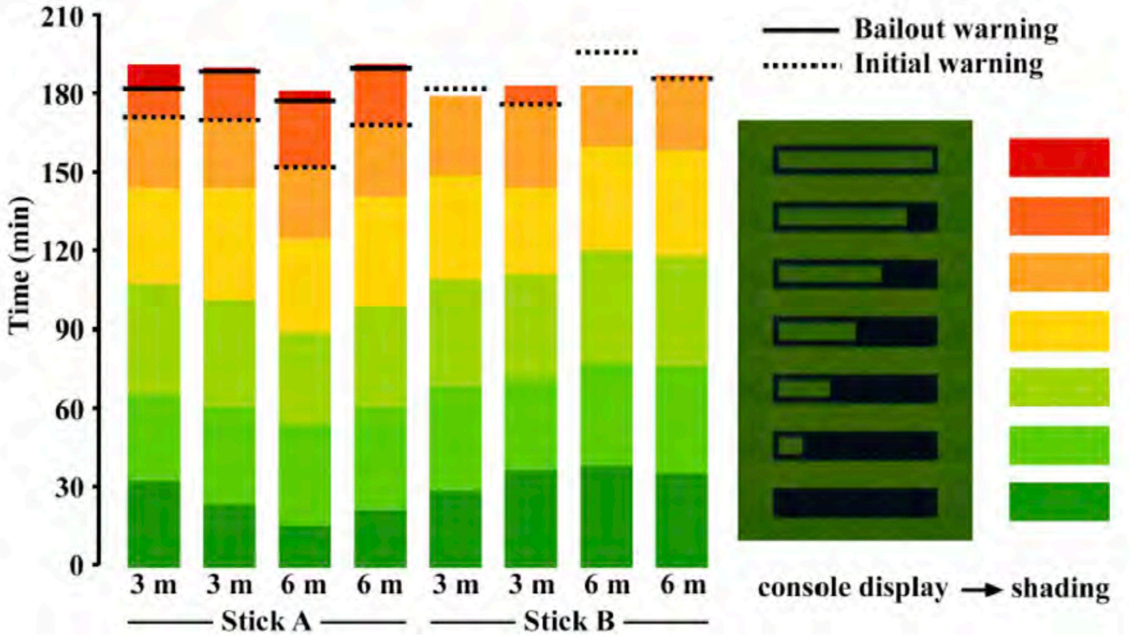

Figure 4. Changes in two temp stick displays evaluated during 8 tests of simulated moderate exercise at depths of 3 and 6 m. CO_2 was injected into the loop at a rate of 1.86 $L \cdot min^{-1}$. The color key represents the temp stick display shown on the right side. The dotted horizontal line represents the alert condition of a single black bar remaining on the scrubber display; the solid horizontal line represents the alert condition of no black bars remaining.

There is a natural concern with temp sticks that they do not measure the actual concern, CO_2. They are imperfect but do provide information that can be beneficial to divers.

CO_2 Sensors

The direct measurement of CO_2 in the breathing loop is a long-standing priority for rebreather safety monitoring. Non-dispersive infrared (NDIR) sensors use infrared light to detect CO_2, but they suffer from the difficulty in distinguishing between CO_2 and the water inherent in the closed-loop systems, requiring hydrophobic barriers and algorithm corrections for gas density to work effectively. Newer technologies include chemical gel patches that display progressive color change in the presence of CO_2.

Critical Information

Rebreather divers are trained to always know the PO_2 they are breathing, but this priority must survive the other demands and distractions of diving.

Alarm Warnings

Many rebreathers incorporate some combination of visual, audible, or tactile alarms to alert the diver, and often the partner, to the development of potentially hazardous situations. Establishing appropriate thresholds and magnitudes for alarms is challenging. Excessive sensitivity can be associated with an unacceptably high rate of false positive warnings and a growing tendency to ignore them ('alarm blindness'). Efforts to avoid excessive sensitivity can lead to insufficient warnings of hazardous conditions or possibly even disbelief in the validity of the warning.

The newest form of warning signal comes in the form of vibrating handsets and/or mouthpieces. Vibration of the mouthpiece can be particularly effective in gaining the attention of the diver. Early awareness of a potentially adverse condition can increase the likelihood of effective intervention.

The most effective combination of warnings and alarms should be implemented to ensure both awareness and timely response.

Head-Up Display (HUD)

A range of information is available to divers on individual gauges and handsets, but looking at them requires both effort and mindfulness. Centralizing critical information into a HUD can reduce the effort and increase the effectiveness of visual warnings. The original HUDs focused on PO_2, often through creative use of Smithers coding to provide a substantial amount of information in a minimalist package. These have been designed to inform the diver, in some cases with additional buddy lights to inform dive partners of more serious states of concern.

The next step in the evolution included a variety of HUD options able to display much more information through a monocular eyepiece. The most critical information - PO_2, depth, and essential decompression guidance - would appear on the 'home' screen, with an increasing array of additional information available on secondary screens or added optionally to the home screen.

The monocular display is powerful. Sophisticated designs require a minimum of refocusing and a reasonably wide effective viewing angle. The structure does, though, create a blind spot to be managed. Ongoing efforts are directed at reducing these burdens by projecting information directly into the mask. It is possible that this approach could expand capabilities in the form of 'synthetic vision' that could not only allow for convenient monitoring but also enhance performance in poor visibility or large-scale environments.

Conclusion

The use of rebreathers has expanded rapidly through the recreational and professional diving communities over the past 30 years. The equipment has evolved, both in fundamental form and in added elements to improve the capability and help protect the health and safety of divers. Some devices like mouthpiece retaining straps and bailout valves can provide critical protections in periods of great stress and hazard. Monitoring and display systems can provide important information on CO_2, PO_2, and a host of other variables important for ensuring safe operations. Checklists can help to ensure proper readiness before operations begin. Advances in design and engineering offer a number of protections, but divers require the training, practice, and commitment to ensure the best application and outcomes.

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QUESTIONS AND DISCUSSION

MICHAEL MENDUNO. I saw on your questionnaire you had a gag strap question?

PETE MESLEY: Yes, the question was "Do you use a mouthpiece retaining strap? The answer was that 75% of rebreather divers did NOT have one.

GARETH LOCK: Something on the pre-jump checklist. And something for everybody else on the checklist bit is the response on that checklist should be something you are expecting to happen, not, okay, check, set, whatever. So, the dil bit, dil is it on, or whatever you are expecting the value. And that is the critical bit about the checklist. It is actually closing the communication loop between the system and what you are expecting. Because if you just say, check, set, it does not mean much.

PETE MESLEY: That is why we have to show the pressure gauge and press the manual dil button to prove that the tank is on. Simply showing a gauge with pressure in it does not prove that the tank is on - pressing the manual add valve (MAV) proves that.

GARETH LOCK: So, the bit then is the dil is what is in your cylinder and what is actually in your computer. So, the gas analysis --

PETE MESLEY: That is the beginning "Handset" check to see whether you have your mix correct. When you do the "DIL ON," so that is the leading question, it will show the pressure gauge of the diluent and do a manual valve pressure check.

GARETH LOCK: But who checks the dil number on the handset against the gas analysis table on the cylinder?

PETE MESLEY: The dil number?

GARETH LOCK: It does not say on your checklist "check the tank." That is the bit about making sure that whatever your check is, it actually closes the communication loop as opposed to an assumption.

PETE MESLEY: So, you want to add a check the mix and then -- check the mix in the tank and check the computer for the corresponding dil?

GARETH LOCK: Yes. If you are going to have an external check, if somebody is going to do that for you, then, yes, you need to do that crosscheck at some point.

PETE MESLEY: Anyone disagree with that?

RICHIE KOHLER: I think you would have done that on your assembly checklist.

PETE MESLEY: What about analysis? Should we analyze as a group beforehand, which is not a bad idea?

GARETH LOCK: Richie, your point then is you do it on the assembly check. Where is that written down? Is it successful?

RICHIE KOHLER: Not to him, but on my checklist, there is this little spot where my analysis is done on multiples.

GAVIN ANTHONY: The European standard for rebreathers has had the requirement for mouthpiece gag straps since 2003. The message I want to get across is if you are buying a CE rebreather, it should have one. If it does not, there is something wrong. I will put it to you as an audience, perhaps making some of the manufacturers suddenly scurry out to their demonstrations outside. How many rebreathers out there have them? Challenge them at the dive shows and everywhere; they should be an integral part of what you see as a rebreather.

PETE MESLEY: That is a good comment. The CE approval issue raises a lot of questions. For example, some units have CE approval with a DSV but not with a BOV. If someone wants to have a BOV, it creates a problem with training in the United Kingdom if you can only train on a CE-approved, non-modified piece of kit. What happens there? Do you tell people to do the course with a DSV and then change the mouthpiece afterwards?

GAVIN ANTHONY: You put the pressure back on the manufacturers to provide what you want.

ATTENDEE: Pete, I was interested to hear about the seal on Diver X. If it happened once, it could happen twice. What was the name of the rebreather?

PETE MESLEY: Biomarine MK 15.

ATTENDEE: And the second question. Should we be plumbed in or plumbed offboard?

PETE MESLEY: For me? I am offboard.

ATTENDEE: And the reason, please?

PETE MESLEY: Because if I am in trouble and switch to my BOV, I want to be plumbed into my offboard gas. I do not have to take the two or three sanity breaths. I want to have an ample supply. But, again, this is the great thing about having a community of people. You have a look at what you think is right in yourself and make an informed decision. The decision I have made is to have my BOV plumbed in offboard.

RON WAXMAN: I want to talk about the gag strap while we have some of the world's leaders with rebreathers sitting in this room. I feel strongly that when this conference is over, we should reach some consensus and consistency. And your first two questions on the slide were spot on. Should training agencies push it? In my opinion, absolutely. Should manufacturers make it? In my opinion, absolutely. And then from there you can build that. Because right now in North America I have seen so many divers that were trained with the gag strap and when the course is finished, they ditch it. And we have to change that starting here and be consistent.

PETE MESLEY: That is a great comment. I think that if everyone has all the information available, they can make informed decisions as to whether they want to use a gag strap or not. At the moment, the information is sporadic and random in training materials. Some have it, some do not. When students are trained by an instructor who is a strong advocate of a gag strap, most of the students will continue to use gag straps. Students not trained to use them as a standard are less likely to do so.

MICHAEL MENDUNO: In talking to people, I do not think the community has bought into them yet. That will be an interesting question for the room how many people are.

PETE MESLEY: How many of you are diving a gag strap now? Show of hands indicates less than half the audience use them.

MARK POWELL: We have seen that a lot of people in this room are not using gag straps. I also see them not used on boats. I think we need to work out why people are not using them. Because, otherwise, we can mandate it as an agency or a manufacturer without success. We have to get to the root problem of why they are not being used.

PETE MESLEY: Great comment, Mark.

GARETH LOCK: The reason I would say that people do not wear them is the perception of risk of needing one. How many people had a near miss that could have been solved by having a gag strap, but then have not told anybody about it? I perceive that the reason why many people do not wear them is because they do not perceive the risk involved.

PETE MESLEY: How do you answer that?

GARETH LOCK: It goes back to this bit about telling stories and we do not have a just culture in place. When people go, oh, you should have worn an MRS, then it is like, oh, I do not want to talk about that because they know they are going to get grief about it. It is about changing the attitudes of the failures and that will help the stories being told.

PETE MESLEY: Good comments.

CHRIS PRESS: The comment about full-face masks was interesting. As an anesthetist if I wanted to ventilate somebody, I would not choose to use an MRS and nosepiece. Is there data comparing full-face and retaining strap or is it a compromise that people like to use something cheaper or whatever? What should the push be, I suppose and, therefore, is the retaining strap a compromise or the ideal?

PETE MESLEY: RF3 included quite a bit on full-face masks. Yes to a lot of the answers. Are they the best way of making sure that you minimize water in your airway? Absolutely. But as far as my understanding goes, that is just in the recreation market. In film, military, and commercial diving it is full-face mask all the way. I know there some in the audience who dive full-face masks and love them. But you are talking about a massive bulky piece of kit which requires more training to properly use it.

CHARLIE ROBERSON: One thing that I have learned is that everything is a compromise in rebreather diving. I probably do not have an excuse because I do dive a BOV and I think a gag strap is probably more appropriate with a BOV. But I suspect that one of the barriers to people diving a gag strap is the idea of bailing out. I know they have a quick release, but if you do not have simple access like you would with a BOV, it is a barrier. It is one more motion or one more thing you have to do to bail out to open-circuit. If you are a DSV diver, I suspect you are less likely to dive a gag strap.

PETE MESLEY: That is a fair comment. I use a gag strap on every dive. You just have to pull it down and because there is enough elasticity in the strap to be able to do that. And you would be surprised how easy it is to do. And normally what people will do is they will just shut it and pull it down. It does depend on what BOV you are using. Some of them are streamlined and smaller. Some of them are larger, which would be a little bit difficult to put completely under your chin, but you are talking about a DSV so they are pretty small.

RACHEL LANCE: My question during the discussion of these protocols, BOVs or whatever you are planning on using, is how frequently do people incorporate the concept that someone with a contaminated or less than ideal breathing gas composition is probably not cognitively all there? All three of those three Hs come with substantial cognitive impairment well before loss of consciousness. Hypercapnia, in particular, with which we have had people develop full-on panic attacks who have no history of anxiety disorder because it creates biological anxiety. And so, your story was unsurprising to me in a way where I think that needs to be part of that discussion, and I was just wondering if this community has a forum for inclusion of those physiological factors.

PETE MESLEY: Absolutely. If Diver X had a BOV, then it would have been simple just to switch over. Now, again, he would be better than he was, but would he have recovered fully? We all know when you are hypercapnic it takes a period of time to get back to normal. But, again, he could have maybe been held there and his buddies keep an eye on him. And then once he comes up into the shallows, he could then have purged his system to reduce the CO_2 level enough to be able to switch on to another gas. He would have been better off.

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Bailout Strategies

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Abstract

Bailout is the term used for an additional breathing system carried by a rebreather diver in case the primary rebreather fails, and is used almost universally in recreational, scientific, military and commercial diving. Most bailout is composed of a separate open-circuit scuba system, but increasingly a second or even third rebreather is being employed instead of open-circuit scuba for very long or very deep dives. This article reviews problems that may occur with the primary rebreather, whether they necessitate bailing out, and the use of a bailout rebreather in that context. The large number of potential configurations may be classified into two main groups, and the advantages and disadvantages of these for different types of diving are discussed.

Keywords: diving equipment, rebreather, safety

Introduction

From the earliest days of rebreather diving, it has been evident that this form of self-contained underwater breathing apparatus (scuba) was much more complex and had a considerably higher risk of failure than open-circuit (OC) scuba (Fock 2013). This led inevitably to the almost-universal adoption of an alternative breathing system, typically OC scuba, being carried with the diver to allow a safe ascent to the surface in the event of the rebreather becoming unusable. The term 'bailout,' co-opted from analogous situations in aviation and finance, has become universally accepted as both a verb and as a noun, when it is typically contracted into a single word.

In the early years of recreational rebreather diving the term 'alpine' diving was commonly employed for a configuration where the diver planned to continue using the rebreather ("staying on the loop") and solve whatever problems might occur without switching to bailout. This minimalist strategy, while perhaps attractive in its simplicity, has not survived real-world experience and has been largely abandoned. It is potentially possible that, with advances in technical design, rebreathers might in the future become sufficiently reliable to make the alpine approach viable, but the potentially fatal consequences of even an extremely unlikely failure continue to make it an unattractive option in the recreational sector. The high standards of safety in the commercial and scientific diving communities preclude it, and the only remaining area where rebreather divers might not carry bailout is during military operations where the negative impact of carrying a bailout system on operational effectiveness may justify its absence. An example is deployment of US Navy Special Warfare (NSW) divers once they have left the SEAL delivery vehicle (SDV) which carries a large quantity of compressed gas for OC bailout. Rebreathers are rarely used in commercial diving, but the limitations of OC scuba at depths greater than 50 msw (165 fsw) in the event of accidental loss of surface-supplied breathing gas has prompted the development of rebreathers for use in this context.

The Rebreathers in Scientific Diving Workshop, held on Catalina Island, CA in 2016, produced the following about bailout strategies (Pollock et al. 2016):

- *W1 - A number of critical issues identified in this meeting are complex enough to require more extensive deliberation. It is recommended that dedicated workshops are conducted to collect, review and publish information evaluating practice and safety on the following topics as they relate to scientific diving:*
- *W3 - Bailout Strategies - supply requirements, equipment configurations (eg, bailout valves, staged bailout, shared bailout). Bailout strategies are complex and are specific to individual circumstances and available equipment.*

The question for technical-level and scientific rebreather diving is not whether bailout is employed, but what form it should take. The use of OC bailout is so ubiquitous for most rebreather dives that it needs little discussion, but dives where the use of a bailout rebreather is logistically necessary or highly desirable are increasing in number and scope. Large quantities of OC bailout gas may be required in either very deep dives or long-distance cave penetrations, and these are applications where bailout rebreathers are starting to be used. Their requirements differ somewhat, in that deep diving requires a large quantity of different OC gas mixes in the same location for decompression, while long-distance cave exploration typically requires gas to be transported or staged some way from the entrance, and these differences have influenced the choice of a bailout rebreather. Before discussing these, however, it is useful to consider potential problems that may occur with the primary rebreather specifically as they relate to bailout.

Rebreather Problems

At Rebreather Forum 3 in 2012, Richard ("Harry") Harris summarized potential problems that may occur when using a rebreather for a deep technical dive (Harris 2014), whether this would require bailing out, and if the use of a bailout rebreather was likely to be successful. Some of his conclusions were scenario- and equipment-specific, so a modified version of his table is shown below (Table 1). The likelihood of and potential strategies for managing these problems will vary considerably with the type of primary and bailout rebreather used and the nature of the dive, and are covered in more detail below.

Table 1. Bailout rebreather decision matrix (modified from Harris 2014)

Problem	Likelihood	Bailout mandatory	Bailout rebreather effective
High/Low PO_2	Moderate	No	Yes
Electronic failure (no PO_2 display)	Low	No	Yes
Loss of oxygen supply	Low	No	Yes
Loop flood	High (was: Low)	Yes	Yes
High CO_2 (scrubber or loop problem)	Moderate	Yes	Yes (was: Maybe)
High CO_2 (respiratory insufficiency)	Low (was: Moderate)	Maybe (was: Yes)	Maybe (was: No)

Electronics failure, high or low PO_2, loss of oxygen supply

A closed-circuit rebreather (CCR) must incorporate a means to monitor the loop oxygen partial pressure (PO_2) and failure of a component in that system (oxygen sensors, displays, and power supplies) may be obvious to the diver but may also be dangerously insidious. Failure to recognize a fault in the oxygen delivery or PO_2 monitoring system resulting in unrecognized hypoxia or hyperoxia has been the cause of a number of rebreather-related fatalities. When recognized by the diver, these problems usually do not require bailing out or even aborting the dive, although switching to bailout temporarily while correcting the PO_2 in the primary rebreather may be necessary or desirable. Many CCRs have redundant methods of PO_2 monitoring (eg, handset and head-up display) allowing the diver to use the rebreather to travel back either to the surface or another place of safety such as a habitat. In some situations, conflicting readings from different oxygen sensors may create sufficient doubt for the diver about the true PO_2 in the loop that bailing out may be the safest course of action. Failures in the oxygen delivery system are often relatively simple to deal with (eg, a solenoid valve stuck open or closed), and a complete loss of the only oxygen supply may not require bailing out if circumstances make semi-closed operation of the primary CCR practicable. Elimination of the oxygen supply and the potentially unreliable PO_2 monitoring system is the principal attraction of semi-closed rebreathers, although they definitely do not eliminate the risk of hypoxia or hyperoxia.

Loop Flooding

The causes of loop flooding can be categorized as procedural (such as leaving the mouthpiece valve open underwater), pre-existing leaks (which are typically detected if adequate pre-dive checks have been carried out), and damage to the loop occurring during the dive. The author has had personal experience with all of these and evidence suggests most experienced rebreather divers have too. The most significant consequence of the loop flooding is water entering the CO_2 absorbent, rendering it inoperable and potentially filling the loop with highly alkaline fluid, a so-called 'caustic cocktail.' A survey of more than 400 rebreather divers with a median rebreather experience of 6 years found that 57% reported experiencing a caustic cocktail, and that there was a positive correlation with experience, suggesting that most rebreather divers could experience a loop flood at some point in their diving career (Buzzacott et al. 2022). Loss of loop integrity resulting in water entry might be regarded as the ultimate rebreather catastrophe, yet despite its frequency and the necessity of the diver bailing out, it has been implicated in very few fatalities (F. Tillmans, unpublished communication). This suggests that loop flooding is not as dangerous as problems with oxygen or carbon dioxide, probably because it is usually obvious to the diver when it has occurred.

Hypercapnia Due to Scrubber or Loop Failure

There should be almost no CO_2 in the inspiratory gas in a functional rebreather. If CO_2 inspiration does occur, it means that gas is either bypassing the scrubber (usually due to faulty assembly) or the scrubber absorbent is exhausted, typically referred to as 'breakthrough.' As inspiratory CO_2 rises, the diver's minute ventilation must be increased to keep arterial PCO_2 within tolerable limits. As inspired CO_2 concentration approaches expired CO_2 concentration, the required minute ventilation rises exponentially, and very quickly reaches an unsustainable point where the diver cannot push gas around the loop fast enough. The most obvious effect of severe hypercapnia on most divers is intense breathlessness, and some anecdotes recount such intense dyspnea that the diver was physically unable to remove the rebreather mouthpiece and start breathing from a separate OC second stage. Such incidents, and other failures requiring a rapid switch to OC bailout, have led to the development of rebreather dive surface valves (DSVs) with an integrated OC second stage that can be breathed without having to remove the mouthpiece. Systems such as this, known as bailout valves (BOVs), were a recommendation of the Rebreathers in Scientific Diving Workshop (Pollock et al. 2016):

- *O11 - Optimal rebreather configuration would provide the diver and rescuers with the ability to change the diver's breathing supply source from the breathing loop to an alternate, known safe breathing gas supply (open-circuit or redundant rebreather system) without the removal of the rebreather mouthpiece or full-face mask unless such a configuration creates additional risk (for example, systems incorporating gas mixtures which might be unsafe to breathe at certain depths should incorporate additional measures to prevent such an occurrence). Optimally, such configurations should be designed to be reliably activated with minimal delay and in a one-handed manner.*

Some individuals have a reduced sensitivity to CO_2 that may be innate or acquired (Sherman et al. 1980). This decreases both the subjective dyspnea from and the ventilatory response to hypercapnia, allowing the arterial PCO_2 to increase well beyond normal limits. These divers are at much greater risk from the adverse effects of hypercapnia, especially cognitive impairment and increased risk of oxygen toxicity, because they are not alerted to it by a sensation of breathlessness (Dunworth et al. 2017). Most divers will not know whether they fall into this category, making any reliance on subjective symptoms to detect high inspiratory CO_2 levels dangerously unreliable. The cognitive impairment caused by hypercapnia is distinct from and additive to inert gas narcosis, resulting in a slowing of performance rather than inappropriate behavior (Fothergill et al. 1991).

A diver with hypercapnia bailing out to OC will need large volumes of gas to breathe their arterial PCO_2 down to normal, in effect repaying a CO_2 "debt," a factor which should be considered during dive planning. This means that much more OC gas will be necessary than would be planned for using normal OC gas consumption rates (see below). If the diver bails out to another rebreather, the mechanics of breathing from it will need to be adequate to support this high ventilatory requirement without precipitating respiratory failure.

Hypercapnia Due to Respiratory Failure

Gas flow in much of a rebreather loop and in the diver's large airways is turbulent during both rest and exercise (Dekker 1961) and therefore depends on the density of the gas. Given the linear relationship between gas density and depth, and that the differential pressure required to drive turbulent gas through a tube increases exponentially with flow rate, it follows that the diver's work of breathing increases with both increasing depth and ventilatory requirements (which are related to exertion). The additional onset of effort-independent exhalation described by others (Mitchell et al. 2007) potentiates the effects of increasing gas density, progressively inhibiting the diver's ability to exhale CO_2. As the metabolic CO_2 generated by their efforts to breathe increases, the diver's capacity for exertion without precipitating respiratory failure becomes increasingly limited, until a point is arrived at where the diver can do nothing except breathe; additional CO_2 generated by any other exertion cannot be cleared. Beyond this point respiratory failure is inevitable without some form of mechanical ventilatory assistance. Thus, gas density poses one of the most important depth constraints in all forms of diving where gas is breathed at ambient pressure, but increasing recognition of its importance by recreational rebreather divers should result in avoidance of diluents with densities exceeding $5.2\ g \cdot L^{-1}$ (Anthony and Mitchell 2016). It remains a major obstacle for specific exploration projects at extreme depths, prompting the recent use of hydrogen as a component of the diluent to reduce its density further than is possible with helium (R. Harris, unpublished communication, 2023).

One feature of rebreather design that influences small airway closure is the pressure maintained in the large airways during expiration, which in turn is affected by the relative depth in the water column of the rebreather counterlung(s) and the diver's lung centroid. If the counterlungs are deeper (positive hydrostatic loading) such as in a prone diver with a chest-mounted counterlung system, the increased pressure in the large airways helps to prevent collapse of the smaller airways. The opposite is true if the counterlungs are shallower (negative hydrostatic loading) which will exacerbate the limitation of gas flow during exhalation.

All of these considerations imply that bailing out to an alternative breathing system, either OC (if even logistically possible) or rebreather, can only be effective if it alters the mechanics of respiration sufficiently to reverse the underlying problem. If the bailout rebreather is identical to the primary unit, this is unlikely to be the case, but the bailout unit can be quite different from the primary rebreather in ways that significantly alter respiratory mechanics, such as counterlung position and scrubber resistance.

Open-Circuit Bailout

The simplicity, familiarity, compactness, and low cost of OC scuba make it the natural choice for the majority of rebreather dives. Its primary disadvantage is its inefficiency, requiring a significant amount of

OC gas to be carried or staged on any dive, where the rebreather truly has an advantage over OC as the primary breathing system. The real benefit over conducting the entire dive on OC occurs because the only requirement for OC bailout is that it be sufficient to reach the surface, and it is typically not used, meaning the same gas is available for the next dive. This has an obvious benefit in remote locations or other situations with complex logistics.

The amount of bailout gas that is required for an individual dive, diver, and team is not always straightforward to estimate. Calculations based on known gas consumption rates during exertion and rest may not adequately account for the increased OC gas requirements caused by psychological stress, disturbance of weighting and trim caused by rebreather loop flooding, and other factors. In particular, a diver having to bail out because of hypercapnia may initially consume OC gas at 2 or 3 times the rate required during hard swimming, although this may not be necessary or even sustainable for more than a few minutes. There is a perception among experienced rebreather divers that carrying insufficient OC bailout is a common practice, but this is not supported by data from the caustic cocktail study (Buzzacott et al. 2022) and research into causes of rebreather fatalities (F. Tillmans, unpublished communication, 2023); loop flooding is a relatively common event that is very rarely fatal.

Bailout Rebreather Configurations

The first documented use of more than one rebreather for a significant exploration dive was Olivier Isler's use of a home-built redundant semi-closed rebreather for his push dives in the Doux de Coly in France in 1991. The RI 2000 was a triple semi-closed rebreather with two back-mounted and one chest mounted loops, along with which Isler carried a large amount of compressed gas, making a heavy and bulky unit that required assistance to don and remove (Figure 1). Its ability to cope with underwater damage was tested in 1997 when a scooter collision in reduced visibility damaged one of the hoses of the left-sided backmount unit; Isler was able to travel back from a penetration of 2500 m (8200 ft) with two functioning rebreathers.

Figure 1. The RI 2000 rebreather used by Isler for his Doux de Coly exploration used two symmetrical backmounted semi-closed rebreathers with a third chestmounted unit. Photo courtesy Olivier Isler.

The concept of a systematic approach to the entire breathing system was significantly advanced by Bill Stone whose failure analysis informed the design of the dual Cis-Lunar rebreather used in the Wakulla 2 project (Stone 2014). The fault-tree representation of this configuration is shown in Figure 2.

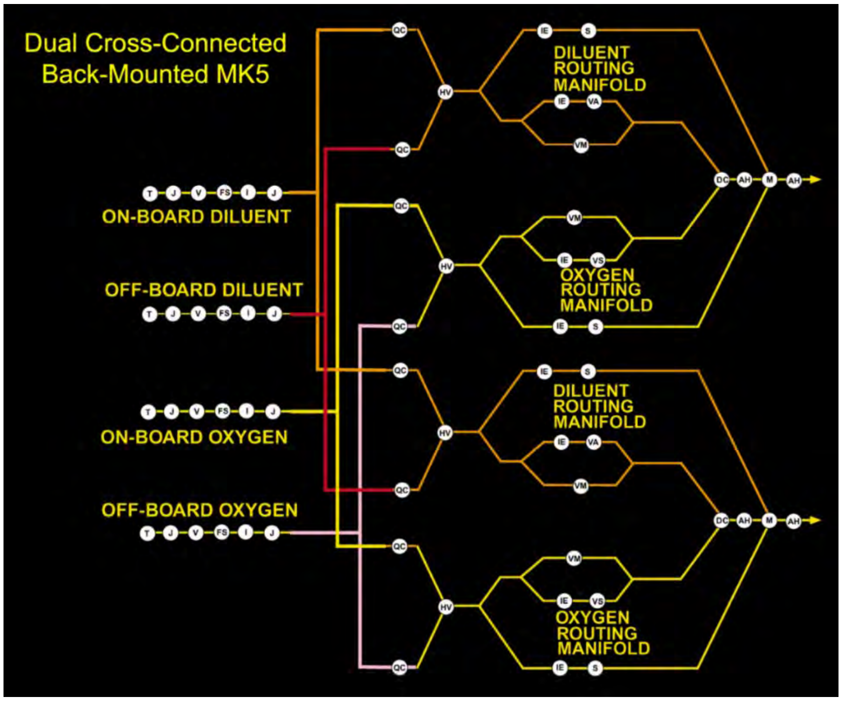

Figure 2. Fault-tree depiction of Cis-Lunar dual cross-connected Mk5 CCRs. Image courtesy US Deep Caving Team, Inc.

Bailout rebreather use can be divided into two groups, symmetrical and asymmetrical. The former describes configurations like Isler's and Stone's where two or more rebreathers are usually combined *en bloc* into a single system, typically backmounted, although dual sidemounted CCRs have been used for a number of significant exploration dives. The asymmetrical configuration means that the diver uses a primary rebreather system, almost always backmounted, with a separate rebreather system either side- or chest-mounted, of a different design to the primary unit, with dissimilar failure modes and breathing characteristics. Some of the advantages and disadvantages of each configuration are shown in Table 2.

Table 2. Advantages and disadvantages of bailout rebreather configurations

	Symmetrical (similar or identical units)	Asymmetrical (different bailout unit)
Examples	• Twin backmounted CCRs • Twin sidemounted CCRs	• Backmounted CCR and bailout sidemount rebreather • Backmounted CCR and bailout chestmounted rebreather
Advantages	• May have combined mouthpiece (no mouthpiece removal to switch loops) • Many parts identical between units (familiarity of use and ease of repair)	• Separate mouthpieces (redundancy) • Different design/configuration from primary unit (eg, sidemount, semi-closed); different breathing characteristics and failure modes • Easier to don and remove; may be passed to another diver
Disadvantages	• Diver is committed to one system • Useless if respiratory failure due to exertion or gas density • May be difficult to distinguish between units during use	• Must remove mouthpiece to switch loops

The two approaches seem to have evolved because of small differences in requirements between deep diving and long-distance diving. In the former, the performance of the bailout rebreather must be similar to the primary unit in terms of efficiency and breathing effort, so duplicating the primary rebreather makes sense (Figure 3), especially as many such dives have little horizontal component so the increased bulk and difficult ergonomics can be better tolerated. During the descent, the integrity of both loops must be continually checked so that frequent switching between loops is necessary.

Figure 3. Craig Challen assists Richard Harris prior to a dive at the Pearse Resurgence in New Zealand using a symmetrical back-mounted rebreather configuration. Photo courtesy Richard Harris.

The asymmetric approach has generally been favored for long-distance diving incorporating a completely or largely self-contained modular bailout rebreather which can be easily removed underwater, allowing it to be staged or swapped between team members (Figures 4 and 5). At more moderate depths, the performance characteristics of the bailout unit that matter most differ from those for extreme deep diving. Long-distance dives tend to have relatively few or gradual changes in depth, so frequent switching between units to ensure that neither unit is flooded is not necessary; one strategy is to check the bailout unit only after any significant increase in depth.

Figure 4. Asymmetric configuration: the author breathing from a sidemounted bailout semi-closed rebreather in Weeki Wachee cave, Florida. Photo courtesy Kirill Egorov/Karst Underwater Research.

Figure 5. Stone and his group developed a bailout system mounted onto a diver propulsion vehicle (DPV) for the Wakulla 2 project, but it was not popular with the exploration divers. Photo courtesy US Deep Caving Team, Inc.

Human factors considerations

The obvious disadvantage of using one or more additional rebreathers for bailout is the added complexity of the equipment package that must be managed by the diver. The potential hazards posed by complexity are difficult to assess objectively, but experience from other activities suggests that with good training and adequate experience, humans can manage complex systems effectively with low error rates. A second rebreather encumbers a diver in two ways: physically and cognitively. The physical bulk of the components (scrubber, hoses, etc.) of an additional rebreather in a position where it has acceptable hydrostatic lung loading may impair the diver's ability to manage the primary unit or perform other essential underwater tasks.

The addition of a second rebreather burdens the diver with an additional set of tasks, some of which may be relatively unfamiliar since the bailout rebreather is only used during a minority of dives. Research into cognitive task switching has shown that cognitive processing efficiency when switching tasks is decreased in the presence of anxiety and when the task being switched to is unfamiliar (Rubinstein et al. 2001). A good example of a strategy to reduce complexity at the expense of a small decrease in redundancy is the use of a dual BOV (Figure 6). Until more sophisticated and specific monitoring systems are developed, the only way the diver can be reassured that the bailout rebreather is functional is to switch back and forth between the two units during the dive, particularly while descending. The actions to do so must be performed correctly and sequentially to preserve the integrity of both loops. The dual BOV considerably decreases the complexity of this task and therefore presumably the probability of an error by the diver. The cost is a much smaller risk of a failure in the dual bailout valve compromising one or both rebreathers. The decision of how to balance these two risks is highly dependent on the diver's experience, personal preferences and the diving application.

Attempts have been made to develop measures of task complexity and to correlate these with human errors (Podofillini et al. 2013). If complexity is considered to be an objective quality of a system, its effect on the performance of an individual will vary enormously depending on training, knowledge and experience of that system, leading some authors to conclude that complexity is inherently subjective (Dörner 1996); the process by which an initially complicated and cognitively effortful task can be reduced to unconscious ease is familiar to anyone who has learned to drive a car. The lesson for rebreather divers here is that the risks of increased complexity and task loading can be significantly mitigated, if not eliminated, by practice with the bailout rebreather system in a benign environment.

Figure 6. The dual BOV developed by Harris and colleagues for use in the Pearse Resurgence. The upper lever switches between loops and may be used to equalize them. The second control, not visible behind the OC second stage, allows bailout onto OC. This device makes the necessary task of switching between loops very simple, at the expense of a small decrease in redundancy. Photo courtesy Richard Harris.

The rebreather diving community has recognized that human factors knowledge from other fields may be useful in reducing accidents. One example is the use of checklists, which are widely used in the aviation and building industries to manage complex situations reliably, and which are slowly pervading other areas such as healthcare where evidence of their efficacy in improving outcomes is accumulating (Boyd et al. 2017). The design and implementation of checklists in technical diving is evolving, but it appears evident that use of any checklist is better than none. Similarly, awareness of other human factors contributions, such as root cause analysis, to diving safety is increasing (Lock 2024).

Conclusions

The use of a backup breathing system in the event of a primary rebreather failure has become established practice for most rebreather diving. Open-circuit scuba is used for most rebreather diving, although for longer, deeper and more logistically complex dives the use of bailout rebreathers is increasing. Although limited, the evidence suggests that most divers will experience a malfunction requiring the use of bailout, and the extremely small proportion of rebreather fatalities attributable to these events suggests that current bailout practices (including open-circuit gas supplies) are adequate.

Use of bailout rebreathers is becoming more common, and units and training programs designed for this purpose are starting to appear. Many different configurations have been adopted, which can be broadly categorized into symmetrical ("twin rebreather") and asymmetrical ("bailout rebreather") arrangements; the advantages and disadvantages of these configurations are highly dependent on the needs of a specific dive team or dive. The ability of a bailout or twin rebreather to function as adequate life support depends on the exact nature of the problem affecting the primary rebreather. The additional complexity of managing a second rebreather during the dive may have significant cognitive costs which can increase the possibility of a dangerous error; this can be significantly mitigated by careful equipment design and progressive familiarization with the bailout rebreather configuration.

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QUESTIONS AND DISCUSSION

TIM BLOEMEKE: Can you walk us through the process of developing your system for bailout rebreathers? Is there anything you have tried and abandoned or just the research and development? I am interested in the errors.

ANDREW PITKIN: I typically dive a backmounted unit with a sidemounted unit as a bailout. I also dive a sidemounted rebreather on its own with open-circuit bailout. A sidemounted rebreather is very hard to configure in a streamlined way. It is possible, but hard. Getting a backmounted unit and a sidemounted unit working together in a streamlined way is difficult. You have considerations about where you put oxygen and diluent, and are they interchangeable, have you got redundancy of both of those things, how much redundancy do you actually need? I think it is very specific. I have been sold on the idea of using a semi-closed unit for a lot of the long-distance stuff because it has much less complexity. We have been using the Halcyon RB80 because it is so simple. You just need to plug in diluent and there is nothing else to worry about, no sensors, no PO_2 displays. It acts essentially as an open-circuit gas extender.

ALEJANDRO GARBINO: Going back to the earlier discussions about diver reportable events, what would you consider the threshold for reporting a bailout event? Should bailout be a never, ever event or is it something that if it happens, does not really matter? Would that be something that reaches a threshold where it should be noted, published, entered into a database, anything like that?

ANDREW PITKIN: If you are talking about the medical sense for a never event, which is that it really should never happen, I do not think we can get there with bailing out from a rebreather. I think it is definitely worth recording it. This goes back to what I was saying about data. We do not have very good data and we need to collect better data to make better decisions going forward. Most of us would agree that most of the problems that we have had are due to human error. And I know that my caustic cocktail was human error and many other incidents I have had were due to my errors. So that is what we have got to get better at. I do not think it is possible to get it to a never event in the medical sense.

PETE MESLEY: My question is what is your primary decision when you are making to use a bailout rebreather or keeping it open-circuit? Is it purely gas extension?

ANDREW PITKIN: Well, initially it was "We just cannot do this dive without a bailout rebreather." But then as we got more comfortable with the concept, it became "Well, we could do this dive and take three or four stages. Let's just take bailout rebreathers with us." You shift. It is hard to say it is a firm decision-making process. It is really about how much effort is it going to be to take three or four stages with me versus just prepping a rebreather.

AUGUSTO FEDERICI: I have a question about dual rebreather bailout strategy. When you switch from the main rebreather to the secondary rebreather, to the bailout rebreather, do you think you must pass through an open-circuit sanity breath or you can switch directly to the second rebreather?

ANDREW PITKIN: What is the context, in an emergency?

AUGUSTO FEDERICI: Not to test the bailout, but if you think you need to bail out so you move to the bailout rebreather. For example, in the case of high CO_2. That is the real question. Due to your lungs.

ANDREW PITKIN: I think if you were suffering from hypercapnia, you were feeling intensely breathless, which would be a very typical symptom of hypercapnia, yes, I would definitely switch to open-circuit and get things under control. It is going to be extremely hard to switch loops in any kind of disciplined fashion in that scenario.

AUGUSTO FEDERICI: Most of the time you have an issue with high CO_2 in your lungs is because you are holding on your primary loop instead of moving quickly to your secondary loop. Let's forget you have an issue with gas density because I believe we all would not have that kind of situation. A common issue in the past was that people would refrain from bailing out because the bailout was open-circuit. They stayed longer than they had to on the loop instead of switching to a bailout. If you have a second rebreather, maybe moving to the second rebreather is an easier decision to make.

ANDREW PITKIN: And the reason they were not switching to the open-circuit bailout was?

AUGUSTO FEDERICI: Maybe because they were really deep.

ANDREW PITKIN: They did not think they had enough gas? Every time I have dived the bailout rebreather, I have also had a bailout valve to switch easily to open-circuit. And usually quite a reasonable quantity of open-circuit gas too.

PAUL TOOMER: What is your strategy for checking your bailout rebreather during dives to ensure that you have confidence in it?

ANDREW PITKIN: That is a great question. The caves we tend to dive in have some suitable points to check them. The first is usually after 10 to 12 m (33 to 40 ft) of descent. If it was going to flood immediately, it would probably have flooded by then. Then it really depends on the cave configuration. Typically, the next check would be after any significant change of depth. The ability to check both loops on a regular basis during descent is critical. It is generally going to be during descent that you have a loop flood if there is a problem with one of the units. I think there is potential value in a water detection system like camera housings have if manufacturers are looking for ideas. Tell us what you do.

PAUL TOOMER: We have used a few different strategies. The first is to get to the bubble check and check that the rebreather is happy. Then the descent to the bottom. After 20 min or so I will do another check on the rebreather before I start my ascent. The next is when I am comfortable in decompression, when I will go onto it again. And then again in the shallows. I did do one dive where I did the entire dive up to the 6 m stop without checking it at all to see how much trust I could have in the unit. We were hoping it would not fold so we checked it for folding. She behaved absolutely perfectly in that case. It is planning the strategy, considering how much time we have in our dive with the objective we have been given to jump from one rebreather onto another, and then all the psychological stuff. Am I going straight to the rebreather or am I going to open-circuit first? I am super interested in the discussion because I would love to release a course on bailout rebreather at RAID as we learn more. The problem now is that there are not that many of us doing it and we all have slightly different strategies.

ANDREW PITKIN: I think that strategies are often situation specific. What works for you may not work for me and vice versa. I agree with you about the psychological side of things. Typically, when we are doing a long cave exploration, there is enough open-circuit bailout gas in the first part of the cave for our support divers. This may cover quite some distance into the cave. There will, though, be a point where we go beyond our open-circuit bailout. I always check my bailout rebreather at that point because I know I am crossing into the zone where I am really depending on what I have with no other option.

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Mixed-Mode and Mixed-Platform Diving

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Abstract

Mixed-mode and mixed-platform diving operations contain inherent risks requiring mitigation. A non-closed-circuit rebreather (CCR) trained diver buddy may not possess the knowledge and skill to assist a CCR diver most effectively, and a CCR diver using a different rebreather platform might not understand how best to aid their team member. Incorporating a mixed-mode or mixed-platform briefing into the dive operation's pre-dive briefing helps to address safety challenges resulting from CCR divers diving with open-circuit team members or from CCR divers diving with others not using the same make and model of rebreather. A mixed-mode briefing includes a CCR unit overview and hazard discussion by component, handling emergencies, and dive phase (descent, bottom, or ascent) awareness. The mixed-platform briefing reviews the operation of each CCR unit and platform-specific emergency procedures.

Keywords: diving safety, multi-platform, pre-dive briefings, rebreather, technical

Introduction

Mixed-mode and mixed-platform diving are commonplace, as evidenced by the preponderance of hands raised in the Rebreather Forum 4 audience when the author inquired about the number of divers engaged in dives involving these two components. Each offers benefits, while the hazards, if unmanaged, set the stage for adverse outcomes in an emergency involving a rebreather-diving team member.

The author credits much of the information presented in this paper to his participation in the occupational dive operations conducted under the auspices of the California Academy of Sciences and the University of Hawaii.

The following definitions are used:

Dive mode: a type of diving requiring specific equipment, procedures, and techniques. Examples include open-circuit, surface-supplied air, rebreather, and breath-hold.

Dive mode is a commonly used term in North American occupational diving organizations, including the United States Occupational Safety and Health Administration (OSHA), the American Academy of Underwater Sciences (AAUS), the Canadian Association for Underwater Science (CAUS), and the Association of Diving Contractors International (ADCI).

Mixed-mode: a dive conducted with divers of the same team or buddy pair using two or more dive modes.

Dive platform: a specific make (manufacturer) and model of rebreather.

Mixed-platform: a dive conducted with divers of the same team or buddy pair using different rebreather platforms.

Mixed-Mode

Benefits

Closed-circuit rebreather (CCR) training courses frequently entail travel; this increases the probability that the prospective rebreather diver's instructor and fellow students do not reside in the same location and may not be readily available as dive buddies after training. Yet a rebreather diver's proficiency in using their unit is critical to their safety and the safety of their team; this is true of newer and of experienced rebreather divers. Since rebreather users comprise a minority of compressed-gas divers, mixed-mode diving operations provide the diver with valuable proficiency-building diving opportunities by buddying with readily available open-circuit divers.

Another more obscure benefit of mixed-mode dive teams is the safety or support diver role during technical rebreather diving operations. Many teams utilize this concept for dives with required decompression—essentially providing a mechanism for someone without a decompression obligation to safely ascend with a diving casualty or to communicate with the surface team. While a safety or support diver role requires training, it does not necessitate that the diver use a rebreather. Using open-circuit scuba can simplify logistics and increase the number of divers that may be qualified for the role.

Hazards

Mixed-mode diving operations possess inherent hazards, which are increased if the open-circuit diver partner lacks rebreather diving familiarity. There are a number of aspects of rebreather operation that may be unfamiliar to the typical open-circuit diver:

Dive conduct

Loop gas volume and content management tend to slow rebreather divers' descents and ascents compared to open-circuit scuba divers. This factor also results in rebreather divers avoiding unnecessary upward and downward excursions during the dive's bottom phase.

Equipment operation

Diving a rebreather requires greater psychomotor involvement than an open-circuit unit. While electronic CCRs have a solenoid that automatically adds oxygen to maintain a constant oxygen partial pressure (PO_2) based on a setpoint (either fixed or user-selected) in the unit's controller, many divers manually inject this gas into their breathing loops throughout the dive. Divers also add diluent to reduce the PO_2 and increase the loop volume. Additional tasking includes buoyancy compensator (BC) and possibly drysuit management, which also exist for open-circuit divers.

Oxygen monitoring system awareness and interpretation

Most CCR units have an oxygen management and monitoring system—oxygen sensors, a controller, and a solenoid—that requires the rebreather diver's attention throughout the dive. Established practices help to mitigate dangerous hyperoxic and hypoxic breathing loop conditions. These obligations are in addition to the depth and time monitoring required of all divers.

Rescue skills

Some rescue skills, notably those required to manage an unresponsive diver, differ on a rebreather. Rebreather counterlungs must be vented on ascent to avoid rapid ascent rates and the potential for the rebreather diver to experience mouthpiece ejection or pulmonary barotrauma from excessive positive breathing loop pressures. This mechanism is in addition to the expanding volume of the BC and the drysuit, if worn.

The rebreather dive surface valve (DSV) or bailout valve (BOV) must be closed to avoid flooding the unit when the mouthpiece is out of the diver's mouth. Additionally, many CCR divers place non-ditchable ballast (weight) on their units. While this convention does not differ much from many open-circuit equipment configurations, the rebreather's design allows weight placement in locations potentially unknown to the assisting dive buddy.

Rebreather configurations typically involve securing straps to keep the counterlungs close to the diver's chest or back. These straps are in addition to the standard harness or BC securing methods on open-circuit equipment. They can cause delays in the dive buddy's ability to remove the rebreather diver's equipment to extricate them from the water.

Mitigation

While all divers should exercise prudence in their buddy selection, it can be even more important for the mixed-mode diving team. Rebreathers require more focus from their users than traditional open-circuit units do; this can reduce the available attention the diver has to place on their dive buddy. Therefore, mixed-mode dive teams should consist of divers who possess proficiency with their respective diving equipment to optimize each diver's ability to monitor and assist a team member if needed.

A mixed-mode briefing focusing on rebreather hazard awareness and mitigation is a cornerstone of mixed-mode dive team safety. Ideally, this briefing is a standardized written document, addressing the salient safety aspects of rebreather operation. Briefings will typically include several sections.

CCR unit overview

The rebreather diver begins the briefing by conducting a general overview of the CCR components and their functions. The diver can follow the gas path starting at the mouth, explaining the opening and closing of the DSV/BOV, mouthpiece security and integrity, and one-way valve function. The overview proceeds as gas moves through the breathing loop hose into the exhalation counterlung, where the diver addresses over-pressure relief valves (OPRV), manual addition valves (MAV), and drain operation. Gas then enters the head, which houses the unit's oxygen sensors and solenoid; the head-up display (HUD) and controller connect here. Next is the scrubber, followed by the inhalation counterlung, its drain, and manual or automatic diluent valve (ADV) operation. It is prudent to briefly discuss how the breathing loop and scrubber bucket components are assembled. The diver explains the rebreather's pneumatics, including the oxygen and diluent gas cylinders, attachments, regulators, and associated hoses. Finally, the diver discusses the handset (including buddy light signals), backplate, harness, BC, and drysuit inflation system operation, and the location and quantities of ditchable and non-ditchable ballast.

Component hazards

Consistent with the unit overview, the CCR hazards discussion begins with breathing loop flood arising from a loose BOV/DSV mouthpiece, a hole in the breathing hose, or an incompletely seated o-ring-sealed connection. A diver failing to completely close the BOV/DSV when removing it from their mouth in the water can also flood the unit. An incorrectly installed, damaged, or missing one-way valve can lead to severe hypercapnia.

Inadequate counterlung volume can also cause hypercapnia, while excessive gas quantities can increase work of breathing and cause pulmonary barotrauma, and even mouthpiece ejection, especially during water entry. Stuck MAVs can also result in counterlung volume excess, hyperoxia, or hypoxia. Finally, drains or OPRVs that do not close completely can allow water into the breathing loop.

In the unit's core, a missing scrubber bucket o-ring or fastening mechanism can lead to a flood and precipitate a caustic cocktail. Hypercapnia can result from an incomplete scrubber packing or assembly, a missing scrubber basket-to-head seal, or a malfunctioning bucket or basket spring sealing mechanism. Hypoxic diluent mixes could result in hypoxia if a diver bails out onto them or an ADV sticks at shallow depths; hyperoxia can occur if a solenoid or oxygen MAV sticks open or during a current-limited oxygen sensor event.

Emergencies

The CCR diver and their open-circuit partner should review their gas-sharing protocol. Rebreather divers should have a strategy to readily share gas with their teammates either via an offboard bailout gas cylinder or a donatable second stage mouthpiece attached to their onboard diluent gas supply. For onboard gas supplies, consideration should be given to the potentially limited volume.

The dive team should discuss the complexities of rescuing an unresponsive rebreather diver. Essential items include maintaining the DSV/BOV in the diver's mouth, how to respond if it is out, and how rescuing divers should position themselves to best control the CCR diver. Counterlung and drysuit OPRV opening and ascent rate management come next, followed by unit removal at the surface and diver extrication.

CCR dive phase awareness

Each dive phase has unique aspects where rebreather use differs from open-circuit. Rebreathers have unit-specific parts inspection and assembly checklists. These lists continue through the pre-dive preparations and pre-entry checks. CCR users need to brief their open-circuit partners on the importance these checklists have on their safety and that of the team. The rebreather diver should also communicate time expectations for parts inspection and unit build. Many open-circuit divers are not familiar with procedures specific to CCR operations.

Rebreather divers may enter the water with their offboard bailout cylinder in place, while others don and connect them in the water. Some divers carry their bailout gas supply in larger, back-mounted cylinders with a deployable second-stage mouthpiece attached for gas sharing with another diver. Dive teams then view the CCR diver from both the front and rear, checking for bubbles indicating equipment leaks.

CCR divers may descend slower than their open-circuit counterparts, allowing more time to add diluent to maintain a consistent breathing loop gas volume and PO_2. Rebreather divers also switch their controller setpoint to the high setting at some point during the descent, if applicable, or raise their PO_2 above the setpoint to check for current-limited oxygen sensors. Many CCR divers pause their descent to accomplish these tasks and communicate completion across the dive team before continuing.

Open-circuit divers may observe that their rebreather diver partners swim slower due to the increased drag of the apparatus. CCR divers may also swim around objects instead of ascending over them. This practice aids breathing gas efficiency by alleviating the need to vent the counterlung during the ascent and then add diluent back when descending after clearing the obstacle. Lastly, the open-circuit diver team member's variable breathing gas PO_2 gas supply, and consumption rates tend to limit the team's bottom time. In contrast, the bailout gas supply is typically the rebreather diver's chief constraint.

Finally, a slower ascent rate allows the CCR diver additional time to vent the expanding counterlung gas to maintain a constant loop volume. This practice reduces the quantity of oxygen addition needed to maintain the desired PO_2 during the ascent.

Mixed-Platform

Benefits

Many rebreather divers prefer to partner with other CCR users to minimize the mixed-mode dive team complexities mentioned previously. Doing so can allow for greater flexibility in dive time and reduce gas quantities required, especially for staged decompression exposures. The smaller oxygen and helium amounts used for deeper diving reduce operational costs, gas blending time, and the logistical burden incurred procuring larger breathing gas supplies.

Partnering with divers utilizing the same rebreather platform has apparent advantages. Still, the large number of rebreather makes and models available on the market increases the likelihood that two CCR divers might own and operate different ones. This factor increased the mixed-platform diving prevalence by expanding a diver's rebreather buddy availability. This practice is commonplace across recreational and occupational diving despite the higher single platform use across dive programs. This factor is probably due to the reduced maintenance costs and the increased training consistency and efficiency accompanying a program's use of a single rebreather model.

Hazards

A diver's lack of familiarity with their partner's rebreather platform presents a significant hazard to a mixed-platform dive team. Equipment configurations vary not only across rebreather platforms, but across divers utilizing the same makes and models of rebreathers. While this variation also exists for open-circuit divers, the increased complexity accompanying CCR provides for significant unit configuration variances. All dive team members must know these differences to optimize operational safety.

The mixed-platform hazard list is considerably less than that of mixed-mode because, to an extent, CCR units share a similar component set with sometimes only subtle differences in component function. To that end, a competent rebreather diver is likely to possess an awareness and understanding of the operation of a CCR unit they do not dive. But there are some areas that are not intuitive and might require more attention.

Monitoring system interpretation

Rebreather divers are already aware of a unit's oxygen monitoring system (electronics), but that does not directly translate into their ability to interpret the system's output. Shearwater Research produces many of the monitoring systems used on current production rebreather units, but some manufacturers produce electronic packages specific to their models; this means controllers and HUD show the diver information that their other-platform buddy might not be as quick to access or interpret. Data relevant to all CCR platforms include indications for hypoxia and hyperoxia. Team members should know the audible, tactile, or visual alarms of the various units used in a team and how and when to assist partners.

Rescue skills

A diver's knowledge, skill, and ability to assist another diver experiencing distress at the surface or underwater is a universal diving safety tenet. Assisting a diver at the surface requires that their team members know the diver's ballast location, harness, and electronics (controller cable) configuration, and offboard gas carriage scheme to doff weights, bailout gas, and/or CCR unit as needed for in-water management and extrication from the water. Rebreather diver configuration variabilities can be substantial, making it paramount that team members are aware of the specifics of each unit. These variations are also seen across divers using the same make and model.

The same configuration variances can confound a team's efforts when assisting a buddy underwater. While ballast may not commonly be jettisoned underwater, especially with a ceiling (physical or physiological) present, many other aspects of the diver's configuration will affect their buddy's ability to maintain the distressed diver's mouthpiece, operate their BOV, monitor and operate their oxygen controller, manipulate MAVs, BC, and drysuit inflators and dumps, and remove their offboard bailout gas cylinders.

Mitigation

As with mixed-mode diving, prudence in buddy selection remains paramount for mixed-platform operations. Responsible team members should be curious about their buddy's equipment choice, configuration, and function. Additionally, mixing platforms requires greater awareness of divers utilizing different rebreather makes and models. Divers must possess proficiency in their unit's operation before taking on this added complexity, especially when dealing with urgencies or emergencies involving their mixed-platform teammates.

Akin to mixed-mode diving, a mixed-platform briefing focusing on unit orientation, operation, and emergencies is vital to safely diving with divers using rebreather models or configurations with which their dive buddies lack familiarity. This briefing should be standardized as a written document, emphasizing unit operations and potential emergencies. Teams may be able to conduct such briefings in 10 min. Briefing details can be discussed under two key sections.

Operation overview

Divers should know how to open and close their buddy's DSV/BOV, and the group should review each unit's flood recovery procedure, including counterlung water removal mechanisms and scrubber water detection if equipped. Team members also review each unit's electronics package, noting components, including controllers, monitors, HUDs, and associated visual or audible buddy warning systems. Next is a brief review of each platform's onboard and offboard cylinder configuration, as applicable. Teams should discuss BOV connections, offboard gas plug-in availability, cross-team compatibility, and BC and drysuit inflator operation and gas sources. Divers must also share ditchable and non-ditchable ballast locations.

Emergencies

Consistent with the mixed-mode discussion, all mixed-platform team members should be able to share gas with another diver. Each diver must also be prepared to respond to an unresponsive team member. Preparation for such a response includes rescuers knowing how to position themselves to best manage the unresponsive diver. This position should allow the assisting diver to maintain the loop in the unresponsive diver's mouth and manipulate counterlung and drysuit OPRVs and BC inflator and dump valves to control ascent as necessary. Divers and surface personnel should also know how to remove the diver's equipment to extricate them from the water.

Community Recommendations

The AAUS (2019; pg. 44-5) standards for scientific diving recommend the following:

> *11.50 Operational Requirements*
>
> > *G. Diver carried offboard bailout is not required under conditions where the onboard reserves are adequate to return the diver to the surface while meeting proper ascent rate and stop requirements, and the system is configured to allow access to onboard gas. These calculations must take into consideration mixed-mode operations where an open-circuit diver could require assistance in an out-of-gas situation.*
> >
> > *K. The diving control board or their designee will:*
> >
> > > *5. Establish policies for the use of mixed-mode and mixed-rebreather platform dive teams under their auspices.*
> > >
> > > *5b. At a minimum, divers must be cross-briefed on basic system operations for establishing positive buoyancy, closing a rebreather diver's breathing loop, and procedures for gas sharing.*

This excerpt from the National Park Service (NPS) Reference Manual – Diving Safety and Operations Manual, Chapter 4 -- Diving Operations, states:

> *4.2.4 Mixed Equipment Configurations*
>
> *A. It is recognized that dive buddies use dissimilar diving modes or gear configurations for a variety of reasons (previous training, dive objectives, dive task assignments, etc.). The use of dissimilar diving modes or gear configurations on a given dive is permitted within NPS dive operations.*
>
> *However, it is recognized that the use of dissimilar gear configurations carries with it the potential for confusion in an emergency. To address this issue, divers are to thoroughly brief dive buddies and others involved with the dive operation on specifics associated with their particular gear configuration and/or diving mode. This briefing will include, but is not limited to:*
>
> *I. Placement and function of alternate gas sources for buddy access in an emergency*
> *II. Placement of and access to diver carried cutting implements*
> *III. Function of buoyancy control device(s)*
> *IV. Interpretation of information displayed on any diver carried electronics or gauges pertinent to decompression management, gas management, PO_2 display, or other dive related information*
> *V. Recognition and interpretation of any alerts/alarms produced by dive related electronics or gauges*
> *VI. Expected buddy response to any alerts/alarms produced by dive related electronics or gauges*
> *VII. Specialized hand signals*
> *VIII. Basic problem recognition and response associated with dissimilar gear configuration*
> *IX. Placement and function of clips, valves, mouthpieces, buttons, hoses, etc. associated with dissimilar gear configuration*
> *X. How to remove the diver from the equipment if necessary*
> *XI. Placement of diver carried weight*
> *XII. Actions required to remove diver carried weight*

The European Scientific Diving Panel (ESDP) has yet to agree on mixed-mode recommendations but plans to establish this during the next edition of its best practices document. The ESDP advises that a risk assessment should address the increased risk imposed by multi-platform (mixed-platform) dive operations and recommends that divers reduce the risk by diving the same rebreather unit. Divers should consider taking a crossover course to facilitate same-unit diving operations.

Global Underwater Explorers (GUE) and Unified Team Diving (UTD) require standardized equipment configurations, gases, and diver skill training schemes that facilitate gas sharing across mixed-mode teams. The Professional Association of Diving Instructors (PADI) also incorporates general recommendations around gas sharing, gas selection, and equipment familiarization recommendations in their CCR training program.

Discussion

Mixed-mode and mixed-platform diving activities are increasingly commonplace, especially in recreational diving. While briefings discussing the salient safety points of these diving activities are prudent, further research is needed to optimize these processes. The author has yet to identify a recreational or occupational diver incident tracking system or database actively capturing mixed-mode or platform diving activity. In the meantime, occupational diving standards-setting groups, and recreational diving training agencies can continue to augment mixed-mode and mixed-platform awareness and briefing guidance by fortifying their standards and instructional materials with additional content regarding these topics. Mixed mode and mixed platform diving was addressed in the Rebreathers and Scientific Diving workshop (Seymour 2016), focusing on the United States National Park Service's recommendation. Additional insights can be gained from the Rebreather Training Council (RTC), the International Standards Organization, and the Rebreather Education and Safety Association (RESA); all interested in the alignment of rebreather industry standards.

Conclusion

Divers should develop and utilize briefings to manage and mitigate potential hazards of mixed-mode and mixed-platform diving activities. The team's awareness of each diver's rebreather unit configuration and operation can be critical to conducting such diving safely. The large number of open-circuit divers available to buddy with rebreather divers make mixed-mode diving activities prevalent, and the variety of rebreather makes and models increases mixed-platform diving probability. While this observation is more apparent in the recreational community, occupational diving, notably scientific diving, acknowledges the activities and provides guidance, albeit limited, for safe conduct. The rebreather diving community should endeavor to acquire more data to better understand how these diving operations affect diver safety. Incorporating appropriate fields into incident reporting systems is a logical step to enhance data collection. Concurrently, diver training agencies, in concert with equipment manufacturers, should develop and provide briefing guidance within their standards, training materials, and operation manuals for instructors to teach end users.

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Advances in Decompression Theory and Practice

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Abstract

Venous gas emboli (VGE) are widely used as a surrogate endpoint instead of decompression sickness (DCS) in studies of decompression procedures. There is no VGE grade that has both good sensitivity and specificity for DCS and peak post-dive VGE are highly variable following dives on the same dive profile. Despite these limitations, there are emerging trends toward interpreting VGE grades measured in an individual diver. However, recent analysis shows that most divers produced a wide range of VGE grades after repeated dives on the same dive profile. Consequently, post-dive VGE grades are not useful for evaluating decompression practices for individual dives. DCS cases are nevertheless associated with an individual diver's highest VGE grades and not with their lower VGE grades, suggesting there is substantial within-diver variability in susceptibility to DCS. Inert gas counterdiffusion following helium-to-nitrogen breathing gas switches has long been considered a principal cause of inner ear DCS (IEDCS). However, a body of literature published over the last 20 years suggests that in most circumstances IEDCS is likely caused by arterialization of VGE which transit to the inner ear and if that structure is gas supersaturated the bubbles grow and cause injury. Conventional decompression algorithms, such as the ZH-L16 Gradient factor settings used by technical divers, do not explicitly control the probability of DCS (P_{DCS}). Instead P_{DCS} increases with schedules for increasing depth and bottom time. As deeper technical dives become more common, so will DCS if decompression algorithms are not adjusted to be more conservative.

Keywords: decompression algorithms, decompression sickness, probability, venous gas emboli

Introduction

This paper examines advances in decompression theory and practice in the approximately 10 years since Rebreather Forum 3. The paper does not cover observations or hypotheses from that period with no immediate practical application. Instead, the paper focuses on advances in theory that can be operationalized. In this context, recommendations are not prescriptive, but rather provide general principles that might be (or not be) useful in planning decompression.

Venous Gas Emboli Monitoring in Individual Divers

Decompression sickness (DCS) is caused by intracorporeal bubble formation from supersaturated dissolved gas. During decompression, bubbles form in gas supersaturated peripheral tissues and enter the venous circulation where they are easily detected by ultrasonic methods and their profusion graded on an ordinal scale. These venous bubbles (venous gas emboli, VGE) are widely used as a surrogate endpoint instead of DCS in studies of decompression procedures both because VGE occur commonly after diving whereas DCS is rare and because VGE profusion is presumed to be correlated with an increased risk of bubbles forming at or impacting sites where they will cause DCS. Figure 1 shows the relationships that justify the use of VGE as a surrogate endpoint for DCS (Doolette 2016).

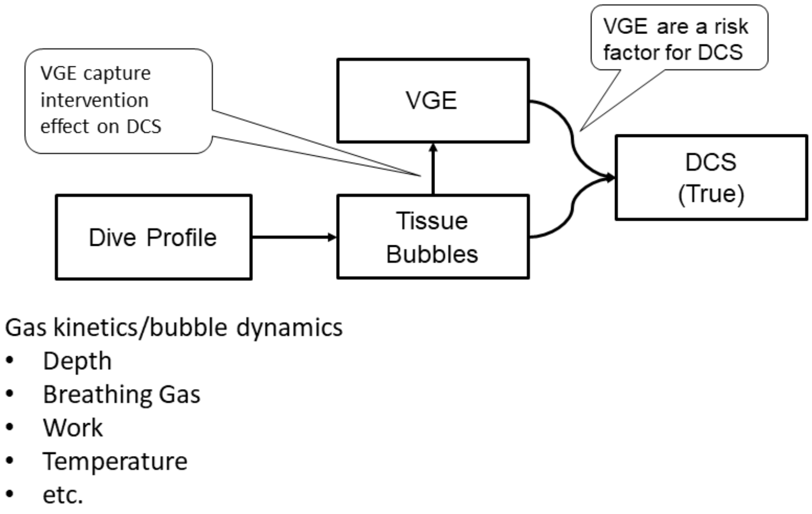

Figure 1. Relationships between dive profile (intervention), VGE (surrogate endpoint) and DCS (true endpoint). VGE can be used as a surrogate endpoint for DCS for interventions that alter tissue supersaturation (loosely collected under the term dive profile).

In large compilations of diving data with both DCS and VGE outcomes, cumulative incidence of DCS increases with increasing peak post-dive VGE grades, see Figure 2 (Sawatzky 1991; Doolette 2016). However, there is no VGE grade that has both good sensitivity and specificity for DCS and peak post-dive VGE are highly variable following dives on the same dive profile (depth/time/breathing gas history) (Doolette 2016).

Despite these limitations, there are emerging trends toward interpreting VGE grades measured in an individual diver. Notably, divers can now purchase equipment used for self-monitoring of post-dive VGE and using the VGE grade to provide feedback on modifying future decompression practice (Germonpre et al. 2020; Azoth Systems. O'Dive, the first connected system for custom decompression system [internet]. Ollioules (FR): Azoth Systems; c2022 [cited 2023 Jul 03] Available from: https://o-dive.com/en/home/). A future application of VGE measurements could be real-time physiological monitoring during diving for real-time control of decompression (Mitchell and Pollock 2023). Validity of these emerging and potential applications of individual VGE measurements rely on an understanding of the within-diver variability in VGE grades as well as the association of VGE grades to DCS in individual divers. However, little is known about how much of the variability in post-dive VGE grades is proportioned between-diver and within-diver. Two small studies (three and 10 divers) suggested there is within-diver variability in post-dive VGE grades (Papadopoulou et al. 2018; Hess et al. 2021). A retrospective analysis of 834 man-dives conducted on six dive profiles with both VGE and DCS outcomes indicates substantial within-diver variability in post-dive VGE grades and DCS (Doolette and Murphy, 2023). Among these data, 151 divers did repeated dives on the same dive profile on two to nine occasions separated by at least one week (total of 693 man-dives). Most divers produced a wide range of VGE grades after repeated dives on the same dive profile (many divers had VGE ranging from grade 0 to grade 4). The most obvious implication of the variability in post-dive VGE is that monitoring of VGE following uncontrolled field dives is not useful for evaluating and recommending decompression practice for individual divers. Since an individual diver manifests widely varying VGE grades following carefully controlled repeated dives that are identical for all practical purposes, different VGE grades following successive uncontrolled field dives cannot be attributed to differences in decompression practice.

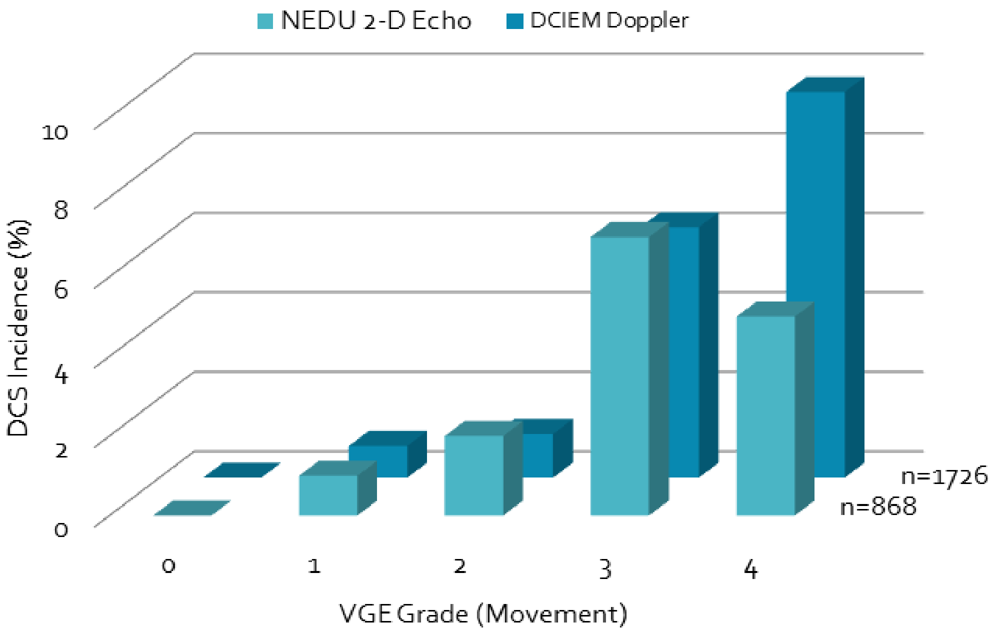

Figure 2. VGE grades and cumulative incidence of DCS. Experimental dives with both VGE and DCS outcomes. Data were collected for various dive trials and binned according to the maximum post-dive VGE grade measured at any site under any condition (rest or movement). Bars represent the cumulative incidence of DCS as percent of all dives with that grade. For the Defence and Civil Institute of Environmental Medicine (DCIEM) data (back), VGE were detected by Doppler flow meter and VGE profusion is represented with the Spencer scale. For the Navy Experimental Diving Unit (NEDU) data (front), VGE were detected by 2-D echocardiography and graded according to a Spencer-like scale derived from the Eftedal-Brubakk scale (Eftedal and Brubakk 1997; Doolette 2016; Mollerløkken et al. 2016). Total number of dives in each data set (n) are given.

Inner Ear Decompression Sickness

The pathophysiology and manifestations of DCS in technical divers are the same as for any other diving communities. However, one manifestation of DCS that appears to be associated with deep technical dives is injury to the vestibulocochlear apparatus (inner ear DCS, IEDCS, often with no other manifestations (Doolette and Mitchell 2003; Guenzani et al. 2016). Retrospective analyses at some treatment centers show an increasing prevalence of IEDCS from all types of diving over the last 30 years which may in part be due to the increase in technical diving over the same period (Azzopardi et al. 2019; Lindfors et al. 2021). IEDCS is characterized by nausea with vomiting, vertigo, and hearing loss which can onset while the diver is immersed and completing the stops prescribed by their decompression algorithm. These symptoms are life threatening for a technical diver who must choose between continuing decompression and risk drowning or omitting a substantial decompression obligation and risk additional serious manifestations of DCS (Doolette and Mitchell 2003).

Two seminal observations embody the 20th century viewpoint of IEDCS. The first observation was manifestations similar to cutaneous and inner ear DCS (pruritus and vestibular dysfunction) with no change in ambient pressure (isobaric) during a 366 msw (1200 fsw) helium-oxygen ($He\text{-}O_2$) saturation dive when divers switched from breathing the $He\text{-}O_2$ atmosphere to gas mixtures containing nitrogen or neon (Lambertsen and Idicula 1975). These DCS-like manifestations were hypothesized to be the result of bubble formation caused by faster inward diffusion of helium directly from the atmosphere into the body (towards blood and tissue containing less helium and more nitrogen) than "isobaric counterdiffusion" of nitrogen in the opposite direction. The second set of observations were case series of IEDCS from deep He-O_2 decompression dives with the onset of symptoms typically during decompression and often not long after a switch to air breathing deeper than about 30 msw (100 fsw) (Bühlmann and Gehring 1976; Farmer et al. 1976). Although both inadequate decompression and isobaric counterdiffusion were considered potential mechanisms of these IEDCS cases, there followed such a deep suspicion of helium-to-nitrogen gas switches during decompression that some organizations abandoned the practice.

The role of isobaric counterdiffusion in IEDCS was re-evaluated in the 21st century with the publication of a physiological model of the inner ear which indicates that following a helium-to-nitrogen breathing gas switch, transient supersaturation can develop in the vascularized membranous labyrinth (the site of the functionally important receptors of the cochlea and vestibular apparatus) without any change in depth, principally due to counterdiffusion of helium and nitrogen between inner ear structures (Doolette and Mitchell 2003). During a long exposure to helium-rich breathing gas, the inner ear takes up helium from the blood perfusing the membranous labyrinth from where the helium diffuses into the avascular, fluid-filled endolymph and perilymph structures. With a switch to nitrogen-rich breathing gas, the diffusion of helium back into the membranous labyrinth exceeds the counterdiffusion of nitrogen in the opposite direction. The magnitude of the supersaturation that can develop is proportional to the magnitude of the change in helium and nitrogen partial pressures. For instance, the gas switch during the Lambertson and Idicula (1975) 366 msw (1200 fsw) saturation dive was from breathing He-O_2 to breathing of a mixture of oxygen, helium and 10 atm of nitrogen, and the model predicted isobaric supersaturation of 0.4 atm. This is sufficient supersaturation for bubble formation in vivo, and this is, therefore, a plausible explanation for the vestibular symptoms reported in that study.

However, the helium-to-nitrogen gas switch during decompression from bounce dives is made at much shallower depths (typically shallower than 45 msw [148 fsw]) and consequently results in smaller change in helium and nitrogen partial pressures than the 366 msw saturation dive. The supersaturation that can develop by counterdiffusion of gases at depths shallower than 45 msw is correspondingly small. The inner ear model predicts much more substantial supersaturation can develop in the inner ear during normal rates of decompression, prior to any gas switch, because the washout of gas is relatively slow. Therefore, the contribution of gas switches to IEDCS during decompression from He-O_2 bounce dives is uncertain.

The 21st century also brought an increasing awareness that IEDCS occurs quite commonly following recreational air or nitrox dives, albeit towards the deep end of the air or nitrox diving range. Among these cases there is a high prevalence of major right to left shunting of venous bubble contrast, indicative of a persistent foramen ovale (PFO) or other intracardiac shunt (Cantais et al. 2003; Ignatescu et al. 2012; Klingmann 2012; Gempp and Louge 2013). This association suggests that IEDCS might be caused by passage of arterialized venous bubbles into the labyrinthine artery. However, this seems an incomplete explanation for the relationship between pure IEDCS and right-to-left shunt. The brain must concomitantly be exposed to larger numbers of VGE, yet IEDCS frequently occurs in the absence of cerebral symptoms. This may be explained by slower inert gas washout in the inner ear than in the brain. Thus, there is a window after surfacing within which VGE arriving in the inner ear (but not the brain) would grow due to inward diffusion of supersaturated inert gas (Mitchell and Doolette 2009).

This mechanism may also be relevant to the onset of IEDCS at depth during decompression when inner-ear symptoms characteristically occur in technical diving. Thus, it is possible that arterialized VGE could reach the inner ear microcirculation at a time during decompression when substantial supersaturation is predicted (Doolette and Mitchell 2003). It may be coincidental that gas switches are often made at a time when the inner ear is supersaturated. However, in technical divers with IEDCS, a PFO or other right-left shunt is not always present (Guenzani et al. 2016). A possible explanation for the arterialization of VGE in the absence of PFO follows from an examination of IEDCS in saturation diving.

Saturation-excursion diving is a technique for deep diving in which divers live for prolonged periods in a dry chamber at a storage depth and periodically enter the water to perform work. Divers undergo very slow saturation decompression to the surface at the end of the operation. Divers commonly make descents (downward excursions) to complete underwater tasks then return to storage depth. Divers may also ascend above storage depth (upward excursion) to complete underwater tasks or (less commonly) to change storage depth. Decompression during these excursions is fast and usually without decompression stops. These excursions sometimes result in DCS, and these cases are characteristically IEDCS without other manifestations and onset during or shortly after decompression (Doolette and Mitchell 2022). The similar onset of these IEDCS cases to those following no-stop diving from the surface prompted evaluation of published cases of IEDCS in saturation-excursion diving to assess whether IEDCS after excursions could also be explained by arterialization of venous bubbles (Doolette and Mitchell 2022). VGE can be detected soon after saturation-excursion decompression, and in dive series with incidents of IEDCS and VGE detection, there is a general association of IEDCS with high VGE grades after an excursion (Doolette and Mitchell 2022). One report also detected both VGE and arterial bubbles in all six divers performing upward excursions (Brubakk et al. 1986). Since the prevalence of PFO is about 25% (Cantais et al. 2003), it seems highly unlikely that all six of these divers would have a PFO or other intracardiac shunt.

A model of bubble dynamics in arterial conditions estimated that the survival of arterialized bubbles is significantly prolonged at high ambient pressure such that bubbles large enough to be filtered by pulmonary capillaries but able to cross right-to-left shunts are more likely to survive transit to the inner ear than at the surface. Estimated transit time of a bubble in arterial blood to the inner ear is 3 s if it shunts across a PFO and 5.5 s if it passes through intrapulmonary arteriovenous anastomoses (IPAVA) — which are present in all divers. At the surface, 20 µm diameter bubbles (small enough to shunt through IPAVA) can survive to reach the inner ear if they shunt through a PFO but not through an IPAVA. However, at great depths bubbles that shunt through an IPAVA can survive to reach the inner ear. Just as is the case following no-stop dives at the surface, there is prolonged gas supersaturation in the inner ear after saturation-excursion decompression, so that bubbles arriving in the inner ear soon after an excursion could grow and cause injury. These results indicate IEDCS after saturation excursions is plausibly caused by arterialization of venous bubbles whose prolonged arterial survival at deep depths suggests bubbles in greater numbers and larger size reach the inner ear (Doolette and Mitchell 2022).

Figure 3 shows the increasing lifetime of arterialized bubbles with increasing depth. The depth at which bubble lifetimes are long enough to reach the inner ear through intrapulmonary arteriovenous anastomoses is approximately 60 msw (197 fsw). This depth approximately coincides with the deepest decompression stops from very deep technical dives (deeper than about 100 msw [328 fsw]) that have resulted in IEDCS (Doolette and Mitchell 2003; Guenzani et al. 2016). It may be that VGE formed during the initial long ascent can be arterialized through IPAVA and can survive long enough to reach the inner ear. The inner ear can be significantly supersaturated during the deepest decompression stops from such dives (Doolette and Mitchell 2003) and the arterialized bubbles reaching the inner ear can grow and cause injury.

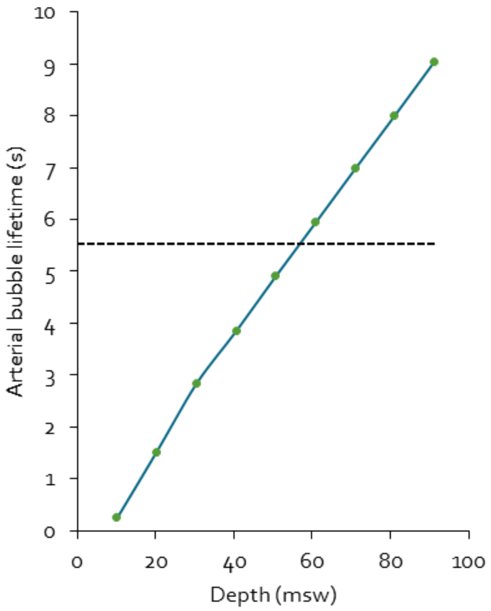

Figure 3. Lifetimes of a 20 µm diameter bubble in arterial blood at various depths for a diver breathing 1.3 atm PO_2 $He\text{-}O_2$. The horizontal dashed line at 5.5 s represents the transit time of a bubble from the right heart to the inner ear through an intrapulmonary arteriovenous anastomosis.

Several operational issues relevant to rebreather diving follow from this right-left shunt hypothesis. At lower inspired PO_2 IPAVA are more likely to be open (Lovering et al. 2015) and lifetimes of arterial bubbles are increased. Thus, if the breathing loop PO_2 is allowed to drop during ascent, the number, size, and likelihood of bubbles reaching the inner ear are increased, along with the probability of IEDCS. Also, exercise opens IPAVA (Lovering et al. 2015) so divers should minimize exercise during early stages of decompression.

Probability of Decompression Sickness of Conventional Decompression Schedules

An underappreciated feature of conventional decompression algorithms, such as the ZH-L16 GF used by technical divers, is that they do not explicitly control the probability of DCS (P_{DCS}). More modern probabilistic decompression algorithms can be used to estimate the P_{DCS} of a dive profile and to prescribe decompression schedules with a specified P_{DCS} (Weathersby et al. 1984; Gerth and Johnson 2002; Doolette et al. 2018). Using such probabilistic decompression models to evaluate decompression schedules produced by conventional decompression algorithms indicates that such schedules do not all have the same $P_{DCS,}$ instead P_{DCS} increases with schedules for increasing depth and bottom time (and consequently with increasing prescribed decompression time) (Gerth and Doolette 2007). This relationship is illustrated for surface supplied open-circuit $He\text{-}O_2$ decompression schedules in Figure 4. P_{DCS} is estimated using the linear exponential multigas probabilistic decompression model optimized around the he8n25 data set (LEM-he8n25). LEM-he8n25 was developed for and accurately predicts P_{DCS} for closed-circuit 1.3 atm PO_2 $He\text{-}O_2$ diving, but overestimates P_{DCS} for the open-circuit $He\text{-}O_2$ dive in Figure 4 (Gerth and Johnson 2002), so the illustration is qualitative only. Nevertheless, the estimated P_{DCS} increases with decompression time, and in accord with these estimates, the actual incidence of observed DCS also increases. The latter is indicated by the number of schedules resulting in DCS (closed circles) relative to the number of schedules not resulting in DCS (open circles). To further illustrate the implication of this relationship, Figure 4 also shows the increasing decompression time and P_{DCS} of DCIEM surface supplied open-circuit $He\text{-}O_2$ decompression schedules for 30-min bottom times at increasing depths (triangles). It is worth emphasizing that P_{DCS} increases with increasing prescribed decompression time if that schedule is executed as prescribed. P_{DCS} can decrease if a diver takes longer to decompress than is prescribed and if the additional time is appropriately allocated.

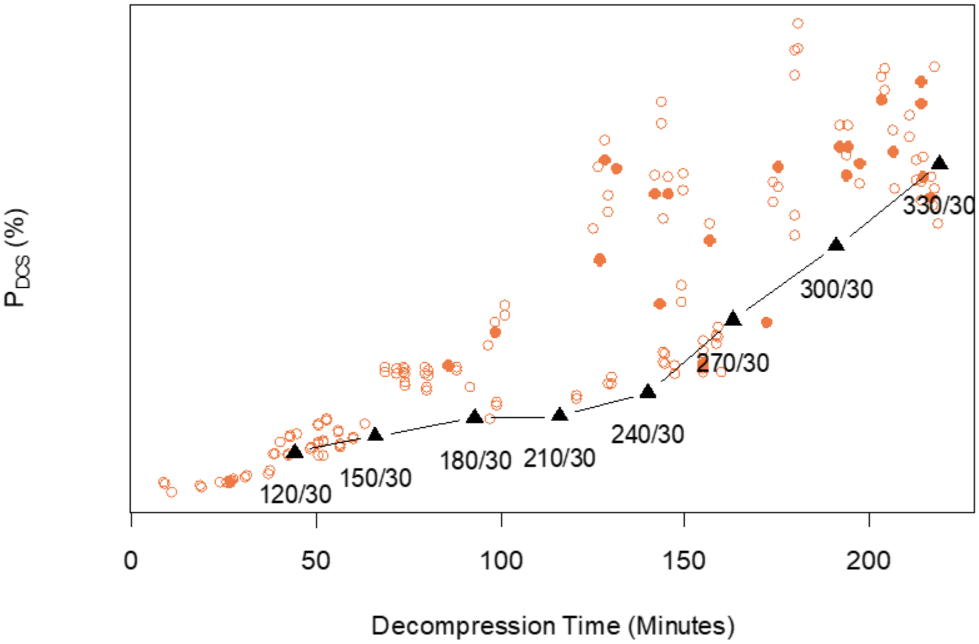

Figure 4. Estimated probability of DCS (P_{DCS}) for dives conducted during the development of the DCIEM surface supplied open-circuit He-O_2 decompression tables. The x-axis shows the prescribed decompression time. The y-axis indicates the P_{DCS} estimated by the LEM-he8n25 probabilistic decompression algorithm. No scale is shown on the y-axis because the LEM-he8n25 model overestimates P_{DCS} for this set of data. Each circle represents a schedule that was tested, typically with two man-dives. Open circles are schedules that did not result in DCS, and closed circles are schedules that resulted in at least one case of DCS. Triangles represent P_{DCS} of schedules in the final DCIEM surface-supplied open-circuit He-O_2 decompression tables where corresponding labels give the depth in fsw and the bottom time in min (all 30 min).

Figure 5 illustrates the increasing P_{DCS} of ZH-L16 GF 50/85 decompression schedules for 30-min bottom time at increasing depths for closed-circuit 1.3 atm PO_2 He-O_2 dives. This figure re-emphasizes that conventional decompression algorithms such as the ZH-L16 GF do not explicitly control P_{DCS}. The P_{DCS} is quite manageable in the depth range <92 msw (300 fsw) of conventional technical diving, but the estimated P_{DCS} becomes extremely high at deeper depths. As deeper technical diving becomes more common, so will cases of DCS unless decompression algorithms are adjusted to be more conservative.

Increasing P_{DCS} with increasing prescribed decompression time is not an obligatory feature of decompression algorithms. It is possible to design iso-risk decompression algorithms that prescribe decompression schedules with the same estimated P_{DCS} irrespective of the depth, bottom time, and decompression time (Gerth and Johnson 2002; Doolette et al. 2018). Recently, sets of parameters were developed for the US Navy Thalmann algorithm that cause this algorithm to prescribe iso-risk closed-circuit 1.3 atm PO_2 He-O_2 decompression schedules for a target LEM-he8n25-estimated-P_{DCS} of 2.3%, 4%, or 5% (Doolette et al. 2018; Doolette et al. 2019). Such iso-risk schedules have a greater increase in decompression time with increasing depth than do conventional decompression schedules. For instance, 4% iso-risk schedules have a similar decompression time to ZH-L16 GF 50/85 for a 77 msw (250 fsw) / 30-min bottom time dive, but increasingly longer decompression times at greater depths.

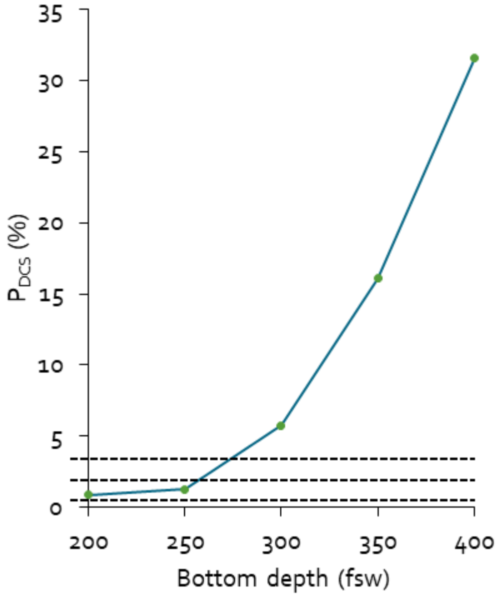

Figure 5. Estimated probability of DCS (P_{DCS}) of ZH-L16 GF 50/85 schedules for 30-min bottom time, closed-circuit 1.3 atm PO_2 He-O_2 dives. The x-axis is depth of the 30-min bottom time. The y-axis indicates the P_{DCS} estimated by the LEM-he8n25 probabilistic decompression algorithm. The three horizontal dashed lines at 2.3%, 4%, and 5% PDCS represent isopleths for which "iso-risk" XVal-He-9 Thalmann decompression algorithms have been developed.

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QUESTIONS AND DISCUSSION

MICHAEL MENDUNO: So what that research implies is that devices that measure your bubbles and then give you advice to adjust your dive schedules are not necessarily based on VGE and DCS.

DAVID DOOLETTE: That is my take on the message from that, yes, that it is not useful measuring in an individual.

MICHAEL MENDUNO: Because we really cannot measure decompression stress.

DAVID DOOLETTE: No. There is some information there. If you have high bubble grades you are at greater risk, but that is too late. It is interesting from a physiological point of view because it means something else other than the dive profile is affecting it. I think we need the technology to evolve. We need to measure at a different time in the dive and probably with different technology. I think there is still potential there if we could measure bubbles that are smaller, if we can measure them during the dive, that might become useful in an individual. Our current gold standard of post-dive peak VGE are not useful for an individual.

AUGUSTO FEDERICI: So about the inner ears, are we going back to deep stops?

DAVID DOOLETTE: No, I do not think so. I think that it is not how deep we start the decompression. I think we probably need to do more. It depends on what you are calling deep stops. We do not need to be starting our decompression deeper, but we probably need to be doing longer stops for these dives that have your first decompression stop at around 60 m (197 ft). That is just a small fraction of the diving we do. That is where we are going. I think we need a different model than what we are using. It is very hard to make gradient factors do that sort of decompression. But we do not have a lot of testing so I cannot be certain which one is better.

AUGUSTO FEDERICI: Or slower ascent.

DAVID DOOLETTE: Slower ascent, but probably from initial start that is probably it, yes. For those extreme dives, 120 m plus, yes.

KEVIN DARLING: Given the extreme variability within individual diving and VGE, has there been any research done to your knowledge looking at genetic biomarkers for predisposition towards DCS.

DAVID DOOLETTE: That is an area of research. I am not sure about genetic, but there is quite an active field of research looking at, you know, some of the phenotypic traits. I do not know that there has been anything very successful that we have been able to point to that makes you predisposed. That is why PFO blew up into this huge thing in the 1980s where there was something you could point out, oh, PFO, that is why you got bent. Everyone was looking for that, but PFO is not it. Approximately 25% of us have PFOs and can have perfectly successful diving careers. I do not know if there is a holy grail of why that person gets bent on that day. I have looked at that sort of data. It is quite stunning to watch. The diver will do exactly the same dive 11 times a week apart, and one time he gets bent. It was not him. It was that day. It is an interesting thing to see.

PASQUALE LONGOBARDI: What about the cytokine particles related to inflammatory response. A lot of manuscripts were published in 2017 in *Diving and Hyperbaric Medicine* stating that cytokines are related to the inflammatory risk, for example, the relative risk for genetic, for nitrous oxide, for obesity, for the age. You spoke about the individual aspect of the decompression. Individual pattern is inflammation. Inflammation is cytokines. Cytokines are in correlation with the percentage, the rate of decompression instances.

DAVID DOOLETTE: I would disagree with that. I do not think there is any data that shows, like we have with VGE, that more of whatever inflammatory marker you have, that that is associated with more decompression sickness. It is a very active area of research, and there is definitely an association of some sort because some types of decompression sickness are inflammatory, but I do not think we have yet the same sort of data that we have, for instance, for VGE, where if you have grade 4 there is a 5 to 10% risk of decompression sickness. Definitely an area of research. Definitely related to decompression stress, but as I said at the beginning of the talk, what I was focusing on, because it is my world, is stuff that you can operationalize today. That is how I make my living. That is how I pursue my hobby. Very interesting area of research, but I am not sure that we can control it.

ANDREW PITKIN: I have a comment and question. The comment is: as a hyperbaric physician, I was often struck by how often, compared with other forms of serious decompression sickness, inner ear decompression sickness seems to start in the water prior to surfacing compared with other serious neurological decompression sickness. I think your new hypothesis dovetails well with that. My question is about observer variability of VGE grading. I know there are a Spencer and a Kisman-Masurel grade scales. There are quite a few subjective criteria within those scales. How much of the intra-individual variability in bubble scoring could be potentially explained by variations in observer grading.

DAVID DOOLETTE: That is a really good question. The KM and Spencer grades are for a Doppler flow meter and they may take a lot of training. The 2D echo has much better intra-grader consistency. But I graded all those dives. So, within a dive series, within a single diver, it was the same operator doing the ultrasound with different machines over the studies, but I graded them all. So none, I guess.

ANDREW PITKIN: Outside of this context, with other forms of echocardiography, it is been well shown that on different days the same observer may grade the same problem in a different --

DAVID DOOLETTE: That is true. There could be some difference. And there could be some difference in the image that you get, you know. A poor operator might get a bad image. You do not see any bubbles and you move a little bit and you see them. So, yes, I think there may be day-to-day variability in the grade you get, but that is real variability. That adds into how useful the bubble grades are if you measure 0 one day and it is really a 4. As far as using it for self-monitoring, I do not think it matters. But I see the point you are getting at. Maybe people are more consistent, but our measurement system is not right. That is part of where I was going with maybe with new technology and a different monitoring scheme, maybe we will find something much more useful. I am hopeful. It is an area I am still working on. I do not think our current methodology is that useful for an individual.

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Closed-Circuit Rebreather Training

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Abstract

Effective training of rebreather divers is essential to minimize the risk of accidents. Recent pan-industry negotiations have resulted in minimum levels of training being agreed to in the form of International Standards Organization standards, and these are expected to be adopted by most, if not all, training organizations. Data have been collected from the majority of training organizations showing trends in overall certification of rebreather divers and regional distribution of certification issuance. Specific safety-related campaigns are detailed with information concerning their implementation.

Keywords: checklists, ISO, mouthpiece retaining strap, rebreather, training statistics

Introduction

International Standards Organization (ISO) standards are being developed to cover the training of rebreather divers and instructors, and several of these have already been published. This paper explains where these standards come from, and what the effect will be on how rebreather divers are trained.

To continue with certification data from the 2012 Rebreather Forum 3 (RF3) meeting and see certification trends, eight agencies submitted certification data to a third-party administrator. The final shows the certification trends over the past 11 years.

This paper explains the challenges faced by both training agencies and manufacturers to maintain a safe environment, while responding to technological, medical and scientific advancements.

Standardizing Rebreather Diver Training

It is important that the diving industry has agreed training standards. This provides a variety of benefits:

- Facilitating comparison of training systems
- Increasing universal recognition of training certifications
- Establishing a "level playing field" between training agencies
- Demonstrating to regulators the self-disciplined nature of the diving industry

The recreational diving industry has a long and proven track record of effective self-regulation. The industry has historically published some standards for the training of rebreather divers through such bodies as the Rebreather Training Council (RTC) and Rebreather Education Safety Association (RESA) but these were not integrated into a single set of diving industry standards. In 2019, it was decided to start work on a series of standards within the ISO framework. Previously, more than a dozen standards had been negotiated for recreational open-circuit diver training under the ISO system, so it was a logical choice to use the same protocol for rebreather training.

The ISO development process is very transparent and open to any ISO member country that wishes to take part. Nearly all countries are members (Figure 1), and any members can send representatives to the international meetings where the standards are negotiated. Switching from the past norm of physical meetings, recent years have seen nearly all sessions conducted as virtual meetings. Any given country can nominate one or more experts to take part in the discussions and negotiations, in this case usually senior figures from the diving community of that country. Additionally, some specific international industry groups are allowed to take part in the negotiations and send delegates, such as the World Recreational Scuba Training Council (WRSTC), RTC, and RESA.

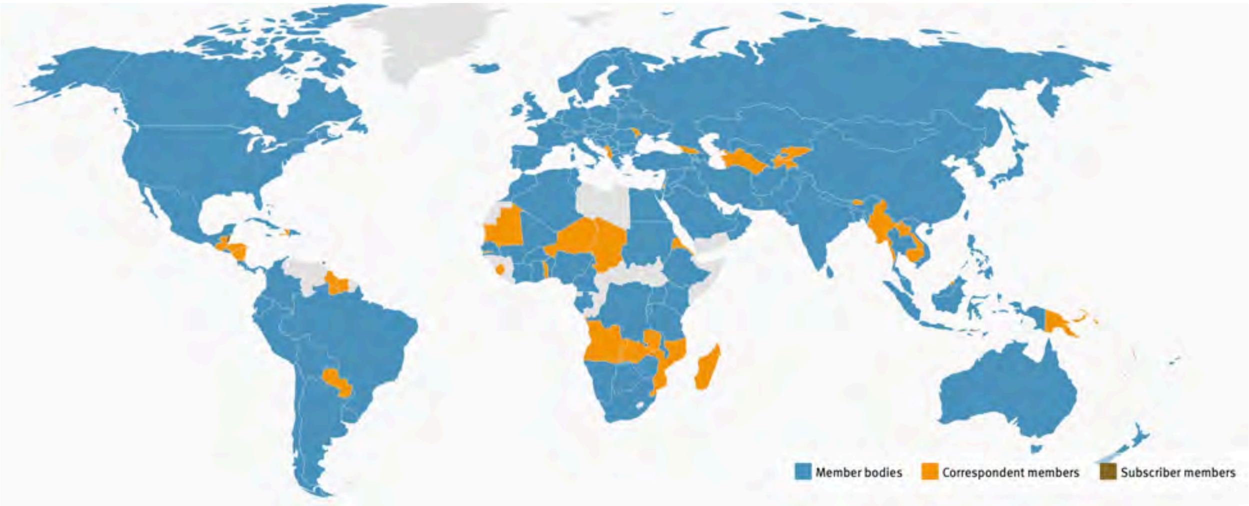

Figure 1. ISO member countries.

The development of each standard takes place over several distinct steps, and versions of the developing draft are distributed internationally for comment until the final version is presented, which is then voted on by all the countries interested. If passed, the ISO standard is then published. This whole process typically takes two or three years for each standard. Standards are then reviewed every five years to see if they need any form of updating.

The standards related to the training of rebreather divers are:

ISO 24804 "Recreational diving services — Requirements for rebreather diver training — No-decompression diving"

A diver able to make dives with a rebreather not requiring mandatory decompression stops using a nitrox or air diluent to a maximum of 30 m (100 ft).

ISO 24805 "Recreational diving services — Requirements for rebreather diver training — Decompression diving to 45 m (147 ft)"

A diver able to make dives with a rebreather requiring mandatory decompression stops using a nitrox or air diluent to 40 m (130 ft) or to 45 m (147 ft) with trimix diluent.

ISO 24806 "Recreational diving services — Requirements for rebreather diver training — Decompression diving to 60 m (200 ft)"

A diver able to make dives with a rebreather requiring mandatory decompression stops to a maximum depth of 60 m (200 ft) using bailout gas mixtures that are not hypoxic at surface pressures.

ISO 24807 "Recreational diving services — Requirements for rebreather diver training — Decompression diving to 100 m (330 ft)"
A diver able to make dives with a rebreather requiring mandatory decompression stops to depths of 100 m (330 ft) or beyond using any gas mixtures.

ISO 24808 "Recreational diving services — Requirements for rebreather instructor training"
Training requirements for the four levels of rebreather instructors.

ISO 24804 and ISO 24805 have already been published. As of September 01, 2023, ISO 24806 and ISO 24807 have been finalized but not yet published. The remaining standard covering instructor courses is still in development and is likely to be finalized later in 2024.

Full RTC members have agreed to adopt the ISO standards as they are published, so all members should be aligning their own standards to ensure that they meet or exceed the ISO requirements.

It is not necessary for every diver or instructor to have a copy of these standards, although it is possible to purchase a copy by applying to the relevant national standards body, a list of these can be found at: https://www.iso.org/members.html. The standards are primarily aimed at the people who run training organizations, and they will certainly have copies of the standards so that they can ensure their courses are compliant with them.

It is unlikely that the introduction of these standards will have an immediate, dramatic effect on the way divers are trained, as it became clear when the standards were negotiated that most training organizations were teaching similar content in their courses. What has now been codified is the specific number of dives and depths required for each course, and this may require some adjustment for some training organizations. Additionally, it was agreed that some content needed to go into courses based on the latest understanding, and this may be new for some training organizations. For example, it has been found that gas density is a significant concern when it comes to planning deeper dives, and so it is now a requirement that this is included in the theory segment of the relevant courses (Table 1).

Table 1. Example rebreather gas mixtures with at-depth densities

Depth (m / ft)	Diluent mixture (O_2/He)	Diluent PO_2 (atm)	Breathing loop density ($g \cdot L^{-1}$)	Breathing loop equivalent narcotic depth (m / ft)
30 / 100	20/10	0.80	4.81	20 / 66
35 / 115	20/15	0.90	5.15	23 / 75
35 / 115	20/20	0.90	4.94	20 / 66
40 / 130	20/25	1.00	5.18	22 / 72
40 / 130	20/30	1.00	4.93	19 / 62
45 / 147	20/35	1.10	5.07	20 / 66
50 / 165	18/40	1.08	5.21	20 / 66
50 / 165	17/40	1.02	5.24	21 / 69
55 / 180	16/45	1.04	5.31	21 / 69
60 / 197	15/50	1.05	5.32	20 / 66
65 / 213	14/55	1.05	5.29	18 / 59
70 / 230	13/60	1.04	5.22	16 / 52
75 / 246	12/65	1.02	5.09	14 / 46
80 / 262	12/65	1.08	5.32	15 / 49

Some new terminology has been defined in the standards, including the following terms to clarify when it may be necessary for additional training to be required when moving from one rebreather to another.

Rebreather Type

Primary rebreather design. Examples: electronically-controlled closed-circuit rebreather (eCCR), manually-controlled closed-circuit rebreather (mCCR), electronically controlled semi-closed rebreather (eSCR), non-electronically controlled SCR (SCR).

Rebreather Unit

A *type* of rebreather having consistent controls, displays and configuration over several models where the operation is essentially the same from *model* to *model.*

Rebreather Model

A specific individual design of rebreather made by a manufacturer.

In future, any training organization could claim to have courses which comply with the ISO standards, so how can a consumer know if their claims are true? There exists an independent auditing body specifically for this reason — *EUF Certification International* — and any training agency can volunteer to have their training system independently audited to see if they meet the requirements of the ISO standards. The agencies that do so are certified as complying with the standards and their status is periodically reviewed. All the major training organizations have been approved by this process in respect to their range of recreational open water training courses, and it is to be expected that a similar protocol will develop with the new rebreather courses.

Rebreather Certification Data, 2012 through 2022

Advancing from the certification data presented at RF3 in 2012, which was from only three agencies, eight agencies (Table 2) submitted certification data in the current effort. The collection of certification data was kept consistent with basic diver information data and level of certification. The objective of presenting this data at Rebreather Forum 4 (RF4) was to understand the current scope of closed-circuit rebreather training. The long-term goal is to build on the record of nearly 30 years (1994 to 2022) of rebreather certifications and preserve the structure for future reporting.

Table 2. Dive training agencies contributing certification data in the current effort (alphabetical order)

BSAC	British Sub-Aqua Club
FFESSM	Fédération Française d'Études et de Sports Sous-Marins
GUE	Global Underwater Explorers
IANTD	International Association of Nitrox and Technical Divers
PADI	Professional Association of Diving Instructors
RAID	Rebreather Association of International Divers
SSI	Scuba Schools International
TDI	Technical Diving International

The total number of certifications issued by eight reporting agencies for 2018 through 2022 are shown in Figure 2. The certification types were put into three categories: basic, intermediate, and advanced (not shown). These categories were chosen to accommodate the various levels of training provided by agencies as well as manufacturer requirements.

- Basic - Entry-level certifications using air as a diluent; minimal decompression.
- Intermediate - Air or low fraction helium as a diluent, modest decompression.
- Advanced - Mixed gas diving and depths down to 100 m (330 ft); substantial decompression.

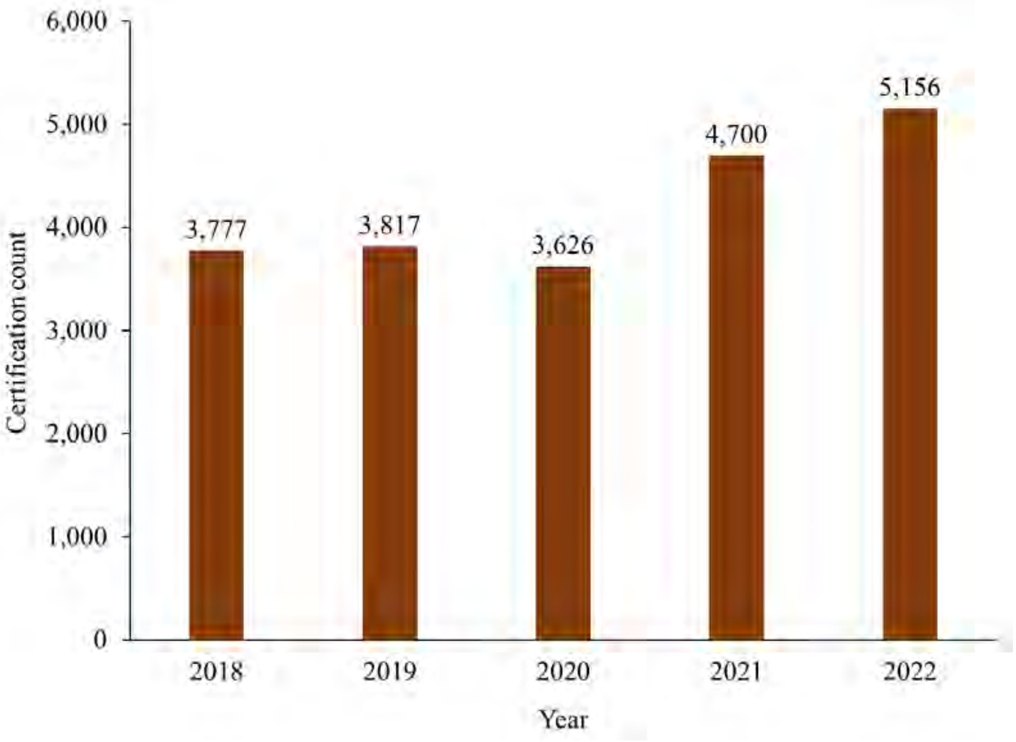

Figure 2. Rebreather certification totals from eight training agencies, 2018 through 2022.

Data Protection and Privacy

The certification data were submitted with very basic personal information to protect diver privacy while screening out duplicate certifications. Each agency organized their data in the proper format submitted them to a third-party auditor. Agencies were not able to see the source data from any other agency. The process was compliant with the General Data Protection Regulation (GDPR; a European Union privacy law). Data assignment was based on the reported home location of the diver, not the location of the training course (Figure 3).

Data Trends

Certifications showed a varying pattern of plateau and growth (details not shown). There was a spike in 2016 in the intermediate certifications. The reasons are unclear but this could have been due to a change in an agency standard or new rebreathers coming into the market. The increased number of intermediate level certifications issued continued through 2022. The reported home location indicated that the majority of rebreather divers live in Europe, approximately 40% of the total count.

Intermediate level certifications represented the largest category of certifications. This likely reflects the larger number of progressive courses as well as unit crossover training.

The mean certification age was 43 years, with the highest percentage of divers being in the 50-59 year range. This was expected given the demands of disposable income and time required.

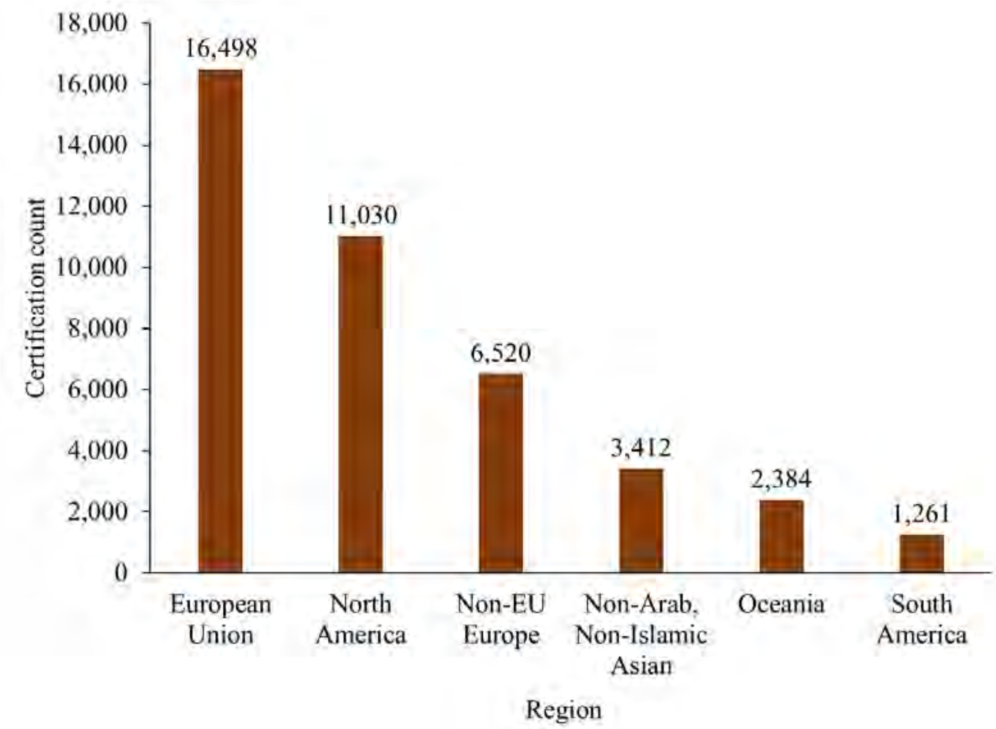

Figure 3. Rebreather certification totals for eight training agencies separated by reported home geographical region, 2012 through 2022.

Rebreather Training

The challenges faced by training agencies regarding new technologies, safety initiatives and updates, and training standards are very real. The RTC has helped develop new training standards as discussed previously, and has promoted multiple initiatives that increase diver safety, for example, the use of mouthpiece retaining straps and checklists.

Relationships Between Agencies and Manufacturers

Since there is increased knowledge and skills transfer, and since rebreathers increase diver capabilities dramatically, training and safety have always been the major challenge when agencies and manufacturers work together. For the most part, this relationship has been harmonious. However, both the agencies and manufacturers are challenged to find a middle ground.

Training agencies are in the business of teaching people to dive and in building careers. Both training agencies and manufacturers want to grow, but the challenge is to grow in a way that safety, quality, service, and appropriate standards are always maintained.

When a diver becomes an instructor, that instructor is nurtured by the agency so that he or she can diversify and teach in different environments using different equipment configurations. When an instructor meets the prerequisites to move on to the next level, and assuming they have no quality assurance or standards violations, they are not held back and subsequently expect to be able to move forward with no opposition.

Many professionals who want to extend their abilities will start to use rebreathers as divers. As with most rebreather divers, they realize how much enjoyment they receive from rebreather diving. Once they meet the prerequisites to become a rebreather instructor, they expect to be able to sign onto a course with a rebreather instructor trainer to certify as a rebreather instructor, similar to the progression required for an open-circuit diver to become an open-circuit instructor.

In some instances, the manufacturer wants no part in the selection of instructors by the training agency, but other manufacturers want to approve who becomes an instructor on their unit, and also maintain a level of control and communication with the instructor.

The problem arises that if a potential rebreather instructor candidate is not given manufacturer permission, they become upset and in some cases disillusioned with both the agency and the manufacturer. The challenge is to find a middle ground where the much needed partnership between agency and manufacturer is maintained, but we are both able to approve more instructors in order to grow both sides of the rebreather industry.

There is indeed a need for a good working relationship between the manufacturers and the agencies, exactly as there are inter-agency relationships, where we communicate effectively regarding issues we may see in the field.

While developing the ISO standards, the ISO Work Group Secretariat advised the group that a person can only be stopped from becoming a rebreather instructor or instructor trainer on grounds of competency, safety, quality assurance, or standards violation issue. Qualification cannot be withhold based on competition or market share issues. With this in mind, the RTC has formed a working group to design a pathway to streamline the application and approval process for rebreather instructors, while maintaining safety, quality of training, and training standards.

Training Material Challenges

CCR failures and outcomes are the same on most rebreathers, but the physical act of solving the problem may be very different between units. Training agencies and organizations like the RTC work with manufacturers so that instructors are teaching the rebreather skills as the manufacturer would have them taught. As an example, it is clear that performing a certain skill on a sidemount rebreather may be vastly different than performing the same skill on a backmount rebreather. A strong working relationship with manufacturers helps to ensure that instructors understand both hazards and solutions and are teaching the skills with knowledge of how the rebreather engineers feel the skill should be done.

Keeping Pace with Technology

Rebreather manufacturers are without doubt pushing the boundaries of technology at a rapid rate. RF4 saw manufacturers previously producing only backmount units release sidemount and chestmount versions, along with several new units using new technologies. The rapid evolution represents a big challenge for training agencies that must keep pace.

Another rising challenge evident at RF4 is the bailout rebreather. Questions remain on the use of units, the experience required of those training with them, and the range of applications. The need to develop materials for use and training is substantial.

Training agencies are not just challenged to write and release new materials for new pieces of equipment, they must also continuously update existing materials. Bringing new courses and updates to the membership and market requires substantial effort.

Agencies must also keep pace with advancements in decompression theory and science. The hazard of respired gas density is one example that has come to the forefront (Anthony and Mitchell 2016), with training agencies needing to ensure adequate coverage within their training materials. The risks and realities of immersion pulmonary edema represents another area needing development to reflect the medical literature evidence that has accumulated over 20 years (Koehle et al. 2005; Kumar and Thompson 2019).

Equipment Standardization

Agencies are in the business of supporting dive centers, and are asked to assist and advise dive centers in helping them grow. When a dive center decides to offer rebreather training or guided dives, they face challenges with the lack of equipment standardization.

Oxygen cells differ from rebreather to rebreather, and this can cause issues if the diver participating in training or guided dives has an issue and has not brought spare sensors, or damages more sensors than they are carrying. Since the sensors have a limited shelf life, many dive centers are not prepared to stock cells for their potential customers. Many dive centers have requested that manufacturers use one style of cells to alleviate these problems.

Cylinders also present some issues in the field, with some units being flexible and others requiring specific 2 L or 3 L cylinders and/or valve configurations.

Practically, dive centers, particularly smaller and remote dive centers, can face substantial barriers to grow their market with the current diversity of equipment.

Additional Challenges

Due to the number of incidents in the rebreather sector and insurance company views of rebreather diving, instructors are being asked to pay very high premiums in some areas of the world in order to teach rebreather diving. The small size of the industry means that the ripple effect from an incident, or worse, a death, is felt by everyone in our industry and has a huge knock-on effect. One of the overall points taken from RF4 was that incidents while using a rebreather must be reduced dramatically.

Manufacturers may utilize a factory trainer (FT) most familiar with their product, but conflicts can arise if an FT is to train instructors in an agency that he or she is not a member of or if certification levels do not match. Agencies are challenged by this less and less because of the great relationship between both parties, but it is important to ensure that these standards are understood and maintained.

The second-hand market is totally unregulated and can cause major issues for manufacturers. Rebreathers may be sold unserviced and/or modified, and in some cases they are sold to divers with no certification. Outdated rebreathers may also be sold second-hand when no training or manufacturer support is available.

Training Agency Integration

It is likely that most training organizations will soon align their own standards with the new ISO standards for rebreather diver training. They have to ensure that their standards at least meet the ISO requirements, but they can exceed them if they wish. It is important to note that the ISO standards delineate *minimum* course content and are not intended to serve as course outlines.

If things continue as they have for the past nearly 30 years, rebreather certification numbers will continue to increase. This is a growing sector of the dive industry, so it is important to monitor. Now that the template for rebreather certification data is well established, future rebreather certification statistics will be easier to produce.

Training agencies will always face challenges with regards to safety and industry advancements, but with groups and organizations like ISO, RTC, RESA, and most importantly, through their relationships with manufacturers, the rebreather market should grow while also working towards enhanced safety.

Conclusions

Having a set of ISO standards in place that have been agreed on by diving industry members offers a long-term form of security for the service providers and for consumers. Rather than having any arbitrary regulations imposed on us by local governments, these standards are ones which the industry has developed as best practice in diver training.

Monitoring diver and professional certifications is important to understand the health and safety of the industry. This data is beneficial to all stakeholders and should be shared, as feasible.

Events like RF4 show how unified the rebreather industry is, and how all the players work together to not only make it an incredible sport, with all the components needed to support it, but also keeping up with safety campaigns and technology.

Acknowledgment

The authors acknowledge the members of the RTC sharing training data.

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QUESTIONS AND DISCUSSION

MICHAEL MENDUNO: So have the eight or more agencies discussed making this an annual data sharing that could go in our statements as a commitment?

SEAN HARRISON: That has not been a discussion. I can speak from TDI's point of view. We have released our certification data and will continue to do so. I think we have released our open-circuit certifications probably two or three times now and certainly contributing to the CCR side of it. We would be more than happy to do that annually or whenever it is appropriate.

MICHAEL MENDUNO: Make a great RTC project going forward.

SIMON MITCHELL: It is in the statements.

ATTENDEE: You mentioned a list of standards that are not complete. When will we have all the levels?

MARK CANEY: There are three remaining levels, but it is hard to say precisely. Standards take a long time to make because it is a very thorough process with the standards going out to all the countries in the world so they have a chance to comment initially and vote subsequently.

RICHARD HARRIS: I did not expect to find a talk on training so very good. I am asking a question that I possibly know the answer to, but it is been going around in my mind for many years. The limit of 100 m on these certifications has been a kind of constant annoyance not just because my wife says, why are you diving to 101 m, but because it actually provides quite a few obstacles in terms of diving projects, whether it is national parks, landowner negotiations, let alone, life insurance and other issues. Could we not have a certification ranking that it is, say, greater than 60 m?

MARK CANEY: We have considered that. I forget the exact wording, but within the 100 m standard it does not say, "you are trained to 100 m, no more." It says, this is preparing the person to be able to dive to 100 m, and then subsequently with the appropriate experience, which would be achieved within certain parameters -- you can expand beyond that, and it does not say how far.

JAMES BLACKMAN: How would the agencies respond or what power do you have when manufacturers block access to instructor training for various political reasons.

PAUL TOOMER: We request information from the manufacturers as to why the instructor or trainer cannot become an instructor or trainer. And we will challenge the manufacturer if it is based on anything other than a safety or current or past quality management issue. This is why that group was formed, because we have got so many good instructors out there that we would love to see on rebreathers. The RTC and some of the rebreather manufacturers have joined together in this working group so we do not have this question in a few years time. Knocking back a really good instructor can look embarrassing for the agency and the manufacturer. It does not look like we are harmonious and we actually are.

JAMES BLACKMAN: It seems like there is a lot of instructors that I know in my immediate area who have been trying to forge the path and are getting blocked by the manufacturers units that they dive on.

PAUL TOOMER: The manufacturers have their reasons in many cases for doing this. Obviously, there are anti-compete laws in the world so the manufacturers should not be making the decision based on another instructor being in that market. They should be making it based on safety and quality management issue that would cause harm.

MARK CANEY: Adding to what Paul said there, which was a very good explanation. When we were making the ISO standards, the ISO Secretariat, who is an expert on the standards world, was very hostile to this concept. He said that standards should not include anything which would allow decisions to be made for competitive reasons. For example, if I want to say as a manufacturer I am going to have only one person in this country or town or whatever who is a rebreather instructor. You cannot put that in the standard. You can only put in things which are safety related. These are safety standards.

NICK JEWSON: Paul, you were emphasizing the problem centers have with stocking oxygen cells for different rebreathers. We travel a lot with our rebreathers. We always take some spare cells, same as we take spares for our camera equipment. We do not expect the centers to supply camera equipment so why expect centers to stock sensors for the different units? Surely, when you are traveling with your rebreather putting spare cells in your bag is not a problem.

PAUL TOOMER: Yes, they should be carrying their own spare cells. But I have been on expeditions where we have run out of the spare cells as well. It is just trying to make business easier for everybody with the consumables. It would be nice if we could be fully serviced should something go wrong. If you blow a low pressure or high pressure hose on your rebreather, any dive center can help you out with that. But they often cannot help you with cells.

ALEJANDRO GARBINO: Do the ISO standards address mixed platform training? Does the instructor have to be using the unit that they are training on or not? I know that that is been a barrier to a lot of instructors.

MARK CANEY: There are different requirements according to the stage of training. In the early stages where somebody is being introduced to a rebreather and they are a novice, the instructor should be on the same unit. In later, more advanced training, more advanced skills, it is not so critical. It is specified according to the situation.

EDMUND YIU: We know that we have many standards for different levels of training, but how do we solve the problem that so many divers have taken a 40 m course and then start going much deeper than they should. I know it is quite common in a lot of other places, especially in Asia, because they are not regulated and there is no dive center to check their certification. Accidents are happening because of that. Also, for rebreather diver certification, when you not dive the unit for a long time, do your certifications still stand? It is a problem if you have got your certification and you never dive the unit. Should we think about a recertification process for divers and units? Because things change.

SEAN HARRISON: We are a self-policing industry. I will only speak from my personal perspective after reviewing incidents and accidents for the last 22 years. Divers routinely dive beyond their limits. They dive beyond their level of certification. Dive operators also allow that behavior. As a former liveaboard captain, I took people out in locations and they actually showed me an open water card and I was dropping them into drifts and any number of situations that were probably beyond their level of certification. We did have backups. We had divemasters supervising. But, to your point, I think it is a complex problem. It is a behavioral problem with divers. I am confident in saying that all the training agencies do a good job in explaining that you are trained at a level of the certification of the course that you took. And then what they do beyond that is really up to them. And, unfortunately, that is partially where the training agency's responsibility ends. Post-training is what people do on their own personal time they are responsible for their own actions. It is very tough. You can put yourself in the awkward situation of being the scuba police and trying to tell people, you are probably going to get hurt if you continue these behaviors. And we do get phone calls like that, but it is a difficult thing to enforce. To your second question about proficiency on different things, different types of diving, whether that is a rebreather or whatever it may be. TDI's stance is you teach at your highest level every two years. If you do not, you become inactive. Then we do have a process for remediation and refreshing. I am sure that other agencies have a very similar policy. It can be hard to document. Rebreathers are a little easier because you can download computer logs to show activity. Open-circuit is a different animal and we do not have the ability to do that. TDI's policy on maintaining efficiency, in any case, is teaching at your highest level at least once every two years.

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Developments in Closed-Circuit Rebreather Diving and Equipment

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Abstract

This article is an abridged summary of my personal experiences in the evolution of rebreather and technical diving. It focuses on engineering and is not exhaustive, but I believe it captures pivotal moments that in themselves have helped shape military, recreational, and technical rebreather diving. There are seven key lessons learnt that in themselves have driven modern rebreather evolution: 1) Electronics and water do not mix; 2) Continuation training is crucial; 3) A good checklist is crucial; 4) Test and understand the limitations of your rebreather; 5) Accept that there is decompression risk and plan accordingly; 6) Knowing where you are and being able to communicate it generates efficiency and reduces risk; and 7) Semi-automated pre-dive checklists and command-based alarms combined with digital sensors are the future.

Keywords: diving equipment, engineering, evolution, gas monitoring, rebreather, safety, sensors

Introduction

We have come a long way since the birth of technical diving as is evident from the attendance at Rebreather Forum 4 (RF4) and other events. There have been significant advances in rebreather diving and technology in recent years, with much of it pioneered by the recreational/technical community; but military diving takes the lead in many initiatives. This article will provide some backstory in support of seven key lessons learned through decades of involvement in the development and use of rebreathers both in the commercial and military sectors.

The Evolution of Technical Equipment Development in Relation to Rebreather Diving

Early Days

My personal introduction to rebreathers started in 1988 when I was employed with my engineering partner, Nick Bushell, to develop a modern set of electronics for a USN MK15.5 rebreather for a company that was attempting to launch them into the scientific and recreational markets. As an electro-mechanical engineer and diver at the time, I became a test pilot. Lesson 1, '*Electronics and water do not mix without some very clever engineering*.' The project never really went anywhere but it had sown a seed.

Then came a period of experimenting with mixed gas diving around the UK and exploring deeper and deeper wrecks on open-circuit. This led to further development for Nick and myself in dive computers and the birth of the first mixed gas dive computer.

The Birth of Technical Diving

Then came technical diving borne of cave diving really and the first nitrox workshop. As a result of that and a chance encounter with Dr Bill Stone's exploration documentation, led to a request by me to meet him and pick his brains about some of his experience with developing rebreathers for cave diving. I needed a new tool for my own exploration, and this seemed a good place to start.

During that phase I met Rich Pyle at Bill's place. That led to a long relationship between the three of us with Rich and I being instrumental in the launch of the Cis-Lunar MK5. The training with Bill taught us Lesson 2, '*Continuation training is crucial*.' You will become complacent, and if you do, rebreathers will bite you.

The next step again involved Mk15.5s on a long-term project in Guam that spanned several years (Gurr 2010). Typically, each year involved nearly three months of diving. We started on open-circuit and rapidly realized it was not workable given the working depths (averaging 60-70 m [200-230 ft]) and the long dive times. We managed to obtain two USN MK15.5 rebreathers and the four 'rebreather experienced' divers rotated them on a daily basis, which often involved in-water swap outs at 30 m during the first team's decompression phase.

We did thousands of hours as a team over the whole project. Lesson 3, '*A good checklist is crucial*.' We had dozens of problems with these archaic technology systems but only at the surface during the pre-dive checks. I also learnt that I could not rely on myself to reliably complete the checks accurately due to complacency creeping in over time.

Technology and Process Advances

The next phase of the rebreather evolution was combining them with other tools. In the first instance, it was with a diver propulsion vehicle (DPV).

Working with Billy Deans in Key West (Billy was the first person to offer open water trimix training) I learnt how to use a DPV with a rebreather. Billy was also in Guam, and we used DPVs a lot on that project. They were also being used in cave diving and slowly several systems became available. One of the first was the German Aquazep scooter, which is what Billy and I had. Using the DPV with the rebreather allowed us to go farther, longer, and deeper. This created the next problem and evolution requirement. The CO_2 removal system (the scrubber) of the rebreather became the limiting factor. Navies globally have pioneered scrubber testing and design, but it was new to recreational manufacturers. Even though Conformité Européenne (CE) standards were released in 2014 for civilian rebreather testing, many systems reached the market with little or no scientific data to support scrubber endurance.

Scrubber endurance is a function of CO_2 generation rate (metabolism/work rate), water temperature, depth, gas type, and importantly, rebreather design (Clark 2022; EN14143 2013). Two rebreathers of differing designs using the same amount of the same absorbent will not have the same endurance.

Military diving has again recently pioneered scrubber design and monitoring with the development of moisture tolerant CO_2 sensors, metabolic rate counters, scrubber prediction algorithms, and better general design to reduce thermal effects. Lesson 4, '*Test and understand the limitations of your rebreather*.'

Endurance also generated personal thermal challenges. Suit heating was initially very basic, often borrowing technology from the motorcycle industry. Military systems are now quite sophisticated, with thermal regulation (sensing) added to ensure that at depth excessive perfusion does not take place, which may result in decompression sickness (DCS). In addition, lower voltages are used to limit cardiac risk.

Longer, deeper, and more environmentally challenging dives led to changes in decompression thinking. Various manufacturers made mixed gas diving computers and included fixed PO_2 algorithms for use with rebreathers. Explorers came up with ways to modify decompression profiles and algorithms in an effort to reduce the risk of DCS. The current popular manifestation of this is gradient factors. Gradient factors offer a way to modify elements of the decompression profile to increase (or reduce) time at stop depths in order to shape the decompression curve and alter the risk of DCS. While not particularly based in scientific research, my own experiences in employing them combined with live Doppler studies, did result in lower bubble scores and lower rates of DCS. Several militaries around the world are looking at gradient factors as a way of mitigation against training and operational dive risk.

Military management and process for decompression diving and risk management is somewhat different from that of recreational divers, with the recreational diver generally far more autonomous than the military diver. This is changing, though, as there is a military need to go deeper and longer. As a result, the whole process and risk management tasking is under review by several key navies. Lesson 5, '*Accept that there is decompression risk and plan accordingly*.' This may mean developing remote location decompression procedures which should include safety diver training, in-water recompression options, underwater communication systems, use of surface oxygen post-dive, and use of the rebreather as a therapy device.

Next came navigation. We could go further but where were we? Again, the military have pioneered this with companies such as Blueprint Subsea and Ceebus leading the way. Autonomous underwater vehicles are also being deployed to support military tasking by linking into the navigation systems. Others, notably Bill Stone, have developed powerful systems for cave mapping.

Acoustic diver tracking systems are now also available that not only track divers but provide real-time rebreather health status. Lesson 6, '*Knowing where you are and being able to communicate it generates efficiency and reduces risk*.'

Another step change has come in sensing. CO_2 sensors have already been discussed, but the real game changer is digital O_2 sensors. Traditionally, galvanic oxygen sensors are used and while they are effective, they require regular calibration and care. The advent of digital sensors with no user calibration requirements and generally improved reliability has largely addressed a major weak point in rebreather designs: the monitoring and control of O_2.

Traditionally, rebreather human-computer interfaces have been simple. Sensors capture and display raw data. This can and has led to 'information overload', especially during high-stress periods. The result has often been catastrophic.

The new generation of sensors combined with modern interactive pre-dive software has significantly reduced diver error/complacency and increased safety with military rebreathers. The final link in this new system is the inclusion of 'command-based' alarms. Basically, this means that when an issue occurs, instead of the rebreather providing data for the diver to interpret, the rebreather makes a decision based on the data and provides a corrective action command such as 'slow down' or 'add oxygen.'

From a military perspective, where the rebreather is just a transport system, and when the user is often tasked with a wider array of technology to contend with, the rebreather interface must be as intuitive as possible. Lesson 7, '*Semi-automated pre-dive checklists and command-based alarms combined with digital sensors are the future*.'

The provision of better rebreather technology, propulsion, navigation, communication, and advanced decompression opens the door to address other key elements such as biometric monitoring, nutrition and hydration, and telemetry.

Conclusion

There has been considerable development in recent decades with what we currently call technical diving. A lot of this focus has been around rebreathers and the advantages they bring. This has been driven by the recreational industry. More recently, perhaps during the last six years, military diving is again driving the next stage of evolution. We are currently in a world where global threats are rapidly changing, and technology is one driver. Military rebreathers are pioneering changes as they first did decades ago.

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QUESTIONS AND DISCUSSION

MICHAEL MENDUNO: Do you have just one oxygen sensor? It sounds like there is no voter logic.

KEVIN GURR: That is a really good question. When we did the original design, my head went, "Let us put three in" because I have always had three. Now, if you ask me tomorrow, I will live with two, allowing for the binary failure mode scenario. I would be more than happy with two. The system does have basic voting logic, but it never really gets activated. It is there in the background.

MICHAEL MENDUNO: So, you do not even have PO_2 on your display?

KEVIN GURR: I can drill down to get it. Fundamentally, it is a resource, but it is not a time-related resource. The only thing I see on the main screen is mission time remaining in minutes based on my resources and depth and current in-water time. There are only three things I see on the main display. Drilling down for more detail is an option.

MICHAEL MENDUNO: On the CO_2 sensors, I think there are about six manufacturers that have some form of these. Are these all optical or are they non-dispersive infrared (NDIR)?

KEVIN GURR: The ones that I have seen are NDIR. I think we are the only ones using the gel patch.

MARK CANEY: I am particularly interested in CO_2 detection in the loop. I think that is a big safety feature for divers if we can get that more widespread and reliable. Considering the positioning of the sensor in the loop, it seems to me the ideal position would be in the mouthpiece itself because you can detect things like mushroom valve failure. Any thoughts on that?

KEVIN GURR: Yes. Putting it there you are really talking end-tidal CO_2, so CO_2 that the diver is exhaling, fundamentally. That is definitely a future design goal. Simon and I have talked about this a bit. It is not practical, though, until the sensors can be miniaturized and made more water-tolerant. That is a future goal. Then we need to be able to link the results of that to something positive. For now, what the sensors do is tell you if you have got no absorbent, you have got a bad sealing system or, and more importantly, if at any point in that dive, especially towards the last third of the scrubber when you might work hard and blow through that scrubber. For me, the CO_2 sensor detecting those things is the game changer. This and the pre-dive testing that it is super important in telling you your current scrubber status.

CHARLIE ROBERSON: I have a question about the optical sensors. Since they require power, unlike the galvanics, do you have a single source failure or single point failure with your power source going to two sensors or are you using a parallel system with two separate power sources?

KEVIN GURR: We have a triple redundant power pack within the system. You can go down to one battery. That is another thing with the alarm. Some problems may be unimportant to operators, like losing one or two batteries if there is another to get the job done. We blank out all the unnecessary underwater alarms that would normally be found on recreational rigs.

VINCE FERRIS: For the CO_2 sensors, how do you do a pre-dive checklist on those to determine functionality?

KEVIN GURR: If you do the prebreathe sequence, which takes one minute, what we are looking for is the CO_2 sensor reading not to change. This shows that the scrubber is functioning. There may be a little bit of CO_2 in the loop, but the value should not change with effective scrubbing. The assumption is that no change means that the sensor is working. There are, obviously, other checks within the electronics for the sensor, background checks, power, and communication, but the number you want to see at the end of the pre-dive is essentially zero.

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Developments in Carbon Dioxide Monitoring

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Abstract

Hypercapnia may arise during rebreather diving due to a tendency to retain carbon dioxide (CO_2) when work of breathing is high, or because of CO_2 contamination of inspired gas, or both. Hypercapnia may cause adverse symptoms such as dyspnea, headache, disorientation, and anxiety. It also predisposes to oxygen toxicity and gas narcosis. Infrared inspired CO_2 monitors are included (sometimes optional) in several rebreathers. They work well if meticulously cared for but are potentially confounded by water vapor and pressure; this can produce false positive alarms. 'Temperature stick' thermistor arrays in the CO_2 absorbent bed can track the progression of the exothermic reaction between soda lime and CO_2 and successfully predict when CO_2 'breakthrough' is imminent. However, they do not detect CO_2 *per se*, and will not detect an absent or incorrectly installed scrubber, or inspiration of CO_2 arising from one-way valve failure. Capnography is the gold standard that would allow detection of both inspired CO_2 and CO_2 retention by the diver (by measuring end-tidal CO_2). This technology is used daily in operating rooms worldwide but is not yet available in any rebreather. The major challenges include developing a capability to measure CO_2 in (or sample gas from) the mouthpiece where there is 100% humidity. Development of capnography for rebreathers is a laudable research priority.

Keywords: diving, hypercapnia, measurement, physiology, rebreather, underwater

Introduction

Carbon dioxide (CO_2) is a consequential gas in diving. As explained below, encountering situations where CO_2 levels in the body rise above normal (hypercapnia) is a relatively common scenario.

Hypercapnia is a problem for several reasons. First, it can cause unpleasant symptoms such as headache, anxiety, shortness of breath, and confusion. These can precipitate panic. If levels become high enough, CO_2 can cause incapacitation and unconsciousness. Collectively, these manifestations are often referred to as CO_2 toxicity. To give some sense of the small changes in arterial blood CO_2 levels required to cause symptoms, around 5.2 kilopascals (kPa) is the average normal level, 6.2 kPa is the upper limit of the normal range, and at over 8.5 kPa sudden incapacitation is likely. For those who like to think in millimetres of mercury (mm Hg), just multiply kPa by 7.5. Experiments show that levels between 6.5 kPa and 7.5 kPa are not uncommon in divers working underwater. The point is that small changes in PCO_2 of 2-3 kPa can have important implications for the safety of the diver.

The second reason hypercapnia is a problem in diving is that it can precipitate other diving related problems. In particular, CO_2 is narcotic, and hypercapnia will worsen nitrogen narcosis. Similarly, hypercapnia is known to substantially increase the risk of cerebral oxygen toxicity which can manifest as a seizure. The mechanism is probably that CO_2 causes a substantial increase in blood flow to the brain, thus increasing the brain's exposure to oxygen when a diver is inspiring a high pressure of oxygen. Loss of consciousness associated with a seizure would often be fatal underwater. Oxygen toxicity is unlikely to be a hazard in scuba air diving, but it is an issue that technical divers must consider because they often breathe oxygen at high pressures for extended periods. It follows that technical divers need to avoid hypercapnia when their oxygen exposures are high.

Normal Regulation of CO_2 Levels

The production of energy to drive virtually all biological processes in the body requires oxygen. When oxygen is metabolized for energy metabolism, CO_2 is produced. Its rate of production is directly proportional to oxygen consumption. During exercise when large amounts of oxygen are consumed by working muscle more CO_2 is produced, whereas at rest when less oxygen is consumed, less CO_2 is produced. CO_2 is a gas, but when produced in the body it is initially in dissolved form. It diffuses through tissue fluids into the blood and is carried back to the lungs. At the lungs, CO_2 diffuses into the alveoli (the lung's tiny air sacs) and in doing so it becomes a gas again. When gas is exhaled from the lungs, CO_2 is eliminated. Not all the CO_2 is removed as the venous blood passes through the lungs, and indeed, it is the pressure of CO_2 in the arterial blood that is monitored by the brain to control breathing (see below). A more detailed explanation of this basic physiology can be found elsewhere (Anthony and Mitchell 2016).

This process of CO_2 elimination is dependent on there being a pressure gradient for diffusion of CO_2 from the tissues to venous blood, and from the blood into the lung alveoli. Put simply, the pressure of CO_2 is higher in the tissues than in the blood, and higher in the blood than in the alveoli, so molecules of CO_2 diffuse in the direction of this pressure gradient. The gradient is maintained by removal of CO_2 from the alveoli by breathing. This is a key point. The more gas that is breathed in and out of the lungs, the more CO_2 is eliminated, and vice versa. In other words, if a diver breathes rapidly and deeply, elimination of CO_2 is increased. Conversely, if a diver breathes slowly and/or with small breaths, elimination of CO_2 is decreased.

Under normal circumstances the pressure of CO_2 dissolved in tissues and blood is carefully and automatically regulated by the body. The brain has what is effectively a CO_2 sensor that monitors blood levels and adjusts breathing accordingly. Thus, if the blood CO_2 starts to rise, the brain will drive increased breathing effort (either by increasing breathing rate, breath size, or both), and if blood CO_2 starts to fall, the brain will reduce breathing effort so that CO_2 levels rise again. All of this happens continuously at a subconscious level. In most people, the brain is 'set' to maintain a dissolved PCO_2 of about 5.2 kPa in the arterial blood.

Why Do CO_2 Levels Increase in Diving?

This control system is imperfect and under some circumstances it can become less precise. If the work involved in breathing increases unnaturally (which occurs in diving because of dense gas, equipment resistance, and lung changes resulting from immersion), particularly if this is combined with exercise, the breathing controller in the brain appears predisposed to allowing the blood CO_2 to rise rather than driving the extra work required to breathe enough to keep CO_2 at normal levels. We refer to this as 'CO_2 retention;' a situation in which there is insufficient breathing to eliminate the CO_2 being produced. The more the work of breathing increases (for example, because the diver is deeper and breathing a denser gas, or because the regulator is performing poorly), and the more CO_2 that is being produced (for example, because of exercise) then the more likely CO_2 retention is to occur. Interestingly, there is significant variability between individuals in respect to their tendency to retain CO_2. In some individuals the brain will adjust breathing to maintain a normal level of CO_2 irrespective of how much the work of breathing increases, whilst others are very vulnerable to CO_2 retention when there is an increase in work of breathing. The latter group is often referred to as 'CO_2 retainers.'

It is notable that CO_2 retention as described above can occur in either open-circuit or closed-circuit scuba diving and that the discussion to this point has had nothing to do with inhaling CO_2 when using a rebreather. CO_2 inhalation can occur if the scrubber material (typically soda lime) is exhausted or if the scrubber canister is installed incorrectly so that gas bypasses the canister. It can also occur if the mouthpiece one-way valves fail. CO_2 inhalation is certainly another cause of CO_2 toxicity because it reduces the efficiency of CO_2 elimination by breathing because the diffusion gradient for CO_2 to move from blood to lung alveoli is reduced. The greater the level of inhaled CO_2, the greater this effect will be. Under such circumstances the blood CO_2 levels may rise no matter how much the diver breathes.

From the above it should be clear that there are two broad causes for CO_2 toxicity in diving: 1) failing to breathe enough to eliminate the CO_2 being produced by metabolism ('CO_2 retention'), and 2) rebreathing CO_2 if a rebreather scrubber fails or is bypassed or if one-way mouthpiece valves fail.

The following discussion addresses current and future attempts to warn the diver that these things may be happening.

Warning Systems for Inhaled CO_2

The Diver Themselves

This is mentioned largely for completeness because of historic views on the matter. It was previously taught that one function of the five-minute prebreathe prior to entering the water using a rebreather was to detect any symptoms of CO_2 toxicity if any of the above causes of high inhaled CO_2 (such as scrubber failure) applied. However, following a preliminary study presented at Rebreather Forum 3 (Graham and Bozanic 2014), a randomized blinded study determined that during a five-minute prebreathe divers were frequently incapable of detecting even a completely absent scrubber, and almost always insensitive to significant partial scrubber bypass (Deng et al. 2015). One of the interesting ironies of this scenario is that divers who tend to retain CO_2 generally suffer fewer early unpleasant symptoms such as a sense that they need to breathe more (likely one of the reasons they retain CO_2), and indeed, may not develop symptoms until they are close to developing serious manifestations such as incapacitation and unconsciousness. They are therefore worse at self-detection than divers who experience symptoms such as shortness of breath at lower CO_2 levels. It follows that divers cannot rely upon recognizing symptoms as a means of detecting high levels of inhaled CO_2 or CO_2 retention.

Temperature Sticks

Temperature sticks are designed to indicate when a scrubber has reached the end of its capacity to absorb CO_2, and therefore the point at which CO_2 could begin to break through and be re-inhaled. They do this by monitoring the temperature change through the scrubber as the soda lime gradually becomes exhausted, and this segues into the key point about these devices: they do not actually detect CO_2 when it breaks through the scrubber; they simply predict when it is likely to occur. An investigation of how accurately temperature sticks achieve this in both the Inspiration and rEvo rebreathers was recently completed (Silvanius et al. 2019). It is a fair summary to say that both devices reliably alarm before the scrubber becomes exhausted and CO_2 breaks through when work rates are not extremely high. In addition to pointing out that temperature sticks do not actually detect CO_2, it is important to understand that they only predict the efficacy of a *working* soda lime scrubber. For example, they cannot detect or predict CO_2 inhalation due to a fault with scrubber installation causing bypass of gas around the scrubber. Nor can they detect inhalation of CO_2 due to one-way valve failure at the mouthpiece.

Inhaled Gas CO_2 Monitors

CO_2 monitors are effectively gas analyzers which use infrared light absorbance technology to detect CO_2 in gas. Several rebreather models incorporate one of these downstream of the scrubber to analyze gas for CO_2 before it is inhaled by the diver. If the scrubber is working well there should be minimal inhaled CO_2 (only that in the extremely small dead space of the mouthpiece). If inhaled CO_2 levels exceed a threshold (usually set around 5 millibars [about 0.5 kPa]) an alarm is activated. Not all rebreathers offer these devices, and their uptake and review by users has been mixed, but improvements have been made. The principal challenge is that the accuracy of the infrared absorbance detector can be confounded by water vapor (moisture), and in the 100% relative humidity environment of a rebreather loop they are prone to giving false positive alarms. The Inspiration version of this device was independently tested and found to be reliable at moderately high workrates for divers provided the user is fastidious in following moisture protection guidelines (Silvanius et al. 2019).

Inhaled CO_2 monitors can detect CO_2 that either breaks through or bypasses the CO_2 scrubber, but because they are typically located somewhere near the origins of the inhale hose, they cannot detect CO_2 inhalation due to one-way valve failure at the mouthpiece. The other important and related issue is that while they can detect most sources of inhaled CO_2, they cannot detect CO_2 retention by the diver which, as described above, typically arises in the absence of inhaled CO_2. That requires a different approach to monitoring, currently unavailable in rebreathers, which is described below.

Measuring CO_2 Levels in the Diver

The only way to detect high levels of CO_2 in the diver, whether the cause is CO_2 rebreathing or CO_2 retention due to inadequate breathing, is to measure CO_2 constantly throughout both inhalation and exhalation, but particularly in the exhaled breath; a method referred to as capnography. The physiological principle underpinning capnography is that the composition of the gas in the alveoli (small air sacs) of the lungs is in approximate equilibrium with the gas pressures in the arterial blood after that blood passes through the alveoli. Therefore, if we can measure the pressure of CO_2 (PCO_2) in the alveolar gas, then we have a good estimation of the CO_2 levels in the diver's blood.

This strategy is used daily in operating theatres all over the world to monitor CO_2 levels in patients undergoing anesthesia. The most common approach in the anesthesia setting is to have a gas sampling system that constantly draws gas from the patient's mouth (or the anesthesia breathing tube, which is effectively the same thing) at about 100 $mL \cdot min^{-1}$ and delivers it via a very narrow tube to a rapid response analyzer. This means that during inhalation the analyzer is receiving gas that should contain very little CO_2, and during exhalation, as the gas comes out of the lung alveoli, the CO_2 content of the sampled gas rapidly rises to a plateau that reflects gas coming from the alveoli with (as mentioned above) levels of CO_2 that are in equilibrium with the arterial blood. To ensure that we are measuring the most representative sample of alveolar gas, we wait until the very end of exhalation because at that point all the gas coming out of the patient's mouth should be pure alveolar gas uncontaminated by gas from the airways (which contains little CO_2 and which should have passed out first, early in the exhalation). Waiting until the end of exhalation is why these measurements are referred to as 'end-tidal CO_2' measurements. This measurement paradigm is depicted in Figure 1. The capnography output is a trace depicting the PCO_2 in the sampled gas (y-axis) vs time (x-axis). The PCO_2 rises during exhalation and falls during inhalation. If CO_2 levels are normal, (per the earlier discussion of normal CO_2 levels) we expect the end-tidal CO_2 to be around 5 kPa (38 mm Hg).

It is not difficult to appreciate the massive advantage of such a system. It will indicate whether there is inhaled CO_2 from any source, be it scrubber failure or bypass, or one-way valve failure. More importantly, it will detect hypercapnia in the diver whether it is caused by inhaled CO_2 or CO_2 retention. Capnography is the only system that will do this. A comparison of the ability of various monitoring strategies to detect inhaled CO_2 from various sources, or retained CO_2, is shown in Table 1.

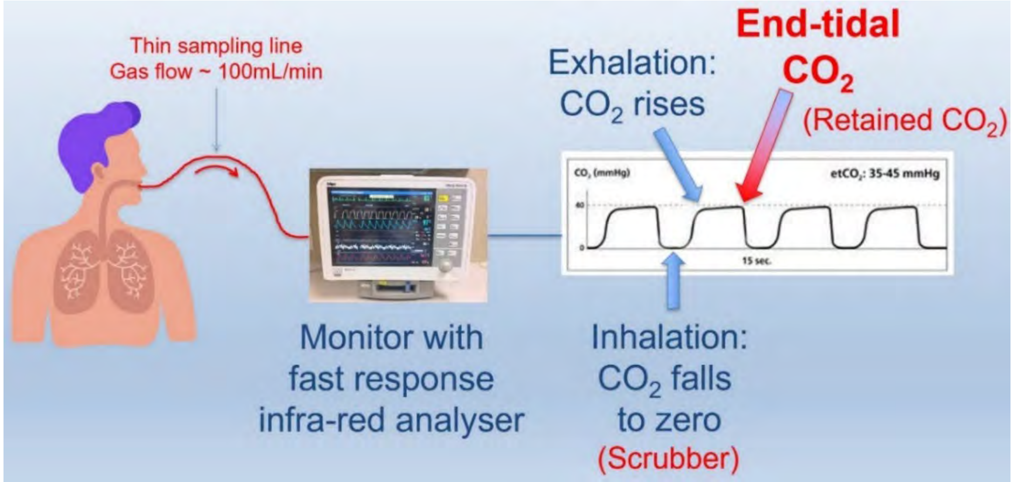

Figure 1. Depiction of the capnography measurement system as described in the text. On the capnography trace notice how the PCO_2 falls to zero during inhalation. If there was CO_2 present in the inhaled gas due to a scrubber fault (or a mouthpiece one-way valve failure) the trace would not fall to zero. The PCO_2 trace rises during exhalation and the plateau represents the passage of alveolar gas out of the mouth. The end-tidal CO_2 is measured at the point indicated, and if there was retention of CO_2 this value would be elevated.

Table 1. Comparison of the various strategies for CO_2 detection in respect of efficacy in detecting CO_2 from different sources. Self-detection refers to the ability of the diver to detect symptoms of CO_2 toxicity. Although some divers will recognize relevant CO_2 toxicity symptoms before the situation becomes dangerous, objective testing demonstrates that this is unreliable (Deng et al. 2015). Capnography is the only method likely to be universally successful.

Measurement method	**CO_2 retention**	**Scrubber failure**	**Inhaled CO_2 Scrubber bypass**	**One-way valve failure**
Self-detection	Unreliable	Unreliable	Unreliable	Unreliable
Temp stick	No	Yes	No	No
Inhale side CO_2 monitor	No	Yes	Yes	No
Capnography	Yes	Yes	Yes	Yes

Unfortunately, capnography is not as simple as it sounds. One must either place one of the infrared sensors described above right at the mouth (in diving, effectively in the mouthpiece), or gas has to be sampled from the mouthpiece and passed to an analyzer nearby. Neither strategy would be easy in a rebreather. Putting an infrared sensor in the mouthpiece is challenging both because of space and humidity. Sampling to a remote sensor (for example, in the rebreather backpack) through a narrow tube would require a lot of power to drive a sampling pump, especially at deep depths where the gas would be dense. There would also be the loss of 100 mL of gas per minute which, although trivial at shallow depths, would become greater at deep depths (for example, 1 L surface equivalent per minute at 90 m [295 ft] depth). In addition, whereas detection of CO_2 in inhaled gas does not need to be particularly accurate (we expect it to be zero so presence or absence is the main issue), if we are going to base dive management decisions on end-tidal CO_2, the measurements have to be very accurate because, as discussed earlier, relatively small changes are significant. Any tendency to over- or underestimate the true end-tidal value would be potentially dangerous when making important decisions (like whether to bailout onto open-circuit) on inaccurate data.

Notwithstanding these challenges, accurate and reliable end-tidal CO_2 measurement in a rebreather remains a monitoring 'holy grail.' No device has currently achieved this. One promising technology which used a non-infrared sensor (unaffected by moisture) in the mouthpiece was reported more than a decade ago (Sieber et al. 2011). However, this did not progress due to some technical difficulties and lack of funding. Another manufacturer claims to have a system for measuring end-tidal CO_2 using an infrared sensor at the end of the exhale hose. An early design for this system reported on diving forums was proven to be flawed due to the mixing of alveolar and dead space gas in the exhale hose (Ineson et al. 2010). The manufacturer claimed to have a compensating algorithm that eliminated this flaw. This claim was viewed with some skepticism by experts, and despite being claimed to work some 13 years ago, the device is still not marketed for sale.

Conclusion

Unfortunately, the diving world is still awaiting capnography in rebreathers. It would be an invaluable research tool and a positive influence on safety. Not surprisingly, the development of this capability was identified by Rebreather Forum 4 as a research priority (Mitchell and Pollock 2023). In the meantime, the best strategies for avoiding CO_2 problems in rebreather diving are to ensure that soda lime is replaced in a timely manner, that scrubber canisters are installed correctly, that one-way valves are working properly, to adhere to recommended gas density limits, and to avoid hard work underwater, particularly when diving deep and breathing denser gases.

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QUESTIONS AND DISCUSSION

BOB MEYER: I have a question regarding hypercapnia since it has been a huge topic of discussion. My understanding is that once you have had a hypercapnic event you go into respiratory alkalosis and then that becomes a reinforcing factor in not being able to restore your normal respiratory function, or that you cannot get the blood reoxygenated within a reasonable period of time because you have altered the blood chemistry. Is that correct? How does that work?

SIMON MITCHELL: There are a couple of things to unpack there. First, it is respiratory acidosis that is induced by high levels of CO_2. Second, there is no oxygenation problem in hypercapnia. There is a small change in the carriage of oxygen in the blood in a hypercapnic state that is sometimes portrayed in diving circles as a problem. In fact, it is of no consequence in diving, particularly where we are effectively always breathing a hyperoxic gas. The problems with hypercapnia are its unpleasant symptoms, the fact that it can increase the risk of an oxygen seizure, and it has a narcotic effect. It is not an oxygenation problem. It does not block oxygenation in any way, especially any way that is relevant to divers who are breathing hyperoxic gas.

AKE LARSSON: My day job is actually inventing the devices you use in your day job. One of the things I have been looking at is ventilation in the intensive care unit under hyperbaric conditions. I have been playing quite a lot with infrared CO_2 monitoring with heliox 30 m and complete water vapor. I can say it works. Because of the water vapor partial pressure, you will have 6.3 kPa at 100 m, so you can manage it.

SIMON MITCHELL: Yes, you can engineer that problem out. I would not be surprised if it is something like what the Lungfish folks have done with their sensor.

OSKAR FRÅNBERG: Do you think that retaining behavior is innate or do you think it is a learned behavior for divers? What do you think rebreather divers could do to limit that?

SIMON MITCHELL: There is evidence for both things. There is an innate element to it. All humans have some degree of variability in what you might call their O_2 response, especially when work of breathing is increased and especially during exercise. However, there is some evidence that this can be modified by certain activities and diving is one of them. There is some evidence that a long history of diving, particularly open-circuit diving where you teach yourself to breathe slowly and try to avoid using more gas than you have to can teach you to be a CO_2 retainer. There is also some evidence that you can increase your sensitivity to CO_2 by doing respiratory muscle training. Thus, there is evidence that CO_2 retention under some circumstances is an innate trait, but you can modify that trait in both directions by different activities, some of which are relevant to diving, one of which is diving itself. The interesting thing for doctors is that diving is often referred to as 'instant emphysema' because it unmasks what you will become if you ever become critically ill with emphysema. In the medical world we talk about 'pink puffers' and 'blue bloaters'. Pink puffers are people who, when they get very bad lung disease, work very hard to keep their CO_2 normal. If they had been a diver earlier in their lives, they would be a non-retainer. A blue bloater is someone who, in lung disease states, does not do the extra work required to keep their CO_2 normal. Their CO_2 increases, causing pulmonary vasoconstriction, eventual right heart failure, and hypoxia; they become blue and retain fluids, so they swell up (hence 'blue bloaters'). So, that is evidence of variability in this innate trait because these patients are not divers. So, that is a manifestation of exactly the same variable trait, but in a different setting. Sorry, for most of you, that would have been gibberish. For the medical people in here, it is actually quite an interesting fact. There is definitely an innate thing, but you can modify it as well.

KEVIN GURR: When you did the temp stick trials, did you look at response time of the sensor system under elevated work rate bursts at all to see if it tracked?

SIMON MITCHELL: No. Those trials are just so time consuming. I think our study involved about 40 or 50 three- to six-hour runs on scrubbers. But your comment is important. As you alluded to in your talk, if you are down to the last bar or two on, say, the Inspiration scrubber temp stick and you are at rest on deco, that is fine. However, if you suddenly decided to do hard work when you have only got one or two bars left, that might be a different story and the scrubber might be more likely to break through. Its 'dynamic response' to this situation might not be so good. We did not test this. It would be a great little study for someone else to do to extend the work that we did. Parenthetically, everyone, if you are someone with academic aspirations and you are a diver there are so many potential studies in diving medicine, that are small, doable, and highly meaningful. In most broader areas of medicine we are just nibbling around the edges with much of the important easily achievable work already done. In diving medicine, there are a lot of study ideas deserving attention.

WINSTON WALKER: For divers who tend to retain CO_2, at what levels does it start to become a problem, and are they more sensitive to the narcotic effects of CO_2 than a chronic respiratory disease patient is?

SIMON MITCHELL: It is very difficult to compare them with chronic respiratory disease patients because those patients are obviously not underwater and subject to all the other stressors that are relevant to being underwater with a high CO_2 level. The main question is at what level does it become significant. We do not have good data on that. Dan Warkander did some relevant work at NEDU, looking at divers' response to increased work of breathing and exercise. He found that once the end-tidal CO_2 level got up over about 8 kPa, substantially beyond the normal level of 5.0-5.5 kPa, there was a high risk of a diver becoming confused and unresponsive. This would be a major life threat underwater. However, I suspect that long before that you are at higher risk of oxygen toxicity and higher levels of narcosis. Thus, 8 kPa is the sort of threshold where you start to fall off your perch, for want of a better expression, but before that there are still risks involved in having high CO_2. Some people will become affected more severely by it than others so that is not an absolute threshold that you could apply to everyone in the general population.

ARNE SIEBER: We were lucky to get some European funds to look into new technologies for measuring CO_2 and oxygen. We looked into technologies for micro-fabricating sensors from ceramic substrates. They worked, but it was not commercially viable. We always have to look at the market. We used waveform fabrication to make some sensors. While maybe 10 worked well, that was not commercially viable. The medical industry is the primary market, and there are alternatives like optic sensing and ultrasonic sensing that already work very well. We were lucky to get the funding to do this research, but in the end we looked into other sensors and decided to pursue fluorescent sensors for oxygen.

SIMON MITCHELL: Thanks for that perspective, Arne. I was extraordinarily excited by your work when you published it and talked about it at the meetings. It is tragic that it could not be developed into something we can use.

KEN BLAKE: All of your experiments were experimentally positive in that you indicated that both the temp stick and the CO_2 sensor for the AP units worked as advertised. I can tell you from an operational perspective they absolutely do work as advertised. My question is this: I was told recently by a manufacturer that CO_2 sensors are less than useful because by the time they alarm you, you are well past the point of being able to do something about it. It is too late by that point. Do you have a comment on that?

SIMON MITCHELL: I think that comment might arise out of the phenomenon that I just described in which a number of subjects in Dan Warkander's work quickly became unresponsive. But from a monitoring point of view, if you had accurate end-tidal CO_2, you would see yourself trending towards that in a progressive way and you would be able to intervene and stop it. The inhalation- side CO_2 sensors will tell you if you are inhaling CO_2 from a scrubber long before that becomes a problem for you. So, no, I do not think that that comment is valid. I think the message might be, and it might be getting lost in translation, that you can flip from feeling okay to essentially incapacitated with CO_2 quite quickly. I think if we had accurate end-tidal CO_2 sensing, you would see it coming.

KIERAN BEVAN: My primary work is in creating coatings and barriers for food. Coffee, for example, needs a good gas barrier. So do dehydrated soups. We create coatings and laminates to address issues. Why not create moisture barrier layers for CO_2 sensors that let the CO_2 pass through?

SIMON MITCHELL: I think most of the CO_2 sensors incorporate hydrophobic membranes. Kev, do you want to say anything about that?

KEVIN GURR: Yes. The patch has a layering of hydrophobic protection on the top of it. It may be slightly different from what you are talking about. Might be worth an extra chat. We are always looking to improve that side of things. There is definitely some susceptibility.

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Demystifying Closed-Circuit Rebreather Scrubber Canisters

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Abstract

Early rebreather divers took their carbon dioxide (CO_2) absorbent for granted. That is, until an August day in 1992 when sodalime contamination was discovered. The Naval Medical Research Institute was tasked with determining the source of the contamination. The Navy Experimental Diving Unit (NEDU) was tasked with finding a replacement sodalime manufacturer and determining new canister durations for US Navy rebreathers. A renewed look at sodalime brought continuing revelations over the next 30 years. Both breathing resistance and canister duration were found to be influenced by the distribution of granule sizes. Chilled sodalime short-circuited the CO_2 absorption process through a mechanism only understood after NEDU created a novel computerized simulation method. The so-called simulated physical model helped isolate the multiple factors operating simultaneously during CO_2 absorption in axial and radial canisters. Most rebreather divers understand that work rate and water temperature affect scrubber duration. However, variability due to human physiology and canister packing can also contribute to variations in canister duration.

Keywords: calcium carbonate, carbon dioxide, simulation, sodalime, Sodasorb, Sofnolime

Introduction—Scientist-in-the-Sea Program

In the 1972 Scientist-in-the-Sea program, the US Navy introduced diving-qualified graduate students to both Navy and scientific diving. That was my first experience with rebreathers. Those rebreathers were the Emerson oxygen rig and the Biomarine CCR 1000, an electronically-controlled mixed gas rebreather that eventually became the Navy MK15.

Before the Navy let civilians dive those rebreathers, CAPT George Bond, MD, the father of saturation diving and the SeaLab project, taught diving physiology (Figure 1). One of the SeaLab aquanauts, Wilbur Eaton, trained us on the technical aspects of rebreather operations.

Figure 1. CAPT (ret.) George Bond at Panama City, FL (1972 Navy photo).

At that time, rebreather scrubber canisters were treated like a gas tank in a car (Figure 2). You had to have one, and you had to fill it, but it did not require much thought. You poured sodalime granules into the canister, sealed it shut, and jumped into the water.

Figure 2. Pails of Sodasorb manufactured by WR Grace (author photo).

That nonchalant attitude proved adequate for decades of diving with granular absorbent. However, on August 21, 1992 everything changed.

Sodasorb Contamination

Discovery

In the summer of 1992, the US federal supply of sodalime had become contaminated. One affected diver reportedly said, "*My rebreather smells like cat piss.*"

Dr. Richard Lillo and his team at the Naval Medical Research Institute (NMRI) in Bethesda, MD (Figure 3), sought to determine the nature of the contamination. By 1995, Lillo and his team concluded that "Contamination of US Navy Fleet sodalime (High Performance Sodasorb®), which contains indicator dye and is used for carbon dioxide absorption during diving, was suspected when an ammonia-like odor was reported during its use in August 1992" (Lillo et al. 1995; *Telephone conversation between Dr. J. Clarke of the Navy Experimental Diving Unit, Panama City, and the Office of the Supervisor of Diving, Naval Sea Systems Command. August 21, 1992).*

The NMRI laboratory further reported that contaminated samples contained ammonia and various amines (Lillo et al. 1996). Presumably, those toxic compounds came from the breakdown of ethyl violet dye.

Figure 3. Naval Medical Research Institute, Bethesda, MD (Public domain).

The Switch

Due to the newly discovered quality control issues with the manufacturer of *Sodasorb*, the Navy Experimental Diving Unit (NEDU; Figure 4) began testing an alternative absorbent, *Sofnolime*, for potential addition to the US inventory. For the rest of 1992 and 1993, NEDU's Unmanned Testing Laboratory conducted around-the-clock canister duration testing using Sofnolime in MK 16 and Dräger LAR V rebreathers.

Figure 4. Control room of the NEDU facility (photo courtesy Steven Frink).

Root Cause

Sodalime is used in hospitals worldwide to absorb CO_2 in anesthesia machines. However, a rare medical emergency involving CO_2 rebreathing occurred in the US sometime before 1989 (the exact date and location are not known publicly). Failure of the ethyl violet indicator in exhausted Sodasorb was the culprit. Although the absorbent had "broken through," the ordinarily colorless pH-sensitive dye had not turned blue, the customary sign of expended sodalime.

Chemistry

A laboratory investigation by the University of Texas Medical Branch Galveston discovered that ultraviolet light from bright fluorescent fixtures could break down ethyl violet dye (Andrews et al. 1990). The study authors recommended increasing the ethyl violet indicator concentration in Sodasorb fivefold.

Two-and-a-half years after the publication of that paper, the US Navy discovered contaminated sodalime. WR Grace later admitted to the Navy that they had at least doubled the indicator dye concentration. Problematically, the Andrews et al. (1990) paper did not identify the chemical products of dye breakdown. Arguably, if those chemical decomposition products were hazardous, a doubling or more of the dye concentration would be ill-advised.

Strangely, no chemists had realized that if ultraviolet and visible light energy can break chemicals apart, then excessive heat might do the same. So, storing sodalime with indicator dye in a hot location on a boat was an incident waiting to happen.

The result of the Navy's costly contamination investigations was that the US Navy would no longer approve diving-grade sodalime containing indicator dye.

The lesson for civilian rebreather divers is that a manufacturer can make drastic changes to its product without advising the diving industry. It has done so on more than one occasion. Because of that, the rebreather diving community should remain informed and vigilant.

Other Research

With the US Navy's attention focused on sodalime, interesting things began to be revealed. The following are four of the more relevant discoveries.

Rebreather divers breathe through the void spaces between absorbent granules. But what if the granules are of mixed sizes, with small granules interspersed among large ones? Many types of sodalime have a wide distribution of granule sizes (Figures 5 and 6).

The Effect of Granule Size Distributions

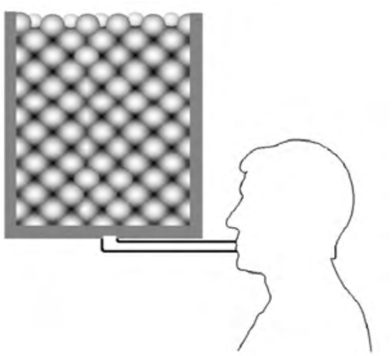


Figure 5. A conceptual illustration of a person breathing through a packed bed of equal-sized, large spheres (author's work).

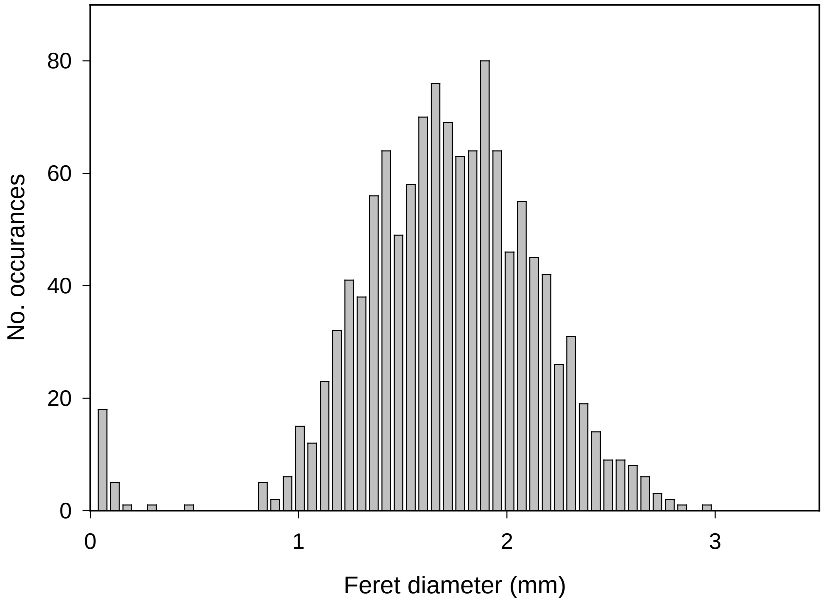


Figure 6. Feret diameter from image analysis of 1230 granules of Sofnolime 812 (Clarke 2002).

Figure 7 illustrates smaller granules filling the spaces between larger granules. As a result, absorbent bed porosity (ф), a measure of breathable void space, decreases from 32% to 12.5%.

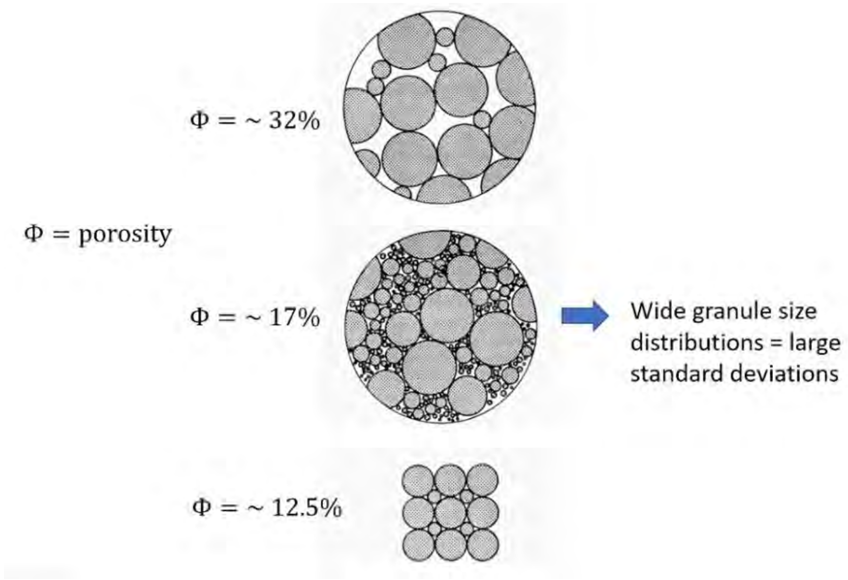


Figure 7. The distribution of granule sizes affects bed porosity (modified from Bear [1988]; used with permission).

When the standard deviation of sodalime granule sizes increases, the following happens:

Standard deviation ↑ → Porosity ↓ → Flow Velocity ↑ → CO_2 Residence time ↓

Canister Duration ↓ Breathing resistance ↑

Flow velocity increases because lower porosity gives you a lesser void volume through which to breathe. Flow velocity, and therefore flow resistance, must increase. A higher flow velocity also means shorter CO_2 residence times, resulting in shorter canister durations.

Sucking a milkshake through a straw is tolerable for a few minutes, but applying that much suction to pull gas through your scrubber for a multi-hour dive would be exhausting. It would greatly exceed allowable limits on breathing resistance by US Navy, NATO, and European standards (NEDU 2015; NATO 2016; European Standard 14143 2013).

Cold Can in a Cold Land

The worst-case scenario for life support equipment is when it has to perform in extreme cold (Figure 8).

In the mid-1990s, NEDU's Test and Evaluation Laboratory was handed a bucket of sodalime and asked, "What's wrong with this?"

Fortunately, the US, UK, and Canada had just promulgated detailed instructions for answering that question (NATO STANAG 1411 [1997]).

Figure 8. Cold water is one challenge, but the exposure of dive gear to the cold air environment in between dives can be far worse (author photo).

Figure 9 is a schematic for a one-atmosphere sodalime activity test bench maintained at a constant room temperature (20±1°C).

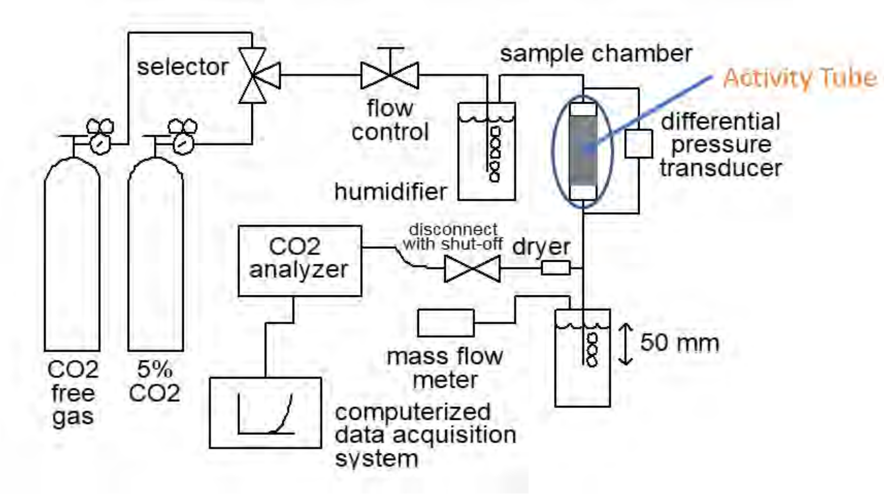


Figure 9. NATO bench test for performance of granular CO_2 absorbent (AdivP-03)

Since the Navy's sodalime problem occurred in the cold, we surrounded the 105 mL activity tube with a temperature-controlled water bath chilled to 1.7°C (35°F).

This NATO test examined the CO_2 breakthrough curve for the cold-soaked sodalime sample. In this case, CO_2 scrubbing was interrupted by an early breakthrough, a partial recovery due to bed activation, and an immediate activity collapse (Figure 10).

Prebreathing the rig would hopefully get you past the initial failure. But you would not expect a canister, once activated, to fail so completely. Apparently, that was why the sodalime was "broken."

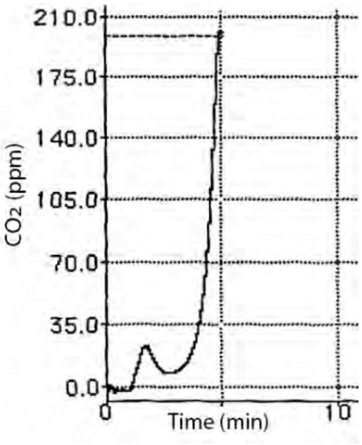


Figure 10. NATO bench test result for a sample of suspect Sofnolime (US Navy data).

To help understand what we were seeing, I wrote a computer simulation that would hopefully explain what we observed. The software was a type of simulated physical model (SPM) based on simple physics, not mathematics, *per se* (Figure 11). More accurately, it can be called a stochastic physical model since its functioning is probabilistic. It had the uninspired name of *Cold Canister* (Clarke 2001).

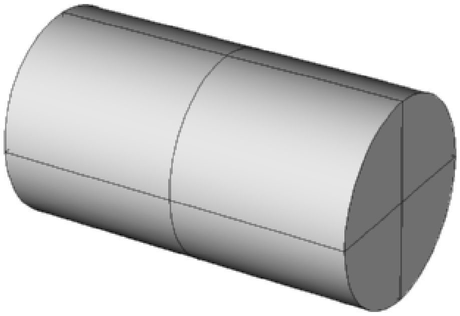


Figure 11. A minimalist representation of a cylindrical, axial canister filled with sodalime absorbent.

Almost 290,000 cuboidal elements (cells) were within the final simulated scrubber canister. The complete model was subjected to virtual experiments with dynamic temperature changes during static cooling, forced convection, and cooling with canister insulation for testing purposes. After the SPM passed those tests, it was ready to simulate CO_2 absorption.

An empirical absorption probability calculation where T is in °F,

$$P = \frac{(T-32)}{(T-12)},$$

applied to each volume element or *cell* recomputed every computational cycle (~1 s). The plot of that equation in Figure 12 is similar to that of the famous Arrhenius equation governing chemical reaction rates as a function of temperature.

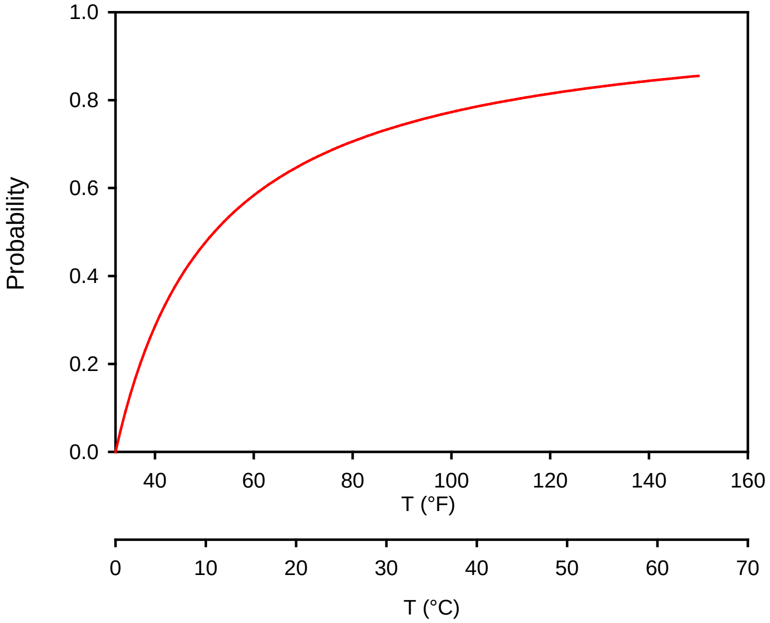
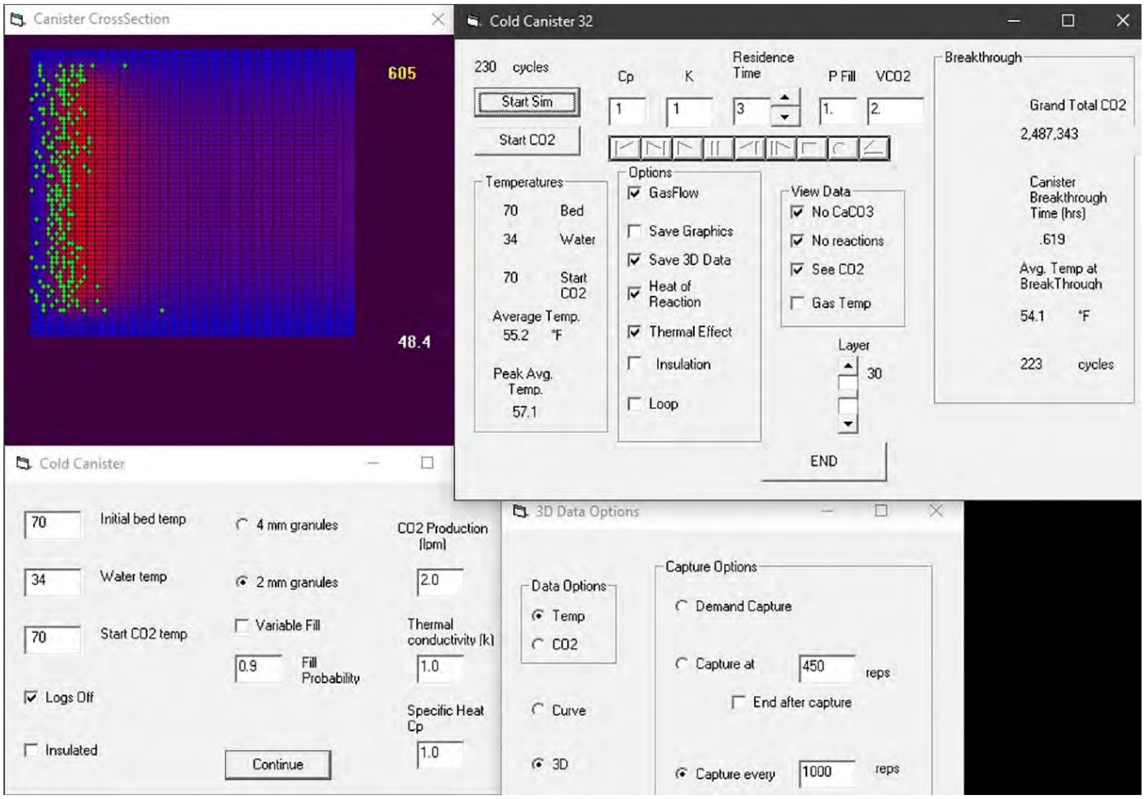


Figure 12. An Arrhenius-like probability curve.

Once a CO_2 "molecule" encounters an empty absorption site on a granule, the local cell temperature controls the probability of an absorption reaction. If the cell is warm, an absorption reaction is likely. If the cell is cold, absorption reactions are unlikely.



230 cycles

Cp: 1
K: 1
Residence Time: 3
P Fill: 1.
VCO2: 2.

Temperatures
70 Bed
34 Water
70 Start CO2
Average Temp. 55.2 °F
Peak Avg. Temp. 57.1

Options
☑ GasFlow
☐ Save Graphics
☑ Save 3D Data
☑ Heat of Reaction
☑ Thermal Effect
☐ Insulation
☐ Loop

View Data
☑ No CaCO3
☑ No reactions
☑ See CO2
☐ Gas Temp

Layer 30

Breakthrough
Grand Total CO2 2,487,343
Canister Breakthrough Time (hrs) .619
Avg. Temp at BreakThrough 54.1 °F
223 cycles

70 Initial bed temp
34 Water temp
70 Start CO2 temp
☑ Logs Off
☐ Insulated
○ 4 mm granules
● 2 mm granules
☐ Variable Fill
0.9 Fill Probability
CO2 Production (lpm) 2.0
Thermal conductivity (k) 1.0
Specific Heat Cp 1.0

Data Options
● Temp
○ CO2
○ Curve
● 3D

Capture Options
○ Demand Capture
○ Capture at 450 reps
☐ End after capture
● Capture every 1000 reps

Figure 13. A screenshot of Cold Canister while running.

As seen in Figure 13, the optional parameters for *Cold Canister* are numerous and varied. The upper left window displays some raw data showing the simulation's progress. The exothermic CO_2 absorption reactions generate heat. The resulting granule temperature is indicated by deep blue to red colors. Green squares indicate cells where CO_2 absorption is active during a given computational cycle.

Real-World Test

Having characterized the SPM performance in thermo- and chemical kinetics pertaining to a packed bed of sodalime granules, it was time to challenge the SPM with the complex results of the NATO bench test. The simulation results appear on the right half of Figure 14. The SPM parameters were 0.6°C (33°F) water and canister, 4 mm granules, CO_2 inflow ($\dot{V}CO_2$) = 1.0 $L \cdot min^{-1}$.

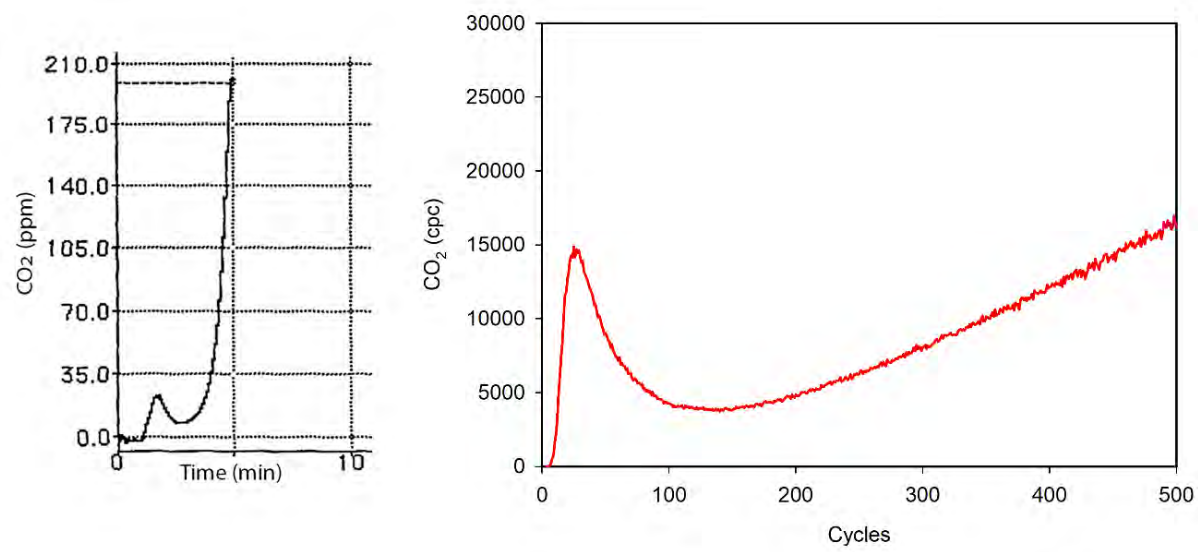


Figure 14. Comparison of NATO test results (left panel, ppm=parts per million CO_2, US Navy data) and SPM simulation results (right panel, cpc=counts per computational cycle).

There was reasonable agreement between the results of the NATO laboratory test on the left and the virtual model on the right. That meant that the simulation could reproduce a real-world operational failure. Furthermore, relatively simple physical-chemical principles could account for mission failure. In frigid water, heat from the nascent exothermic reaction zone is conducted away by the surrounding cold granules, quenching the absorption reactions.

Exploration

An axial flow canister in a horizontal configuration, as in Figure 15, is modeled in many of the following figures. Exhaled breath flows from left to right through the canister.

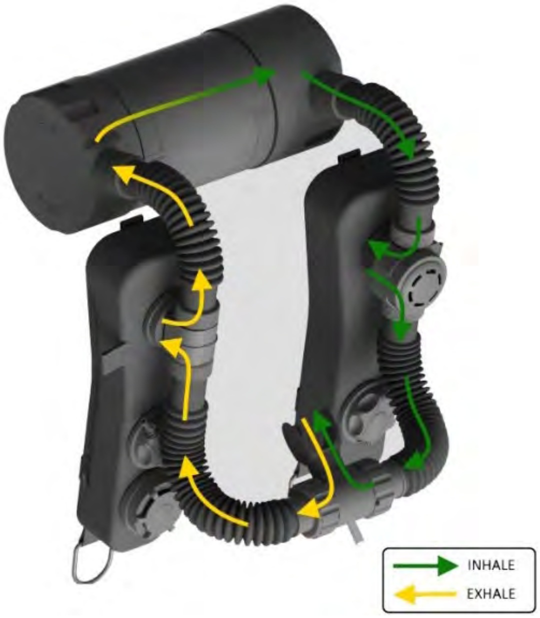


Figure 15. A gas flow path for a rebreather with an axial scrubber (illustration courtesy Dive Rite).

Figure 16 is the raw data appearing during the running of a simulation.

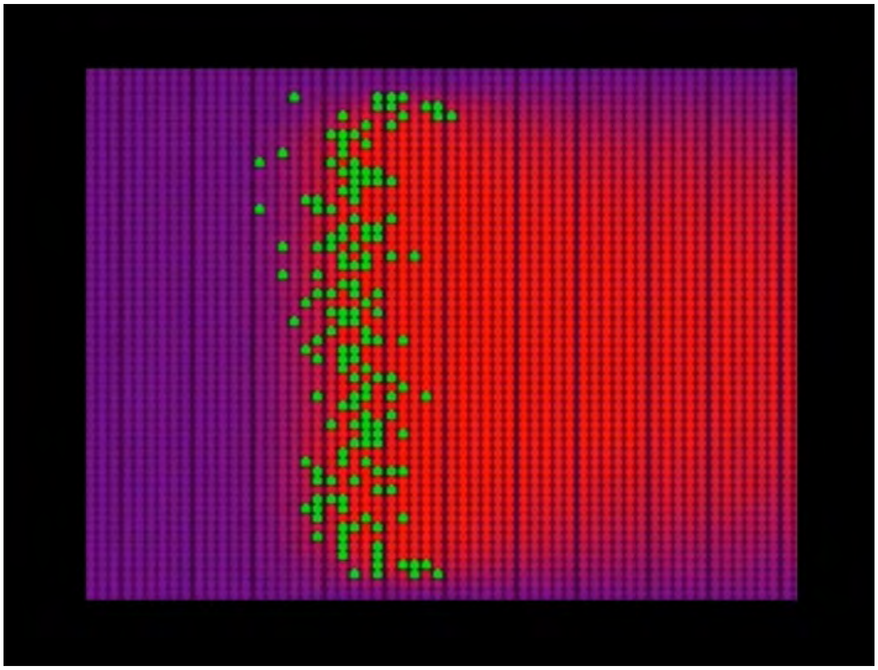


Figure 16. Raw 2D data for 27°C (80°F) canister in 24°C (75°F) water (author photo).

Post-processing of the raw data yields a 3D visualization of an axial flow canister surrounded by cold water (Figure 17; colored black). The cutout reveals the warmer absorbent bed and beginning absorption reaction zone.

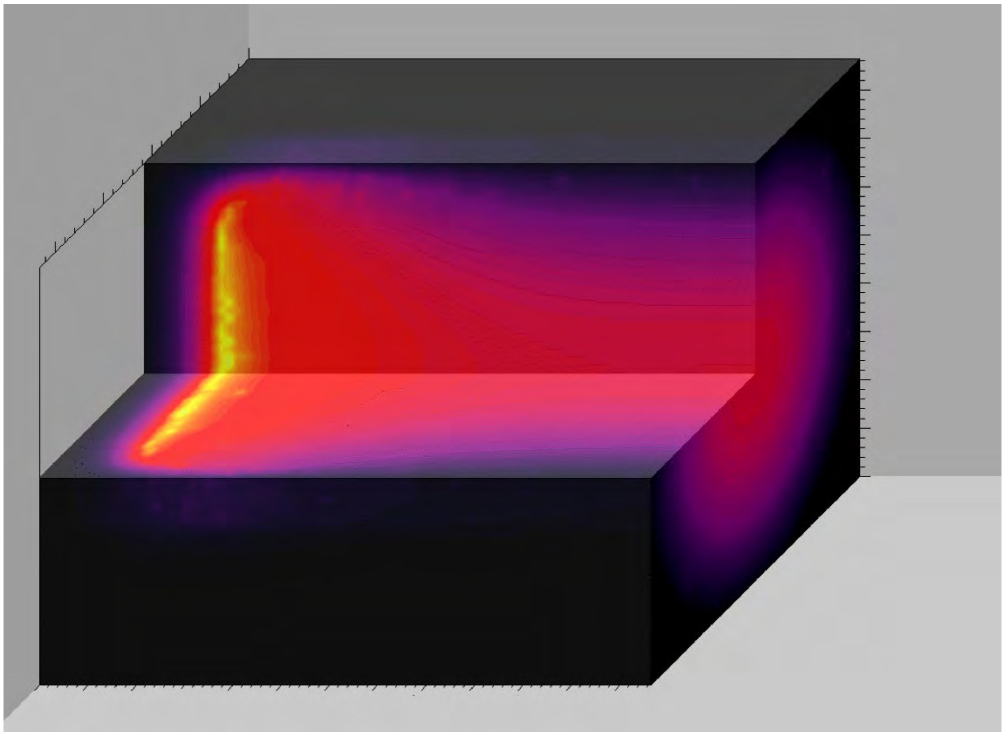


Figure 17. A 27°C (80°F) canister in 1°C (34°F) water. CO_2-containing gas flows from left to right (author image).

Radial Canisters

Next, we have a radial canister with cold gas containing expired CO_2 entering the central cavity and progressing radially toward the outside plenum (Figure 18).

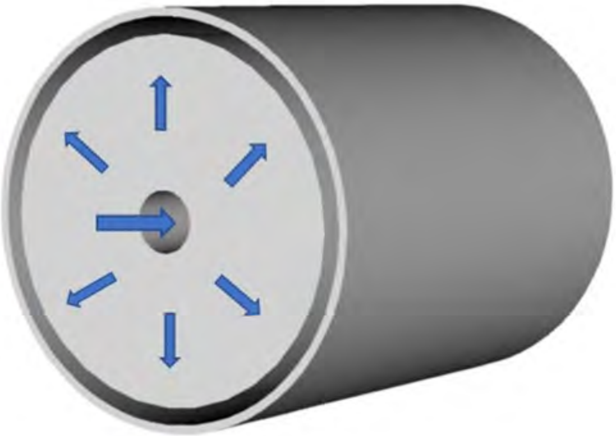


Figure 18. A radial canister with gas flowing from the inside to the outside plenum (author photo).

In Figure 19, a 32°C (90°F) canister full of 2 mm granules is cooled from the middle out by CO_2-containing air chilled by 1°C (34°F) water (Clarke 2022).

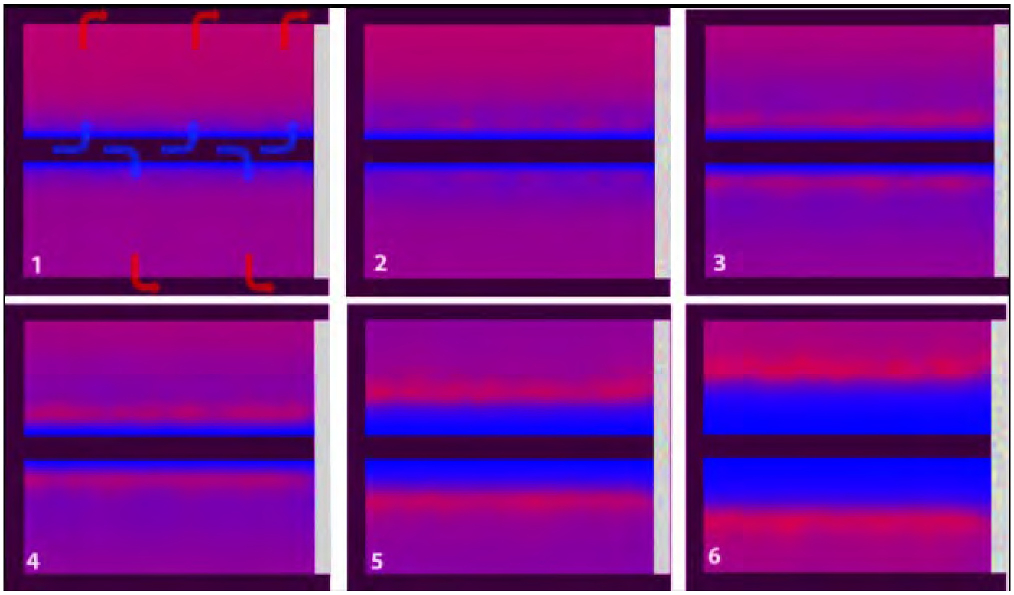


Figure 19. Freeze frames from a video of CO_2 flow through a radial scrubber (author photo).

In frames 2 and 3, you can see random processes at work as spots of localized heating begin to consolidate, partially offsetting the effect of the cool gas inflow.

Carbonate Deposition
Instead of plotting temperatures, we can plot calcium carbonate deposition. Figure 20 shows carbonate deposition at the moment of a breakthrough of a 21°C (70°F) canister in 21°C water. The granule size was 2 mm.

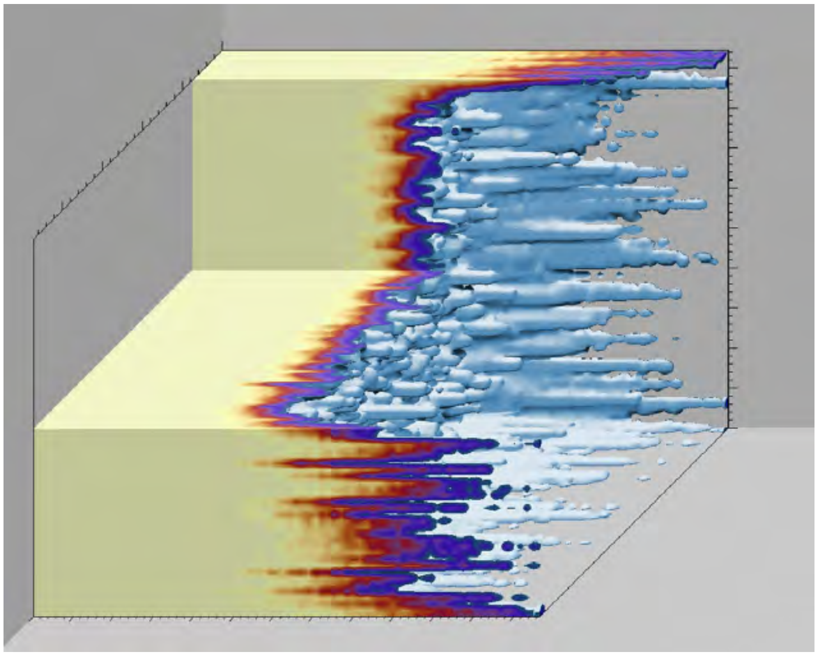


Figure 20. Carbonate deposition at breakthrough at 21°C (70°F) with 2 mm granules (author image).

The amount of carbonate deposited is color-coded. Blue and brown colors represent partial carbonate deposition. Yellow represents the complete filling of CO_2 absorption sites.

We Are Not the Same

As any high school student knows, the harder you work, the more oxygen you consume and the more CO_2 you produce. In response, the harder you breathe. Understandably, then, rebreather canister duration drops with exercise because of increased CO_2 inflow analogous to filling a bucket with water. The more water coming in, the faster the bucket fills. However, we cannot rule out an effect of the concomitant increase in diver ventilation.

The ventilation versus CO_2 inflow conundrum may depend on individual variability. The significance of that variability was eloquently stated by the physician William Osler over a hundred years ago (Figure 21).

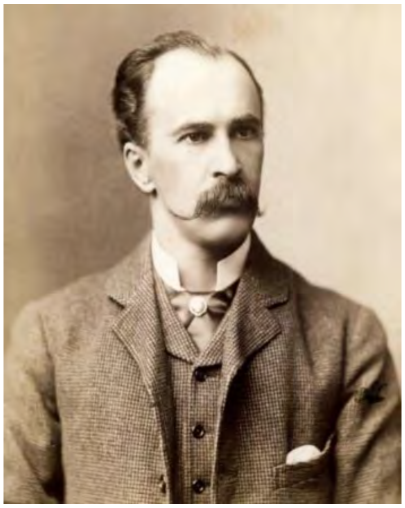


Figure 21. Dr. William Osler (public domain).

"Variability is the law of life, and as no two faces are the same, no two bodies are alike, and no two individuals react alike and behave alike under the abnormal conditions which we know as disease" [or diving*] – Dr. William Osler (1849-1919) [*amended by J. Clarke].

Have you ever been enjoying a scuba dive with a new dive partner and had to end it early because their air consumption was higher than yours? If so, that is one indication that people are different. While most people assume differences are attributed to training and experience, there is an often-unrecognized component based on physiology and probability.

To put substance behind that statement, Figure 22 is the graphical representation of experimental data, plotting the reported means and standard deviation obtained in various biomedical studies of exercise performance in young, fit divers. They include respiratory exchange ratio or the dimensionless ratio of carbon dioxide expired for a given oxygen consumed (R, 0.92±0.07 (mean±SD), n=63, Morrison et al. 1976); oxygen consumption (1.52±0.21 $L \cdot min^{-1}$, n=8, Knafelc 1989); and the ratio of ventilation to oxygen consumption (ventilatory equivalent, 26.7±4.0, n=63, Morrison et al. 1976). In the bottom right of Figure 22 are plotted the weights of sodalime packed in oxygen rebreather canisters by Navy divers (2597±142 g, n=41, Naggiar et al. 2022). These graphs assume the data were normally distributed, as in a bell-shaped curve.

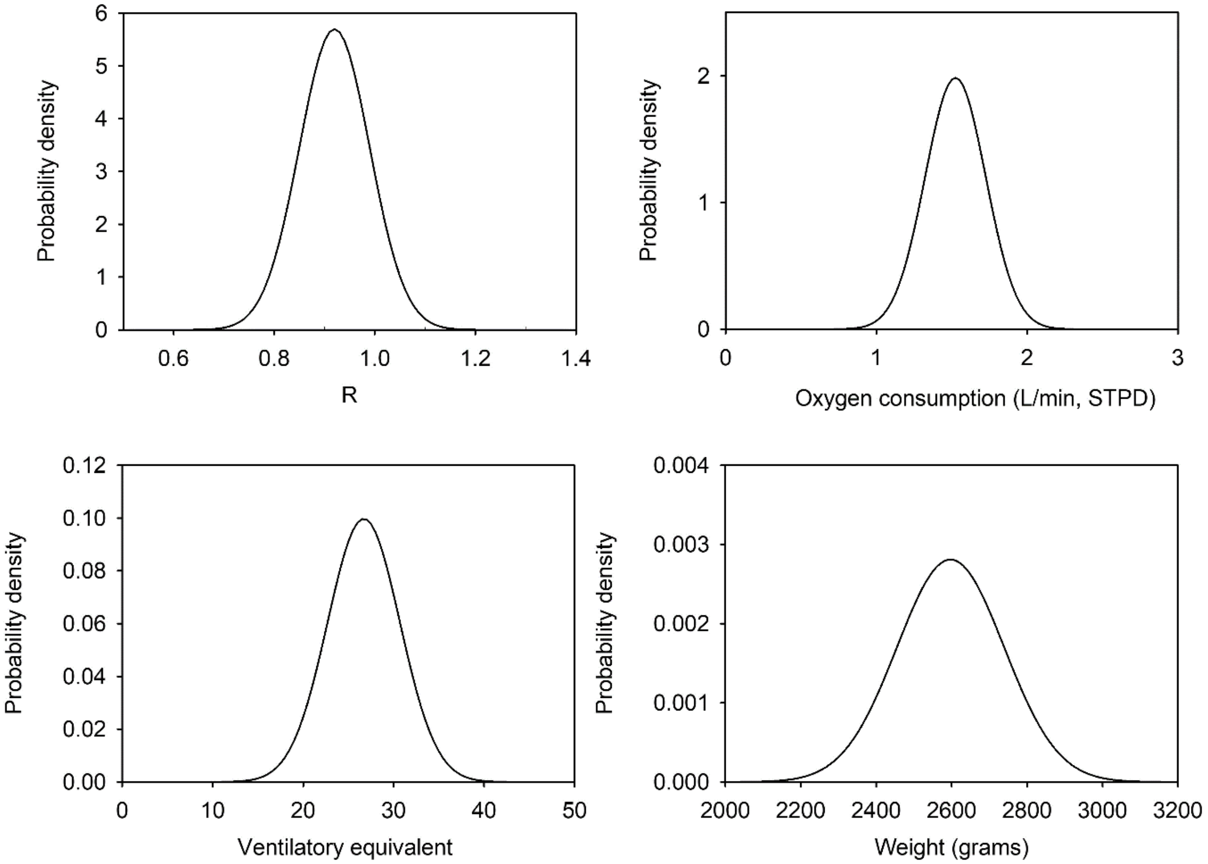


Figure 22. Experimental variables are plotted from measured data, assuming the data are normally distributed (author's illustration of statistical summaries of various data sets, as described above).

Based on physiological control mechanisms, oxygen consumption, CO_2 production, and ventilation ($\dot{V}O_2$, $\dot{V}CO_2$, and $\dot{V}_E$, respectively) are usually tightly controlled to maintain a reasonably constant arterial CO_2. However, that control does not apply to a group of divers collectively called *CO_2 retainers*. Some experienced divers may be so relaxed underwater that they do not increase ventilation as much as expected when workload increases. Other divers may have innately abnormal responsiveness to CO_2. In both cases, those divers might allow arterial CO_2 to rise above normal levels.

The SPM allows CO_2 and ventilation to increase in tandem or to have ventilation fixed at a constant value, as might happen with a CO_2 retainer. In the next section, we explore the consequences of that constancy.

Are We Filling a Bucket?

In a rebreather scrubber, are we filling a bucket with CO_2 during a dive (Figure 23)? Or is something else happening?

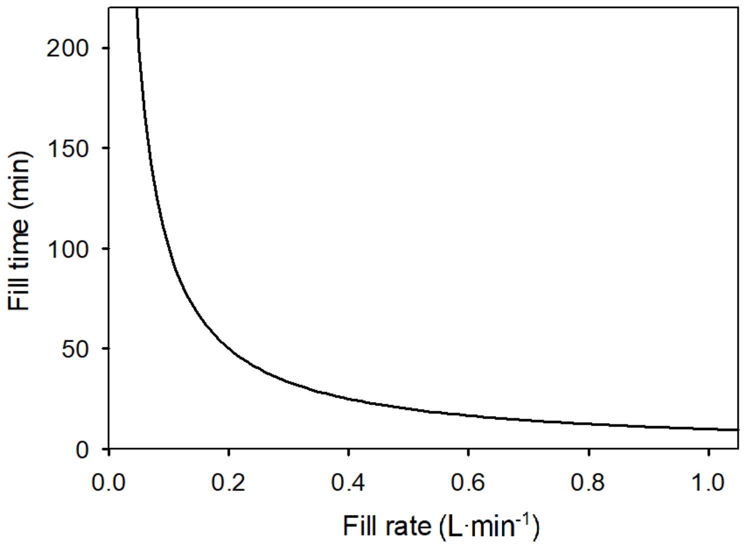


Figure 23. The time it takes to fill a 10 L bucket with water at varying fill rates.

For simulated absorbent canisters, some unexpected behavior appears when breakthrough time is plotted against CO_2 injection rates. In Figures 24 and 25, SPM simulations were run at differing CO_2 residence times (Tr) and ever-decreasing intervals between CO_2 injection rates.

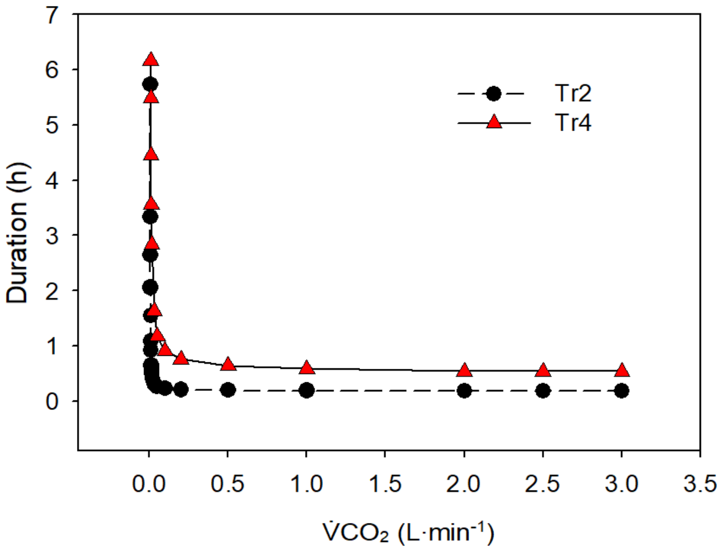


Figure 24. The relationship between CO_2 production rate, CO_2 residence time, and canister duration (author's work).

There were three major findings from this series of simulations.

1) Increased ventilation flow rates (simulated by reducing CO_2 residence times from 4 to 2 computational cycles), reduced canister durations. The captions in the upper right of each plot indicate those residence times (Tr).
2) At low CO_2 inflow rates, increasing CO_2 reduces duration (the bucket fills faster) as expected.
3) At high CO_2 inflow rates, however, increasing CO_2 does little. Instead, duration is influenced mainly by gas flow rate (residence time).

All three findings had been reported in a laboratory study 36 years ago (Radić et al. 1987). That laboratory study showed the expected relationship between canister duration versus the rate of CO_2 entry into the canister.

Figure 25 is the result of subjecting published data from Radić's Table 1 to nonlinear curve fitting routines in Sigmaplot 11.0 (Systat Software, San Jose, CA). Higher ventilation rates (lower curve) suppressed duration, presumably due to decreased CO_2 residence time within the canister.

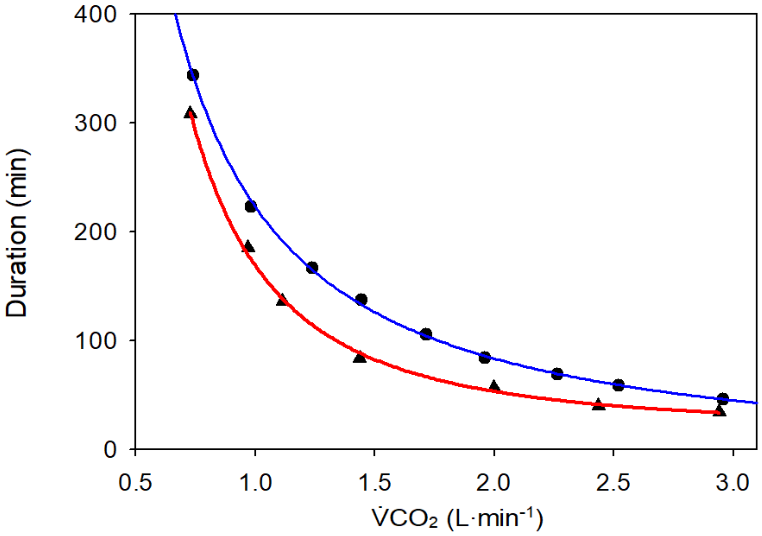


Figure 25. Laboratory studies of the effect of ventilation ($\dot{V}_E$) on CO_2 scrubbers. Upper curve = $\dot{V}_E$ of 27 $L \cdot min^{-1}$, lower curve = $\dot{V}_E$ of 53 $L \cdot min^{-1}$ (author's curve fits of data from Radić et al. 1987).

The curvilinear shape of the curves in Figure 25 are as expected from a *filling-the-bucket* analogy (Figure 23). However, some other factor must explain the extended duration at lower ventilation ($\dot{V}_E$) rates (upper curve). In other words, the CO_2 residence time is critical to the laboratory tests of Radić et al. (1987) and the SPM (Figure 24).

Consolidation
The following image is partially explanatory. It compares the raw data at canister breakthrough for three CO_2 injection rates ($\dot{V}_{CO_2}$). As $\dot{V}_{CO_2}$ increases, the CO_2 absorption sites become more consolidated. They form a tighter cluster of green squares in the SPM *canister*.

The raw data in Figure 26 reveals a steadily increasing consolidation of active regions of CO_2 absorption as they move further to the right on the duration hyperbola. The more CO_2 is available for absorption, the more the diffuse pattern of canister heating morphs into a tight reaction zone or "fire line."

Reaction consolidation yields positive feedback, capturing inbound CO_2 molecules and slowing down the progression of the reaction zone. Slowing the downstream movement of a well-consolidated reaction zone results in an extension of canister duration by delaying absorbent canister breakthrough.

Summary of SPM Results

First-Order Effects

The similarity of the shapes of Figures 23-26 strongly suggests the obvious; that the rate of filling of a canister with CO_2 is important.

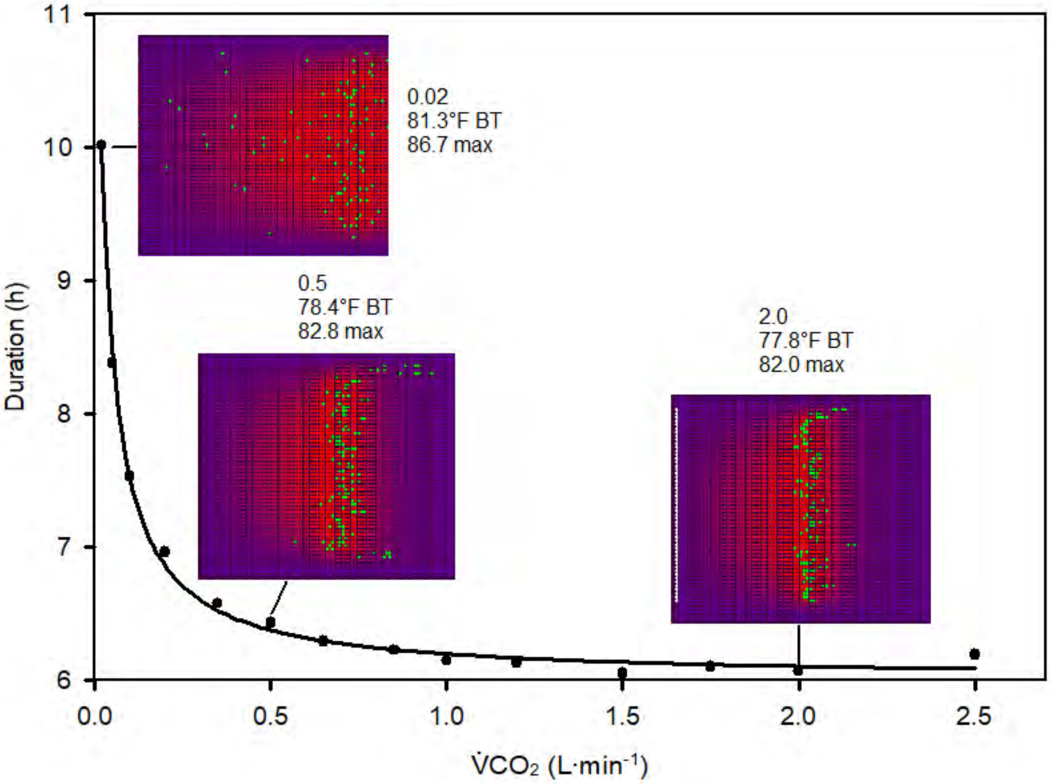


Figure 26. Consolidation patterns and the average temperature at breakthrough (BT) as a function of $\dot{V}CO_2$. Tr = 4 at 21°C (70°F) (author's work).

Second-Order Effects

A decrease in CO_2 residence time accelerates the downstream movement of an absorption reaction zone, just as an increase in wind speed in the vicinity of a wildfire increases the downwind movement of that fire.

The SPM teaches us that consolidation of the actively absorbing zone of a rebreather is more likely to occur at high $\dot{V}CO_2$ than at low $\dot{V}CO_2$, and at lower ventilation rates than at higher ventilation rates. Consolidation leads to increased localization of heat due to exothermic absorption reactions. Acting as a form of positive feedback, the localization of heat increases the probability of CO_2 absorption, reducing the probability that CO_2 escapes scavenging by the canister and inhalation by the diver. In other words, canister breakthrough is delayed.

Conclusions

Sodalime granule size matters, but what about variation in granule sizes?

Increased dispersion of granule sizes tends to decrease granule bed porosity. Decreased porosity decreases canister duration due to increased local flow velocity (reduced CO_2 residence time).

A cold scrubber canister in a cold land.

A short pre-breathe may not fully activate a frigid canister. If possible, store the canister cool – not frozen.

Daily changes in physical and physiological conditions can affect canister duration.
Do not assume that you are going to end your dive within canister limits.

Regarding CO_2 absorption within a scrubber canister, are we just filling a bucket?
At high CO_2 loads, CO_2 residence time (ventilation rate) has a secondary but critical effect on canister duration. The worst time for a rebreather diver to increase ventilation is near the end of a dive. Swimming against the current on a rebreather nearing the end of its canister life might expose the diver to high CO_2 levels.

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QUESTIONS AND DISCUSSION

AKE LARSSON: Questions about simulation. First, what is the flow profile you are using - flat, parabolic, or what? Second, if you change from an axial flow to radial flow, would there be a significant difference in the dependency on the ventilation rates?

JOHN CLARKE: The flow profile was flat. Nothing about the modeling is easy, so I kept it simple whenever I could. Flow is not contoured along the periphery of the canister because the canister is a packed column, not an open tube where you might find parabolic flow. Interestingly, even assuming simplicity, you get dramatic changes in the thermal contours based on the absorption probabilities. Additionally, I did the radial canister simulation to teach myself how they work. But, to be honest, I have not spent a lot of time with that. But now I have been inspired to go back and look at radial canisters a little bit more. To make a comparison between radial and axial canisters, they both must have exactly 288,000 volume elements. I have not taken the time to do that yet, but it is on my to-do list.

DAVID DOOLETTE: You said earlier that the reaction front is not linear and the temp stick assumes that. I was not quite sure what you meant. So you meant the profile perpendicular to where your temp stick is is not linear so the positioning of that in the canister might be important?

JOHN CLARKE: More correctly, the reaction front may not be linear. In most simulations, you are getting a more or less linear profile across from one side of the canister to the other, so the position in the canister is perfect. But in the particular profile you are speaking of, a central peak was advancing ahead of the rest of the canister. So, if you had a temp stick in the center, the measured temperature would be ahead of the rest of the front. That will give you an advanced warning if the center triggers the temp stick, saying, "Okay, we are about 75% done here." In reality, you may have a little bit more canister time remaining. The critical point is to not assume that the temp stick can know what is happening across the canister. Having the temp stick information is much better than not knowing anything. Still, the actual profiles can be more complicated than you think.

DAVID DOOLETTE: I have another question. You spoke about the importance of testing the temperature of the gas and the surrounding water. Would you comment on depth? If I had my rebreather that is tested at 90 m (295 ft), can I take it to 250 m (820 ft) and assume I am going to get the same duration out of my canister?

JOHN CLARKE: That question gets asked a lot, but the simulation cannot address it yet due to limited data. At NEDU, we did a comparison test with a MK 16. We ran it to a depth of 90 m (300 ft) on air and 90 m on helium. The question was, is air going to give you a longer duration, or is helium? In the helium environment at 90 m, I saw a longer duration than with air. I did not put that in my book because that is only one data set collected at NEDU on a military rig. I have talked to several people, Avon and others, who are interested enough to finally resolve what happens when switching gases going to different depths. We tend to make the assumption, and I think it is false, that just because you go deeper at higher gas density, you will have a shorter canister duration. In reality, it seems to depend on the thermal capacity of the gases. In our test, that gave helium an advantage over a denser gas. The question is still out there, though. We need more data. We need different rigs and different rig configurations. The MK 16 does not have an axial canister. We need some data in axial canisters, and we need breathing machines that can work at pressure. NEDU is fortunate in that we can do that for military rigs.

DAN REYNOLDS: Presumably for every depth and workload there would be an ideal scrubber shape in terms of aspect ratio excluding the effects of temperature. Is there research on that or is that still an unknown?

JOHN CLARKE: There are too many variables for the amount of data we have. Ideally, instead of spending $100,000^{US} testing a canister at depth, it would be great to have software that could do it for us. But I think we are quite a way away from that. As you know, any model is only as good as it is validated by real-world data. I was amazed and pleased when our initial validation on that little canister duration with the peak in it was revealed. But now there are so many other questions, like what else can it do, and many "what ifs." I am afraid we are a long way from using simulations to replace laboratory testing. Unless we find some young engineers and students to carry on that work, we may be stuck with testing durations at NEDU and elsewhere.

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Emergency Procedures for Technical Closed-Circuit Rebreather Projects

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Abstract

An emergency plan specifies procedures for handling sudden or unexpected situations that can arise during dive operations. The objective is to prevent fatalities and injuries through proper planning, and if injuries do occur, to treat and evacuate the injured in a safe and timely fashion. Closed-circuit rebreather dives, particularly ones with extensive run times, can present a unique set of challenges for the prudent dive planner, often depending on a number of factors such as location and what assets may be available to the team. Prudent planning and definition of all potential hazards are the first step in being prepared for an emergency. No singular emergency plan will work in every scenario, as each project will present a unique set of challenges and assets. This paper is intended as an outline for what a well-drafted dive plan should address.

Keywords: accident, close call, diving, emergency planning, incident, safety

Introduction

With today's global network of advanced technical training, the growing popularity of trimix, closed-circuit rebreathers (CCRs) and underwater propulsion devices, the depth and range of the technical diver continues to extend deeper and further afield. With this expansion comes a commensurate amount of risk to be mitigated or managed and an increasing complexity when responding to diving-related incidents and emergencies. Diving operations should lead with risk mitigation, but there must also be readiness for when things go wrong. Long before dive operations begin, the formation of a dive plan or standard operating plan (SOP) and the ancillary emergency action plan (EAP) is paramount to the execution of a cohesive emergency response. Modeled after both military and commercial dive operations, the SOP must take into account all possible scenarios regarding the support, rescue and evacuation of an injured member, with redundant and layered assets whenever possible, but with the limited material assets, finance and supports systems available to the technical sport diver. In a well-drafted SOP, specific incidents may be used to highlight different levels of need or the singular importance of a particular aspect of the emergency action plan, without going into excessive detail about the events themselves. Examples referenced throughout this presentation are drawn from actual events. They are used to exemplify the need for emergency procedures, not as comments on specific cases.

Definition of an Emergency

Definitions of an emergency include a serious, unexpected, and often dangerous situation requiring immediate action, and an unforeseen combination of circumstances resulting in events that call for immediate action.

To the new open-water diver, the loss of a mask or regulator mouthpiece is an emergency, but to the technical diver, it is a minor inconvenience, one easily managed with training and experience. Divers should train for and practice emergency drills until they can be reliably completed with minimal stress. It must also be appreciated that either the magnitude of a problem or the development of a sufficient number of things going wrong at the same time can overwhelm even the most experienced diver. The key is to be able to manage the emergency as best as possible, and as someone lending aid, being adequately trained and prepared to do so.

Emergency will be defined here as a situation in which a procedural response by the victim would have little or no effect, and assistance by others is required to return to a normal state.

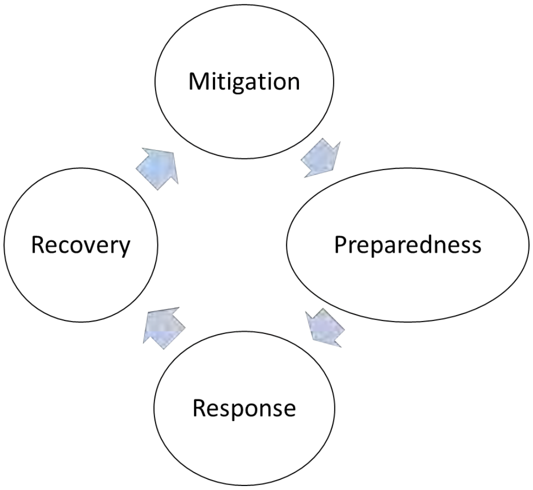

Figure 1. The four phases of emergency management.

As technical divers plan deep, remote or highly complicated dive profiles or projects, four phases of emergency management should be considered: mitigation, preparedness, response, and recovery. In effect, it is a continuous cycle of learning from experience and putting those lessons to action. The hope is that the majority of time can be spent in mitigation and preparedness, rather than response and recovery.

Mitigation
Preventing future emergencies and/or minimizing their effects. Mitigation takes place before and after any emergencies, by examining past emergency events and learning from that experience, being honest to earmark shortcomings and deficiencies. The goal is to learn not just from our own missteps but also from the mistakes of others to minimize the likelihood of repetition. Round table mitigation can arrest the normalization of deviance in which so many incidents find root.

Preparedness
Being prepared for an emergency starts on the first day of dive training. Training will influence how a diver reacts to a situation. Likewise, it also forms how a diver prepares before a dive and manages events post-dive. This carries through to expedition and team dive planning where it is imperative to be prepared well before an emergency occurs.

*<u>Plans and preparations</u> made to save lives and to guide response in a rescue situation. Drafting a detailed dive and emergency plan

*Use of checklists for equipment, emergency supplies, CCR assembly and CCR pre-dive.

*Having qualified and equipped emergency medical technicians (EMTs)/paramedics on support team.

*If available, contacting area hyperbaric chamber operators to understand their pre-chamber procedures as well as confirming general availability. It should be noted that day-to-day availability will always be a variable, but it is important to know whether the diver must first go to an off-site emergency department and if there are any chambers that are either permanently closed or no longer accept emergency patients (wound care only).

*Understanding what emergency transportation may be required to reach the facility. Will they require ground transportation? Is air-medical evacuation needed?

*Overlapping/Layered coverage for support, evacuation medical/support of remaining dive team.

*Redundant communications/satellite phones/adequate translators available,

*Taking into account all variables and choosing the best/safest option: weather/tides/people/equipment**.** Will the team conduct a dive with a long run time if there is a high current? Will the weather negatively impact support personnel from being able to safely and efficiently effect a rescue? What will occur if there is an equipment failure topside during the dive? It would be impossible to force all variables, but taking a step back from the in-water operations would reveal more variables that must be considered.

Dive Plan/Standard Operating Plan (DP/SOP)

Detailed DP/SOP should be drafted and distributed to all team members prior to operations. During work up and planning, online sharing of a digital outline for team interface and discussion helps familiarize the team with each aspect of the plan. The final version should be made into a water-resistant and bound manuscript and be distributed to all members prior to dive ops.

Regular team discussions leading up to, and then pre- and post-dive meetings during dive operations will help clarify and amend action items due to changing conditions or concerns.

DP/SOP should outline everything related to the project: team member bios and contact information, daily tasks and rota, logistical details like travel and procurement, mission and/or daily goals, equipment specifics and techniques to be used. These documents should cover all dive logistics including tables for operational and emergency dive gases and procedures for all gas management.

Prior to conducting any dive operations previous experience and projects are discussed in detail to provide insight and experience to new team members.

DP/SOP documents should always include a project specific emergency action plan.

Note: No singular DP/SOP will work for every dive project, but the basic outline can and should be adapted to the specific needs, challenges, assets and the support a particular project has available.

Emergency Action Plan (EAP)

The EAP is highly detailed and specific document relevant to the type of dives/environment/equipment and assets the project or dive(s) will have.

These documents will list all emergency contacts, including the nearest hospital(s), chamber(s), air, land or sea ambulances available and confirm (as far as possible) the availability of these assets during dive operations. Persons/Points of contact should be established for each facility.

*Routes and distances from dive area to emergency assets should be detailed and maps included. The greater the detail in evacuation and resources the better.

*The EAP should describe emergency medical technician/support roles, both primary and backup, and includes a list of all available medical equipment. The document should detail anticipated emergency transport procedures prior to dive operations, for example, which oxygen cylinders are to travel with the injured diver, who is to travel with them, and the location of team member personal emergency data folders.

*The EAP document should clearly define the roles and responsibilities of each team member and assures the dive safety officer or dive marshal has a clear line of communications, with appropriate and available in-water, medical and rescue assets.

There should be abbreviated and preferably laminated copies for the dive safety officer or dive marshal for quick reference.

Note: No singular EAP will work for every dive project, but the basic outline can and should be adapted to the specific needs, challenges, assets and the support a particular project has available.

Response

Response to an emergency requires taking action to save lives, reduce injuries or injury severity, and to prevent further issues while minimizing the risk to responding persons. This should be achieved by putting EAP plans into effect. All emergency supplies clearly marked and readily accessible. All personnel should be familiar with their location and know how they might be expected to assist. Establishing clear leadership, direct communications, and alternatives for each assigned roles can facilitate responsiveness. Assuring layered support to primary and backup assets can help for triage, management, and evacuation if needed. Secondary or backup assets can be critical for the continued support of any remaining in-water dive team if an immediate suspension of operations is not possible.

Recovery

The recovery phase includes actions taken to return to a normal or enhanced safety situation following an emergency. Post-incident assessment is essential to both understand current events and improve future safety. The focus of the post-incident assessment should not be to establish blame but to understand all factors contributing to an event and the outcome. A process that engages all participants can be most effective. Open communication of events and mitigation strategies can help to ensure improved safety for future activities.

Emergency Scenarios

Technical CCR dive teams can face unique and varying challenges based on environmental conditions, equipment/mechanical failure, human error or other variables on any project. Whether it was a series of events developing into an incident, or a single catastrophic event, this is a list of some of the most commonly planned for emergencies.

Loss of Gas/ CCR Failure

The following gas loss/bailout scenarios are based on a dive profile requiring an extended decompression obligation. Operationally, if a diver suffers an equipment failure but is able to stay on the loop (semi-closed, use of off-board gas, etc.), and still manage the unit in a controlled ascent, this would still be considered an emergency. There are often many different makes or models of CCRs and even differing configurations of the same models, so establishing familiarity with all team members' CCRs on a project will facilitate assisting in an emergency. Minimal requirements include plugging in offboard gas, isolating leaks, and recognizing potential issues by observing head-up display (HUD) or handset information.

Bailout rebreathers (redundant back- or sidemount) are becoming more common. Use of these systems can substantially reduce the amount of open circuit bailout required, but with the cost of added complexity. Given the complexity and task load of managing two CCR units simultaneously, this procedure may not be practical for all types of dive profiles or for all divers. At present, open-circuit bailout is still the primary response to a total CCR failure. A diver going onto open-circuit bailout may be dependent on support from his buddy and the support team. This will particularly be the case if the team bailout strategies are employed and individual divers may not be carrying sufficient bailout gas to allow independent safe ascent.

Dive buddies should ensure that the proper gas switches and dive computer setting changes have been made (ie, to open-circuit mode). They should also ensure that topside has been informed of events through established protocols (eg, surface marker buoys [SMB]). Similar conservatism/gradient factors and dive profiles should be implemented so buddy teams move through decompression together where feasible. If there is no constant in-water support diver, buddy teams should always stay close and move/surface together when the more conservative profile clears a decompression stop.

Note on open-circuit bailout: A team approach with checks and balances to all gas management, in particular for cylinder labeling and analysis should be utilized. All gases should be analyzed twice, by two separate teams, and clearly labeled with maximum operating depth (MOD) and contents. Gas pressures on cylinders should be checked pre- and post-dive and pressures logged every day to ensure readiness.

Unconscious Diver (Hypercapnia, Hypoxia or Hyperoxia)

All dive team members and support divers need to be familiar with all the equipment being used, in particular the location of all integrated weight systems and buoyancy compensator device (BCD) inflator(s) to facilitate rescue of an incapacitated diver. Pertinent details are presented in four actual unconscious diver scenarios to illustrate possible responses and outcomes.

Incident A: After 20 min at 120 m (394 ft), a CCR diver bailed out and initiated an open-circuit ascent along the main line, with his buddy. The buddy signaled with an SMB and the team was met by a support diver at 50 m (165 ft). The diver switched to a staged bottle, one not part of the emergency gas plan, and subsequently began to convulse rendering the diver unconscious. The support diver brought the victim to the surface but despite the efforts by on-scene medical personnel, the diver never regained consciousness and died.
Cause: Mislabeled cylinder with a high FO_2 for that depth

Incident B: At the conclusion of a 30 min, 70 m (230 ft) dive, an open-circuit diver was at his 10 m (33 ft) stop when his buddy noticed a camera falling. The buddy looked up to find the diver convulsing and subsequently falling off the line. The buddy was able to gain control of the unconscious diver and deployed an SMB. Topside, a support diver was deployed and brought the diver to the surface where he regained consciousness, making a full recovery.
Cause: During decompression the diver confused his two decompression gases and breathed too high an FO_2 at depth.

Incident C: Two CCR divers were conducting a 40 m (130 ft) dive and 30 min in when one diver noticed that his buddy was unconscious with the loop out of his mouth. The buddy inflated both the BCD and drysuit on the unconscious diver, traveling with him to 33 m (108 ft) where the rescuing buddy arrested his own ascent and allowed the stricken diver to continue to the surface. The rescuing buddy completed his decompression obligation while topside support noticed the unconscious diver on the surface and began in-water resuscitation, initiating CPR and oxygen administration once on board. The stricken diver regained consciousness and made a full recovery.
Cause: Out-of-range/Faulty cells resulting in improper calibration of CCR.

Incident D: Two CCR divers were 20 min into a 70 m (230 ft) dive when one diver lost consciousness. His buddy gained control of the stricken diver and made a rapid ascent to the surface with the intent to immediately descend and being his own decompression. The boat operator was unable to get the unconscious diver into the boat resulting in an extended surface time for the rescuing diver. Subsequently, the rescuing diver became paralyzed while the unconscious diver's body was lost. Air rescue was delayed, and four hours passed before the paralyzed diver reached the hospital. There was no recovery of the unconscious diver and the buddy suffered permanent paralysis due to decompression sickness.
Cause: Out-of-range/Faulty cells resulting in improper calibration of CCR

In all four incidents, there was a dive buddy to render assistance/rescue, otherwise we would never know what happened and each story would certainly have ended in tragedy.

Three of the incidents had a dedicated support diver(s) to assist with recovery and a medically trained/equipped responder(s) on board to resuscitate and administer oxygen and further medical assistance pending evacuation.

In the final example, the boat operator was alone onboard the vessel, and could not pull the unconscious diver aboard. This first diver's body was lost at sea when the second diver (rescuing buddy) became partially paralyzed on the surface. There was only a small cylinder of oxygen available on board which was quickly consumed. This illustrates the risk inherent in completing a rescue attempt by omitting a decompression obligation, even if the intent was for a short surface period, it now created a second casualty to the original emergency.

Observations
Always dive with and remain in contact with buddies, the primary means of assistance or rescue.
Have topside support (not just a boat captain) that can assist in an emergency.
It is best if topside support is a qualified and equipped in at least basic life support and is a certified oxygen provider with a sufficient supply of oxygen for a worst-case medical event.
When aiding an unconscious diver, render all assistance possible without risking yourself and creating a second casualty.

Note: Although not used in any of these incidents, the use of a gag strap or full-face mask could make a difference in an unconscious CCR diver scenario.

Decompression Illness
The two incidents described here occurred in remote locations that required complex evacuations and extended time to execute.

For the record, in both incidents the divers had done everything "right" as far as tables and computers were concerned, but nonetheless both were in really bad shape within minutes of surfacing which ruled out in-water recompression.

Incident A: While 240 km (150 mi) offshore, and a 48 h transit to the nearest port, a diver was partially paralyzed and unable to hold any fluids, rendering him in danger of dehydration. On board was a fully equipped paramedic who was able to provide intravenous fluids, oxygen, and continuously monitor the diver's vital signs. The group, equipped with two satellite phones, contacted DAN which arranged for a faster boat to intersect the dive boat and transport the diver to a chamber.

Incident B: While on a liveaboard in a remote island atoll, a diver became symptomatic with decompression sickness during a surface interval. Despite the diver being at a hospital, less than five hours after the dive, there was no hyperbaric chamber in operation within 1600 km (1000 mi). DAN was contacted and within 24 h, had arranged an international pressurized jet for medical evacuation.

In both cases, there was a 100% resolution of all symptoms.

Observations

Multiple factors resulted in the complete recovery of both divers. Having plans and reliable (and redundant) communications in place allowed for effective management even in extremely remote locations. On the boat, an equipped EMT and abundant supply of oxygen can save lives and improve outcomes. All divers should hold adequate medical and dive insurance appropriate for the level of diving being conducted to reduce the potential cost burden.

In-water recompression

The use of in water floating decompression stations can be useful for dive operations, both for safety and diver comfort. Depth appropriate open-circuit gases can be easily staged for both normal and emergency and the bottom divers can be monitored by in-water support divers during the shallow (eg, 15 m [50 ft] to surface) phase of decompression. These systems can allow for more relaxed and worry-free decompression. Support divers can be rotated in and out of the water as needed. Bottom divers can clip onto the bar to alleviate stress of holding on in even a moderate current and to prevent sinking or drifting in case of compromised consciousness (eg, from oxygen toxicity or DCS). The secondary use of the system would be for emergency in-water recompression. Appropriate planning, equipment, personal conditions, and victim status can allow treatment of divers if a decompression chamber or immediate evacuation to one is not an option. It is important to note that while in water recompression is conceptually simple, it requires substantial organization, resources and conditions including ample support divers, breathing gases, equipment (note: full-face mask is preferred), reasonable water conditions and a patient who is conscious and in control of their faculties and functions. Weather and water conditions and other water hazards make in -water recompression inappropriate even if all other elements are in place. The medical and research communities have been divided on the utility of in-water recompression but support for it under well-defined conditions is growing (Mitchell et al. 2018).

Lost Diver

Incident A: At 30 m (100 ft), a team of four open-circuit divers penetrated a wreck with the plan to enter and explore a specific, small, compartment. Over the course of the dive, the visibility was disturbed. As no penetration line was used, three of the four divers were unable to find their way out of the compartment and to their staged bottles, before running out of air. The fourth diver and sole survivor was able to get out and surface, alerting topside of the situation.

Incident B: At 30 m (100 ft), two separate teams of CCR divers penetrated a wreck, unknown to three of the four. The first team was on a "trust me dive" with the intent to transit the wreck without a line, unaware of the second team following. When the first team failed to find the exit, they turned to find that they had been followed into the wreck and were now in a zero-visibility situation, confused and with no line to back out. They remained in the silted compartment for hours, beating on the side of the wreck, in effect trying to beat their way out. A separate pair of divers were alerted by the banging, effected a rescue plan and were ultimately able to locate and extricate all four divers. The total run time for this dive was six hours, including a two-hour decompression.

Observations

In both incidents there were gross violations of wreck diving standards and protocols, but in the second, the use of CCR provided the time needed to effect a rescue. The second case is an example for which there was no plan for this rescue beforehand, relying on a combination of clear thinking and good fortune to deliver a positive outcome.

Diver Adrift

In the context of technical diving, being adrift would only be an emergency when the plan was not to be adrift. In areas of high currents or tide, in shipping lanes or other restricted areas, a drift profile is either too dangerous or outright forbidden.

Scooter failure, broken mooring line, poor navigation, strong current or a combination of any of these could result in a diver not making it back to the mooring/ascent line. If this occurs a prearranged system of colored surface marker buoys may be used to indicate the primary type of problem the diver is experiencing.

To prepare for this, the support boat (or second boat) manned by a pilot and support diver is outfitted with a radio, global positioning system (GPS) and a 50 m (165 ft) weighted emergency drop line with the appropriate breathing gases. If the area is affected by dense fog or limited visibility, a high-flyer radar reflector should be carried as well.

When an SMB surfaces indicating that a diver is adrift, the backup boat would follow it and slowly drop the emergency line down to the diver looped around their surface marker buoy line. When available and allowed by conditions, the support diver may enter the water with additional gas and to further assess the situation.

A third standby vessel may be needed to ensure adequate support for the main line and divergent divers.

In the case of a main down line breaking and all the divers are drifting in a clutch, the support teams use both vessels to follow and divert traffic, alerting the appropriate authorities of the situation. If possible, the support divers will wrangle the team into a cohesive group for the longer shallow stops.

Missing Diver

EAPs should consider all options in case of a missing diver. If a diver has not surfaced as planned, a surface search should be effected and immediate calls made to the appropriate search and rescue agencies/coast guard/police/naval units, etc. Once all topside search and rescue efforts have concluded and all possible endurance for underwater survival has been exhausted, the emergency has concluded. Any and all search and recovery activity from here forth should be well thought out and planned prior to any action in that, you may be party to a request for the search and recovery of a lost diver. Not everyone can handle the mental stress of this type of dive and in the cave community there are dedicated dive teams who are called when a diver does go missing in a cave. They somberly accept and methodically plan for this tragic eventuality. In the open ocean, unlike most cave systems, there is more opportunity for a person to be deemed unrecoverable the more time they spend underwater. If a search and recovery is effected, it must be timely and well planned with the safety of the recovery divers being more important than all other considerations. Emotions run high in these events as does a sense of moral obligation and that can cloud good judgment.

Trauma/Medical Emergency

There are inherent risks in many diving related ocean activities for traumatic injury, from boating accidents and mishaps, animal encounters, and catastrophic equipment failure to name just a few. The cause is not the point, but the response is. Be prepared by having adequate medical supplies, good communication with a plan for evacuation. Also be prepared for non-diving medical issues that could arise whilst at sea, or in preparation for diving, due to unforeseen underlying health issues. Yearly physicals by doctors who understand diving and at least moderate exercise capacity are important for anyone looking to push the envelope on CCR.

Conclusion

As technical CCR divers continue to push the envelope, we need to constantly review, amend, and update our plans for when things go wrong. Be honest with yourself and your peers when things go sideways and focus on the permanent fix. Stop the cycle of normalization of deviance and listen to the voice that questions. Being prepared takes work, but it is well worth the effort. Rather than bask in the arrogance of how smart, talented or experienced we are, we as leaders in the dive community, have a responsibility to set the example, and continue to grow with the changes and challenges the technical dive community presents.

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Acknowledgments

Four phases of emergency management: https://www.upstate.edu/emergencymgt/about/phases.php
Unconscious Diver incidents I spoke from my own personal experience as a witness (incident A) and conducted first-person interviews with Joel Silverstein, (incident B) Dave Conlin (incident C), and Joseph Augusto (incident D)
Further documentation provided for the *Unconscious Diver* section
Incident A: Author's personal recollections of events, dive log, and post-incident report Kea Greece 2009
Incident B: OXTOX Incident report USS Monitor, NC, USA 2004
Incident C: NPS AAUS Presentation (Sellers), 2012
Incident D: Author interview and report from Tom Huff, 2005
Decompression Illness
As a witness to both incidents as dive leader, and drawing from my own records and post-incident reports of each event.
Incident A: Guntram John Weisbrich, Gulf of Thailand, 3/11/2007
Incident B: Gary Mace, Chuuk, Micronesia, 11/8/2010
Lost Diver
Incident A: Author interview with the Howard Spialter, re: deaths on the Spiegel Grove, FL, USA, 3/18/2007
Incident B: Interviews with Antti Apunen and Aron Arngrimsson, re: Sata, shipwreck, Palau 9/5/2022

QUESTIONS AND DISCUSSION

JOE BOSQUEZ: We talked a lot about bailout rebreathers. And you can see the gas logistics with the bell. Have you used habitat scrubbers? That is definitely something we have been working a lot with in cave country.

RICHIE KOHLER: No. The bell was just a commercial hardhat bell so there was no scrubber capability on that. There was no helium recovery unit or anything like that. Going back to 2006, when I did a project with some of the members of AP Diving, we thought about having an active, up and running, preflighted unit, an Inspiration, in the water at pre-dive and hanging like Navy divers do. They have an MK 15 that they go to in case they need bailout. We contemplated that, but because of the complexity and our lack of practice we felt it would be too dangerous to start in a real diving environment. So I would not say we were ahead of our time because we did not do it, but the concept has been there for a while and I am glad to see that it is moving along.

MICHAEL MENDUNO: I have two questions. I was reacting to your talk about team diving. And I know that a lot of people who were surveyed solo dive, and I noticed in the fatalities a very large percent are solo dives. I am wondering if we are going to have some kind of consensus statement on team diving. Do you now plan on in-water recompression if you are more than two or four hours away from a chamber? Is it now part of your plan that you are prepped to do in-water with masks and the whole bit.

RICHIE KOHLER: We did, on a project in 2021, have a hyperbaric researcher and doctor with us. We were close enough to an open and operating chamber that we did not need in-water recompression. But if we are doing a project where it may be appropriate, we will plan for it. I do want to emphasize that I would love to talk to anyone who has ideas for a good protocol for a team approach to bailout rebreathers.

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Thermal Management and Diving Safety

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Abstract

Diving is conducted in a broad range of thermal environments, many of them involving some degree of cold stress. Coldwater diving can magnify many hazards, including compromises in physical performance, decision-making, and decompression safety. Appropriate thermal protection is important for divers, with hazards created by both inadequate protection and overprotection. Divers are best served by prioritizing safety over absolute comfort and being mindful of the total potential impact of any practice or equipment to be used. Hypothermia is not a realistic concern for any kind of normal diving activity, and passive protection will often be sufficient to maintain physical performance and clear thinking. Active systems may be appropriate in some cases, but they can also adversely affect decompression safety. Careful consideration should be given to if and how they should be used. The best practice is to minimize unnecessary and fast heating before, during, and after diving. No dive computer effectively assesses the thermal status of divers, let alone measures the true impact of a host of related factors on decompression safety. While real-time monitoring might one day allow for dynamic decompression algorithm adjustment based on thermal state, this likely remains well in the future. At present, the obligation for safe thermal management remains with the diver.

Keywords: cold stress, decompression, health, hypothermia, physiology, thermal protection

Introduction

Diving is conducted across a broad range of thermal environments, from a peak beyond 38ºC (100ºF) to a minimum of -1.9ºC (29ºF). Water has a 3500-fold greater heat capacity than air, allowing massive transfer of heat energy to or from an unprotected body. Effectively, temperatures that may be comfortable in air may be intolerable in water for more than short periods if a diver is unprotected. While overheating is possible in the warmest water, especially for an exercising diver, the much more common issue is cooling stress, and thus will be the focus here. This report is developed as a follow up to a paper delivered in the Rebreather Forum 3 conference (Pollock 2014).

Hazards of Cold Water Diving

All diving involves hazards, but several can be magnified by cold water. The state of the hands is often the primary limiting factor, resulting from a necessary compromise between thermal protection and dexterity. Even light gloves can adversely affect performance, with the degree of impairment increasing with the bulk and flexibility. Both dexterity and sensitivity are compromised, which can affect the ability to equalize middle ear pressure and to locate and manipulate equipment. Buoyancy control is more difficult due to compromised dexterity and the additional equipment and ballast weight worn. Managing a greater gas volume requires more compensation during both descent and ascent, sometimes even manipulation of multiple systems, often a drysuit and separate buoyancy compensator. Greater control issues relate to both ballast weight retention and ballast weight release (ditchability). Many divers prioritize ballast weight retention, but the appropriate course of action may be retention or ditching depending on the situation. Once more, a compromise to allow for both should typically be found.

Vertigo can be more of a problem in cold water, not just due to the dexterity issues for equalizing, but also since hoods can increase the likelihood of external ear squeezes, and a ruptured tympanic membrane that introduces colder water into the middle ear can produce a greater effect. Practically, the likelihood and magnitude of both alternobaric and caloric vertigo may be increased. Cold water and the restrictive suits worn to protect against it are also two of the multiple risk factors for immersion pulmonary edema.

The thermal state of divers can have complex effects on performance, decompression stress, and decision-making. In addition to the acute effects, repeated coldwater exposure is also a primary risk factor for the development of exostoses (surfer's ear), expressed as an overgrowth of bony tissue in the outer ear canal.

The primary focus of this discussion is on the physiological hazards of cold stress, practices that can influence them, and strategies to manage them.

The Importance of Thermal Protection for Diving

Divers frequently ask what thermal protection is appropriate for a given set of conditions. The only simple answer is that it should be sufficient for impairment to not be a problem. Thermal stability is increased with larger body sizes, lower surface area to body mass ratios, greater subcutaneous fat thickness (natural passive insulation), and greater muscle mass (increasing metabolic heat production through non-shivering thermogenesis, shivering thermogenesis, and exercise). The thermal state is influenced by activity levels, and even by limb movement that can alter the surface exposed to the ambient environment.

Thermal stress can play an important role in physical performance, concentration, decision-making, and decompression safety. Consideration of thermal protection should include the pros and cons of the available options and the most appropriate prioritization. Figure 1 shows two strategies for prioritization. The comfort-focused approach is probably the natural default, with comfort as the top priority. There is certainly logic in this, since a diver who is comfortable is less likely to have issues with either physical performance or concentration, and is probably less likely to make poor decisions due to discomfort. The problem with this approach is that the potential impact of overwarming on decompression safety - which may be substantial - will often be ignored or given minimal consideration as an afterthought.

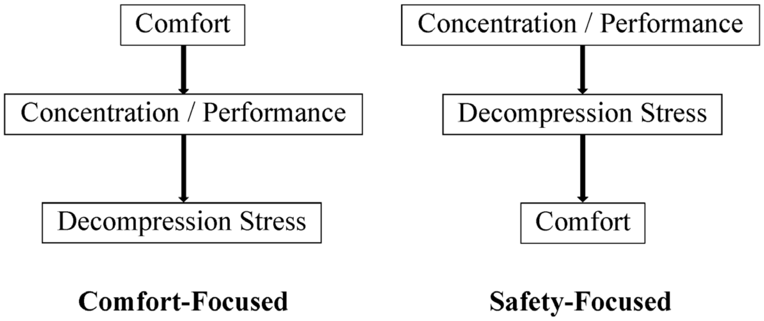

Figure 1. Comfort-focused vs safety-focused schema to prioritize planning for thermal protection.

The chief problem is that the increasing array of thermal protection strategies, particularly those involving active heating, can influence decompression stress to a degree often not appreciated by divers. It is important to remember that the availability of tools and options does not necessarily mean that they are safe. The best example of the impact of manipulating skin temperature on decompression stress was provided by a study completed by the US Navy (Gerth et al. 2007). Clamping skin temperature at warm and cool temperatures had truly dramatic effects on allowable bottom times and rates of decompression sickness. Fundamentally, inert gas uptake during the descent and bottom phase of a dive is increased when a diver is warmer, and decreased when a diver is cooler. Inert gas elimination during the ascent and stop phase is increased when a diver is warmer and decreased when a diver is cooler. Details of this work and the impressive magnitude of the effects on decompression outcome are described in another paper in these proceedings (Pollock 2024). The critical point is that the importance of the timing and intensity of both thermal state and exercise are probably second only to the dive profile in influencing decompression risk. While the Gerth et al. (2007) study is important for its control and elegance, similar patterns were seen previously in a field bubble study of coldwater divers who were either well protected or inadequately protected (Dunford and Hayward 1981), and in a more recent laboratory study of nitrogen uptake and elimination with different clamped skin temperatures (Pendergast et al. 2015).

The impact of thermal manipulation on decompression stress means that it should not be an afterthought. A safety-focused approach is likely to provide greater overall protection for divers. Ensuring sufficient protection to maintain concentration and physical performance is the top priority, with consideration of the potential impact on decompression stress right behind it. Comfort remains on the list, but definitely in last position.

The thought of downgrading the importance of comfort may be unwelcome to some divers, but the reality is that there is little concern for physical injury as long as the ability to preserve concentration and physical performance is maintained. It is important that these capabilities are preserved on all dives, so additional protections may be needed for longer dives or those likely to involve lower levels of physical activity. The critical aspect is that excessive warming, that most easily achieved through active heating systems or exercise, should be approached with great caution. Active heating may be appropriate, and even necessary, in some situations and for some divers, but the potential impact on decompression safety should be weighed carefully. This must be done by the divers and team leaders since it is a notable weakness that the influence of active heating on decompression stress is not adequately addressed by manufacturers. These are "buyer beware" tools.

One of the challenges of active heating systems is the risk of failure, which exists on any dive. A major limitation is that active heating systems tend to provide less passive protection than purely passive systems do. This means that, in the case of system failure, the diver may experience a greater degree of compromise than would otherwise be the case.

The potential issues can be illustrated through an example. A diver planning a relatively long and deep coldwater dive might want to opt for battery-powered, active heating. Having the active heating on during the descent and bottom phase of the dive will increase the inert gas uptake. This can be moderated if the device is set to the lowest acceptable setting, but there will remain some uptake influence. If the system continues to operate throughout the dive the increased uptake may be partially met by augmented elimination, However, if the system fails late in the bottom phase or during the ascent and stop phase the discomfort can be acute given the lesser passive protection common to active heating ensembles. In addition to the discomfort, this creates the warm/cool pattern of augmented inert gas uptake and impaired elimination that creates the greatest risk from a decompression perspective. If a diver gets cold it is often normal for a question to form as to whether or not accelerated decompression would be a good idea. This is where divers can get into more trouble. The reality is that the diver who is cool or cold during decompression should be increasing stop time to allow sufficient inert gas elimination since the rate is impaired. The decompression profile should be extended for safety in this scenario, not abbreviated. There is a need to control decision-making for safety purposes, not comfort purposes.

A question that often comes up at this point is whether the risk of hypothermia is important enough to justify an accelerated exit. Hypothermia is frequently discussed in relation to diving, so this may seem reasonable, but the reality is that it is much more of a fanciful hazard than a meaningful risk. The suits worn for diving, even the less than ideal and partially failed ones, provide sufficient protection to practically eliminate the risk of hypothermia. Hypothermia, by definition, requires the body core temperature to drop below 35°C (95°F), which is a substantial fall from the normal 37°C (98.6°F) reference temperature. This is not easy to achieve. A diver may be cold, and even miserable, but it is vanishingly unlikely that they will become hypothermic over the course of even a fairly extreme dive. For example, a diver in -1.9°C (29°F) polar water completed a 43 min dive in a drysuit with a failed front entry zipper that was flooded from the start, experiencing only a 0.3°C (0.5°F) drop through the dive (Pollock 2007). The diver was cold and shivering, but nowhere close to the threshold for hypothermia. Prospective studies have demonstrated similar outcomes. An evaluation of 16 oxygen rebreather divers wearing 10 mm neoprene farmer john and jacket wetsuits resting at 6 m in a 5°C (41°F) pool experienced an average core temperature drop of only a 0.7°C (1.3°F) over a six-hour dive, again not close to the threshold of hypothermia (Chapin et al. 2021). An evaluation of 13 rebreather dives wearing a similar 10 mm wetsuit configuration during resting dives at 9.1, 15.2, and 22.9 m (30, 50, and 75 ft) breathing air or heliox experienced similar modest mean core temperature drops well above the threshold for hypothermia (Kelly et al. 2023).

While hypothermia is not a realistic threat for most diving situations, cold stress is still very important. Divers need to be able to think clearly and perform effectively to do what is needed. The stress of cold hands is probably the most debilitating. This is most likely to occur in extremely cold water when a dry mitt/glove or actively heated mitt/glove fails. Water temperatures below 8°C (46°F) require careful consideration, particularly if long run times with obligatory decompression are involved. Divers must be prepared to manage adverse events with multiple priorities to avoid jeopardizing safety.

Controlling Heat Exchange

The four major avenues of heat exchange are radiation, convection, evaporation, and conduction. Radiative heat transfer, the flow of electromagnetic energy from and relatively warm body to a relatively cooler body, is often appreciated between dives on sunny days, but radiative loss in cool or cold water is generally not a major pathway. Buying suits or undergarments with "titanium" or similar linings marketed to reflect heat energy back towards the body are likely of limited value. Convective heat transfer, that mediated by currents of moving gas or liquid, is most noticeable in cold water with ill-fitting wetsuits that allow substantial introduction of water during movement. Convective heat loss can be substantially reduced with effective dams at neck, wrists, and ankles, and even more effectively eliminated in leak-free drysuits. Evaporative heat loss, resulting from vaporization of surface water, normally occurs at the skin and in the respiratory tract. Evaporation from the skin is not a problem during immersion since evaporation is not possible in a saturated environment. This is true for no-suit, wetsuits, and drysuits once the last has been sealed for a few minutes. Respiratory heat loss, on the other hand, can be important in open-circuit diving when cold, dry inspired gas must be warmed and humidified with each breath. Respiratory heat loss is substantially reduced in closed-circuit diving since the gas in the circuit is saturated with water vapor. Closed-circuit gas is also warmed by the exothermic carbon dioxide scrubber reaction. Unfortunately, the exothermic reaction warming is less of a benefit than often desired since there can be substantial cooling of gas in the inspiratory and expiratory arms of the circuit.

The major avenue for heat loss in cold water diving is conduction, the heat flow between objects in physical contact. The high heat capacity of water produces conductive loss rates 20-27 times greater than those found in air. The inverse of conduction is insulation, and it is insulation that is most important for diver protection.

Thermal Protection for Cold Water Diving

Passive protection

Passive warming is provided by wetsuits and by drysuit plus undergarment ensembles. As discussed above, passive protection can be substantial, even if not to the highest level of comfort. Passive insulation is provided by a range of materials and designs. Manufacturers have put a lot of effort into designing suits that are comfortable, sometimes with multiple materials to protect mobility. An unfortunate shift, however, has been away from the provision of actual test data on system performance. Independent, standardized test results are almost never made available. Divers are increasingly forced to rely on marketing material and community enthusiasm to make decisions. This may not be a problem for ensembles used in moderate conditions, but the deficiencies of even the best systems become apparent in colder water. Testing systems in water temperatures ≤4°C (39°F) may not be necessary for warm water divers, but the experience can be much more informative than the promotional claims.

Drysuits are available in thin "shell," trilaminate, traditional, "compressed" or "crushed" neoprenes, and other variants. Suit weight, flexibility, durability, and other options will differ, giving divers a lot to consider. Selections may be made for water temperature, environment, bulk, weight, or visibility.

The undergarments and trapped gas provide the majority of the insulation in a drysuit system. It is generally not the material that is most important in providing insulation, but the gas that is trapped within it. Persistent loft is most desirable, that which is maintained even when the drysuit and undergarments are affected by hydrostatic pressure. Both flexible and rigid form garments can trap gas, with weight and bulk sometimes being considerable. The hope for aerogel-encapsulated materials that could trap gas and improve insulation with very little weight and bulk has not been realized. The extremely light material that works very well in aircraft insulation applications does not work well with the forces and motion associated with diving and laundering.

Argon was proposed as an alternate to air for drysuit inflation to capitalize on its lower thermal conductivity (and therefore higher insulation value). It has been shown to be of fairly limited practical value, however, so is less often seen. One of the problems is distribution, which is not uniform when hydrostatic pressure pushes the free gas to the top of a suit space. The hint of association with argon in undergarments can now be seen, but it is unclear how it is incorporated and what if any role it plays in improving insulation. Testing has been conducted on embedding hollow microspheres into polymer plates that can be built into suits (Demers et al. 2021), but the stiffness of such plates would undoubtedly create mobility issues demanding inconsistent coverage, especially in the vicinity of joints, making the effectiveness less than clear.

Active protection

Active warming was once primarily provided in the form of hot water suits for commercial operations, but battery-powered, electrically heating garments are becoming increasingly common for all forms of diving. Improvements in battery technology have increased the amount of heat energy that can be delivered and the operational duration.

The popularity of this technology is undeniable, but thoughtful use is important. Foremost, only systems specifically designed for diving application should be used. Serious injury can result from using systems not designed for the diving environment (Johnson-Arbor 2022). In any case, the use of active heating adds complexity in terms of equipment required, power and charging needs, and duration limits. While personal comfort can be improved, the potential to adversely affect decompression safety must be borne in mind. The work described above (Gerth et al. 2007) demonstrated that decompression stress can be increased by keeping divers warm throughout dives, and that the stress will increase dramatically if warmth during the descent and bottom phase is followed by a loss of warmth during the ascent and stop phase. Use of these systems may still be appropriate, but only with a full appreciation for the implications and with appropriate strategies in the event of failure.

Monitoring Thermal Status and Decompression Stress

Thermal stress is determined by the thermal protection worn and used, diver habitus, and physical activity. It is not established by water temperature, which is the only thermal measure regularly captured by dive computers. Core temperature is unlikely to be helpful since, as discussed above, it tends to change little over the course of a dive. Skin temperatures could be more informative, but measures from many sites would be needed to capture the regional differences that could play a role in altering vasomotor response and, subsequently, inert gas uptake, elimination, and tissue solubility. It is true that some dive computers capture a single skin temperature measure, typically from the anterior chest, but this does little to describe what is happening across the entire skin surface. The norm for controlled laboratory studies is to compute mean skin temperature from 10 different site measures. The number of sensors needed to capture the dynamic conditions of real-world diving would be much greater. For example, there could be vast regional differences for a drysuit diver with an intact suit, with small or large leaks in one or more limbs, with different or variably insulating layers, etc. Simply put, current decompression algorithms cannot assess the impact of thermal state in a meaningful way. Real-time monitoring might one day allow for dynamic decompression algorithm adjustment, but this will require many, many sensors and a vast collection of temperature data, high resolution inert gas uptake and elimination data, and outcome data. Collecting the necessary skin temperature data will be possible in the future with garments that can incorporate as many sensors as needed, but getting simultaneous high resolution inert gas uptake and elimination data will be more difficult. This is unlikely to be achieved for many years. And even once the necessary data are available it will be another huge hurdle to effectively model the impact of a host of subtle differences on risk and outcome. The concepts are relatively simple, but the data requirements to turn concepts into effective tools are truly daunting. Realistically, human decision-making that takes into account thermal states over the course of a dive will remain best practice for the foreseeable future.

Practical Guidance on Thermal State to Minimize Decompression Stress

Practical guidance to minimize the potentially negative impact of thermal stress through the diving timeline is summarized in Figure 2.

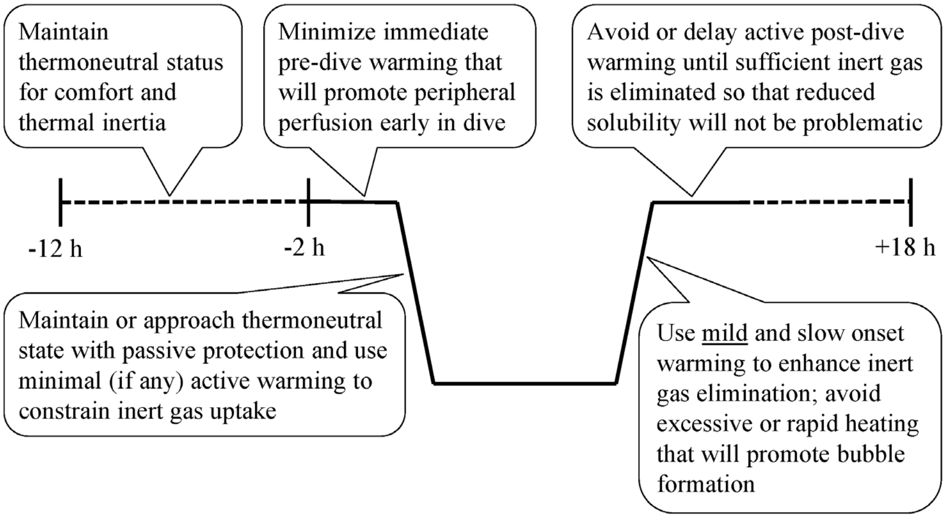

Figure 2. Guidance to minimize the negative impact of thermal state on decompression stress.

It may be desirable for divers to be cool during the descent and bottom phase, but this is likely only realistic in a limited range of conditions. The more achievable goal is to have divers avoid active warming pre-dive and to remain as close to thermoneutral as feasible during the pre-dive, descent, and bottom phases. This is more likely to be achieved by dressing for diving in a cool space and minimizing exercise and active warming throughout the descent and bottom phase. The net effect is a reduction in unnecessary inert gas uptake. Mild and slow onset warming can then be encouraged during the ascent and stop phase. The "mild" nature of warming is important to minimize complicating effects. Rapid warming will decrease the solubility of inert gas in the superficial tissues and can promote local bubble formation and "skin bends". Employing exercise to promote warming can also be problematic since anything more than very light exercise with low joint forces can promote bubble formation in any working tissue. Restricting efforts to mild warming takes discipline for a cold diver, but this is, again, the prioritization of safety over comfort. Mild warming can be achieved if the diver passes through thermoclines during the ascent, if an active heating garment is turned on to a low setting or slowly increased from a low setting to higher settings, or with very light exercise with low joint forces. Any effort to warm up beyond passive insulation during the post-dive period should be delayed to reduce the inert gas load. This means no hot showers, hot tubs, or exercise, all of which can increase bubble formation and overall decompression stress. The time required is difficult to quantify, but it must be remembered that cooling impairs inert gas elimination, so the risk window is prolonged, sometimes substantially. Practically, it is unlikely that warm drinks would have a measurable impact, so some relief is possible with them, but the focus should be firmly on minimizing unnecessary stressors in the post-dive period. Very practically, if a diver feels the need to get into a hot shower or pursue any other active warming post-dive the dive profile should be moderated to add a safety buffer. If delayed gratification is a possibility, warm thoughts about a future hot shower, hot tub, or exercise are best.

Conclusion

Thermal state can influence physical performance, decision-making, and, directly and indirectly, decompression safety. Management of thermal stress benefits from advance planning and careful consideration of all effects of any practice or equipment to be used. Divers should, as a rule, minimize unnecessary warming in the pre-dive period and the descent and bottom phase of dives, and employ only modest and low physical strain warming during the ascent and stop phase. Post-dive warming should be delayed to allow until the inert gas load is substantially reduced.

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QUESTIONS AND DISCUSSION

JAKUB SIMANEK: I have a question about repetitive dives in cold water. Do you have recommendations for warming between dives?

NEAL POLLOCK: My recommendations would not change for repetitive diving. I favor using passive protection if function and reasonable comfort can be maintained. My goal is to maintain thermoneutrality where feasible. I would avoid active warming and exercise between (or following) dives. If active warming is needed it would be best set on the lowest level acceptable for the descent and bottom phase and then slowly increased (incrementally) during the ascent phase, avoiding excessive heating at all times. Keeping active heating at a low level between dives could minimize discomfort and reduce a desire for more aggressive warming such as in a hot shower or hot tub that would quickly reduce the solubility of dissolved gas and promote bubble formation.

JAKUB SIMANEK: You focused on the outside thermal protection. What about warm food, like hot soup and so on?

NEAL POLLOCK: It is common practice to give conscious cold victims hot fluids. While this is fine for subjective comfort the actual amount of warming provided is very modest. Picture a bathtub half full of water, about the volume of an adult body, at a temperature around 35ºC (95°F), the threshold for hypothermia. Now picture a liter of fluid as hot as you could drink it. Pour it into the bathtub. Does it do much? No. The warm fluids do not provide much warming but they may make the person feel better. Warming the gastrointestinal tract likely does not generate the same risk as warming peripheral tissues that hold more dissolved inert gas.

MARK CANEY: As rebreather divers know, it feels nicer in cold water breathing from a rebreather because you are getting warmer gas. Is there any benefit to actively heating the gas that a diver breathes?

NEAL POLLOCK: There have been cases in which additional active heating of gas has been employed in rebreathers. One manufacturer recently constructed a shroud to wrap around a scrubber canister to augment the exothermic warming of the scrubber reaction. There can be discomfort breathing gas warmed above 50ºC (122°F), but lesser temperatures are well tolerated. Actively warming breathing gas can increase comfort, possibly with less risk than warming peripheral tissues.

DAVID DOOLETTE: Can I add something to that? When you go into very deep diving, you have to heat your gas. Below 120 m (400 ft) or so you have to actively warming your gas. Otherwise, you can get hypothermia just from the heat loss. And the gas in your rebreather, depending on the design, is not particularly warm. It is warmer than open-circuit gas, but if you have an inspiratory counterlung you will be breathing gas near the water temperature. You lose most of the heat as it passes through the counterlung. So you can benefit from active heating.

NEAL POLLOCK: I mentioned the Piantadosi and Thalmann (1980) study that addressed unrecognized hypothermia. They recommended minimum inspired gas temperatures increasing beyond 107 m (350 ft). At that point the minimum inspired temperature was to be -3ºC (27°F), with step increases to 12°C (54°F) at 183 m (600 ft). So while it will be uncommon for rebreather divers to spend sufficient periods at these depths to make it a priority concern, there are certainly situations in which active warming of breathing gas may be important.

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ALEJANDRO GARBINO: Has anyone looked at measuring either systemic vascular resistance or some derivatives of that to compare the different insulation properties other than using clothes?

NEAL POLLOCK: There is interest in Europe in flow-mediated dilation. I have never been convinced that it shows anything of particular value. But beyond that, I do not know.

I want to take the opportunity to add a comment regarding something that came up earlier today. There was a discussion about identical dives. I believe that it is rare for the experience of different divers to be truly identical. There will often be minor differences that can have meaningful impact. We have to be careful. Divers have different size, shape, body composition, garment insulation, etc. There are a lot of things that can alter responses.

SANDRA CHAPMAN: You mentioned the significance of the impact of thermal stress on cognitive performance. Could you expand a little bit about the research that is been done in that area. I know there was an ONR (Office of Naval Research) funded project at NEDU (US Naval Experimental Diving Unit), but it was a little flawed by a subjective test that had learnability factors.

NEAL POLLOCK: I do not know of well-controlled studies that have resolved the questions. Projects often include cognitive measures as an add-on.

ATTENDEE: Do the results relate to skin bends only or bends in general?

NEAL POLLOCK: Skin bends can be driven by skin warming. Active heating garments certainly have the potential to promote skin bends. Whether mild warming would precipitate whole body bends, I do not know how much data we have. When someone comes in to be treated for decompression sickness, we know little or nothing of their tissue temperatures. Temperature monitoring is not done. Even if reports having an active warming garment on high or on low, the effect on tissue temperature is unknown. We simply do not have quantifiable data. What we do know is that skin bends can develop. We also know from the Gerth et al. (2007) NEDU study that whole body warming from the outside can have remarkable impact on decompression outcomes. Twenty percent of the subjects developed symptomatic DCS in the warm/cool group with a 30-min bottom time.

ATTENDEE: Do you see a day where manufacturers are going to incorporate temperature sensors to detect our core temperature and incorporate that into the decompression software?

NEAL POLLOCK: Core temperature readings will probably not do much in most cases. There is interest in figuring out how the thermal information matters, but the presentation included demonstration of how core temperature does not change much even when a drysuit is flooded in -2ºC (29°F) water. Core temperature values are likely to be fairly uninformative. Skin temperature will ultimately be more informative, but currently not easy to collect. Mean skin temperature is classically calculated in laboratory studies with 10 sample site measures. Efforts with four sample sites have been used, but there is greater risk of missing important differences. Temperature data are difficult to interpret in any case. Temperatures will vary with surface area to body mass ratio, tissue insulation, clothing insulation, exercise, and environmental conditions. A tremendous amount of field data is needed to begin to model the impact of specific differences. We are at a point where we understand the risk concepts, but do not have sufficient data to inform decompression algorithms in a meaningful way. Current models are actually quite rudimentary. We have a long way to go before models can effectively predict physiological effects.

JANE RUCKERT: I was interested in the plots that you had with the body temperature and the hand temperature and you point out that the body temperature basically did not change with the drysuit and wetsuit, but the hand temperature showed something like a 5ºC (9°F) difference.

NEAL POLLOCK: Some of the findings were difficult to interpret in that study. The drop in hand temperature indicated that they were not adequately protected, but the subjects were described as using their own equipment and there were no details on handwear. I can say that hand discomfort is frequently the biggest limiting factor in cold water diving. A flooded dry glove can quickly prompt an abort decision in cold water. The problem is that we do not know what was worn or the amount or character of the protection provided.

Handwear is critical, at best striking a balance between warmth and dexterity. Dry mitts with ample insulation can be warm, but will severely limit dexterity. Flooded dry mitts or gloves can be so ineffective that coldwater dives must immediately end. Actively heated gloves can reduce the bulk somewhat but again can be grossly inadequate if the heating is lost. Thick wet mitts with minimal compressibility, often in the form of a three-finger mitt (thumb, index finger, and three fingers) can offer a good compromise on thermal protection and dexterity in addition to being less prone to catastrophic failure. There is no single solution, but there are a variety of options that may be fit for purpose.

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Use of Closed-Circuit Rebreathers in Malta Shipwreck Diving

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Abstract

This paper examines the transformative impact of rebreather diving technology on Malta's underwater cultural heritage exploration, preservation, and management. Located in the centre of the central Mediterranean, Malta's human story is inextricably linked to the sea, reflected in the volume and diversity of underwater cultural heritage on the seabed surrounding the islands. The adoption of rebreather diving by Maltese heritage managers and maritime archaeologists has revolutionized the excavation, recording, and sharing of submerged artifacts and sites. Malta has over the last decade been at the forefront of deep-water archaeological practices through the excavation of the Phoenician shipwreck by divers at a depth of 110 m (360 ft). The use of rebreathers enabled the successful excavation and documentation of the site, an approach that has now been applied to the general management of Malta's unique underwater cultural heritage.

Keywords: accessibility, deep-water archaeology, maritime archaeology, photogrammetry, public outreach, underwater cultural heritage management

Introduction

Malta is a small European nation in the center of the Mediterranean consisting of three main islands – Malta, Gozo, and Comino. With over 7500 years of human activity on the islands, it is no surprise that the rich cultural assets are visible to all those who live on or visit the islands. Evidence of Malta's rich history is also present on the seabed – out of reach, and therefore out of sight for most people. The adoption of rebreather diving technology by Maltese heritage managers and archaeologists has ushered in a new era of exploration, enabling the recording, and sharing of Malta's underwater cultural heritage. This article delves into the challenges faced in exploring and preserving Malta's submerged history, and the transformative role of rebreather diving in developing innovative approaches to the management of underwater cultural heritage. Malta's underwater cultural assets are not just plentiful but also very diverse. From prehistoric seafarer's, who reached Malta from neighboring Sicily to the intrepid Phoenicians and from the all-powerful Romans to the British, the Maltese Islands bore witness to intensive maritime activity. Moreover, both world wars touched the shores of Malta albeit with different intensity. All this human activity is reflected on the landscape of Malta, but also on the seabed surrounding the island. Preserving and understanding Malta's underwater cultural heritage is not only approached as an academic pursuit; it is considered imperative for maintaining a connection with the island's historical roots that in turn provides an essential ingredient for national identity. Submerged sites also serve as tangible links to Malta's past, offering valuable insights into the ebb and flow of civilizations across the Mediterranean. Beyond the local context, the preservation of Malta's underwater heritage contributes globally to our understanding of maritime history, providing unique perspectives on seafaring technologies, trade routes, and naval warfare.

Underwater Exploration in Malta

The history of underwater exploration in Malta is closely linked with the early evolution of diving equipment. Since at least the early 1900s, British servicemen used hardhats to work on Royal Navy ships in Maltese dockyards. With the advent of open-circuit scuba systems, members of the British military were quick to set up local scuba clubs, taking advantage of the clear and warm Mediterranean waters. Many of the earliest archaeological discoveries were made in this context, with the first 'project' being organized off Gozo as early as 1958 (Figure 1). It is within the setting of these early diving exploits that local inhabitants started to emulate British divers, often using homemade equipment. The technological leap offered by scuba expanded the possibilities of what could be discovered and studied beneath the surface.

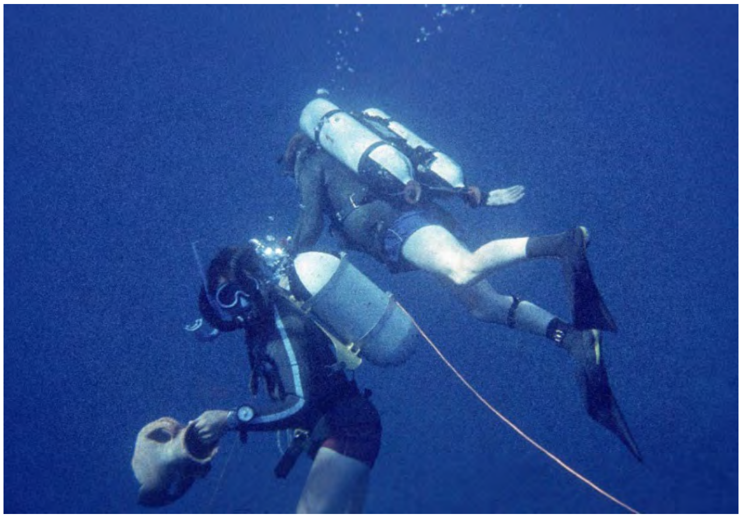

Figure 1. Divers decompressing while recovering amphorae from the seabed off Xlendi bay, Gozo c. 1961 © John Woods/Heritage Malta.

Technology in Use

Although rebreather diving has been available for decades it is only in the past 10 years that this technology has taken root in Malta. It is no exaggeration to state that rebreather technology has revolutionized underwater exploration in the Maltese Islands. By extending dive times rebreathers have opened new horizons for those working with Malta's underwater cultural heritage, since garnering a better understanding of Malta's rich maritime history is often tempered by the challenges of exploring and preserving its underwater heritage. The main challenge is depth. Most historic shipwrecks are situated at depths that often exceed 55 msw (180 fsw). Such depths present logistical, technical, and safety challenges. Researchers face the same complexities of deep diving as do any individuals who descend beyond 50 msw (165 fsw). Besides the obvious safety factors, one of the biggest challenges facing researchers working at depth is limited bottom time. Moreover, individuals in the field, with many years of underwater project experience using standard scuba gear and diving on air had to 'go back to school.' Specialized training was undertaken, and advanced certifications were obtained. Additionally, authorities needed to be convinced to invest in the expensive equipment needed to undertake rebreather training and eventually fieldwork.

In Malta, three words are used to guide approaches to all that is linked to underwater cultural heritage: Explore, Record, and Share. The sections below highlight how each of these three key approaches has been impacted using rebreathers.

The adoption of rebreather diving technology has propelled Malta's underwater archaeological exploration into a transformative phase. Heritage managers and archaeologists, equipped with rebreathers, have unearthed previously unknown sites, and conducted in-depth exploration projects that were once deemed impractical if not impossible. The transition to rebreather technology not only enhances safety in deep-sea activities but also significantly reduces the costs associated with exploratory projects, primarily due to the mitigation of rising helium expenses. Today, rebreather divers inspect anomalies detected during sonar searches using a state-of-the-art autonomous underwater vehicle (AUV). The first dives are aimed at determining the exact location of the site as well as its identity and the state of preservation (Figure 2). These assessments facilitate the next phases of work to be undertaken.

Figure 2. Rebreather divers exploring a newly discovered site © John Wood/Heritage Malta.

Exploration of an archaeological site goes beyond traditional wreck diving. One such example of this is the ambitious excavation of the Phoenician shipwreck at a depth of 110 msw (360 fsw). This is the first archaeological excavation by divers beyond 100 msw (360 fsw) and, to date, also the deepest. Over four seasons (2018-2021), each lasting no more than four weeks, the team proceeded to remove approximately 8 m^3 (300 ft^3) of very compacted sediments (Figure 3). In turn, this facilitated the recovery of numerous artifacts such as amphorae, cooking pots and a human tooth. Some objects recovered from the site are unknown to the academic community and results from this excavation are impacting academia well beyond the realm of underwater archaeology.

The adoption of rebreather diving technology stands as a transformative chapter in Malta's underwater archaeological exploration. Heritage managers and archaeologists have harnessed the capabilities of rebreathers to discover, record and share submerged sites that were once inaccessible. The in-depth exploration of specific sites, such as the Phoenician shipwreck at 110 msw (360 fsw), showcases the capabilities of rebreathers in facilitating intricate archaeological projects. Documentation is an essential part of the archaeological process, be it on land or underwater. In fact, it is not uncommon to refer to excavation without documentation to looting or vandalism. However, traditional archaeological recording techniques involve tape measurements, strings, spirit levels and hand drawings that are not compatible with extended depths and limited bottom times. This necessitated the application of a recording technique that is just as scientific and accurate as traditional methods but is not limited by time restrictions (Gambin et al. 2023). The approach utilized throughout the Phoenician Shipwreck Project was one of daily 3D photogrammetric recording, providing a millimetric record of the progress of the excavation, providing the same level of information collected from traditional recording methods, if not more (Figure 4).

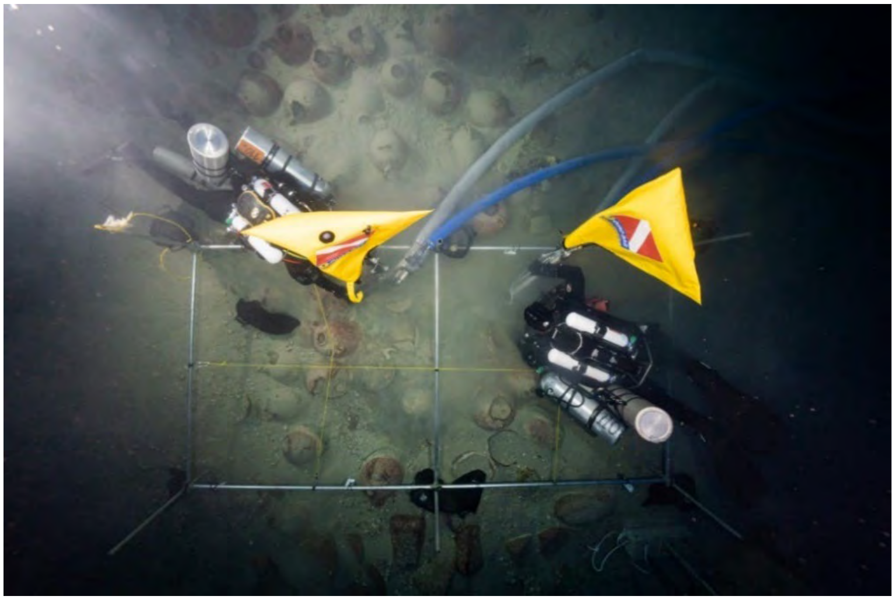

Figure 3. Rebreather divers excavating the Phoenician shipwreck at a depth of 110 msw (360 fsw)
© John Wood/University of Malta.

Both high-resolution video and stills are integral to photogrammetric documentation. Rebreather diving has played a pivotal role in advancing the production of detailed 3D photogrammetric models of deep shipwrecks in Malta. Photogrammetry involves capturing a series of overlapping photographs of an object or site from different angles and distances, which are then processed to create accurate 3D models. The extended dive times and enhanced manoeuvrability afforded by rebreathers allow archaeologists to meticulously photograph every aspect of a shipwreck. The resulting dataset, when subjected to photogrammetric software, generates highly detailed and accurate 3D models. These models have a two-fold importance, the scientific value, and the public outreach potential. The 3D models are a virtual representation of the site and act as a baseline record of the condition of the wreck at a particular moment in time. This data can then be used comparatively with any future data sets that are gathered to accurately determine and measure changes to the site. Researchers can measure and annotate features of interest, facilitating detailed analyses of construction techniques, cargo distribution, and other archaeological characteristics. Moreover, these digital replicas provide a valuable means of preservation, allowing archaeologists to revisit and study the site without physical disturbance. From a public outreach perspective, these models offer an invaluable opportunity to share heritage sites and objects that would otherwise remain out of sight and out of mind. Virtual exploration offers the opportunity of discovery and appreciation to everyone, and not only to the minority of divers and researchers that may otherwise experience the site. Raising appreciation is a direct path to increasing protection.

The extended bottom time provided by rebreathers also allows for unhurried and meticulous photography, ensuring that every angle and feature is thoroughly documented, capturing detailed snapshots of Malta's deep-water shipwrecks. These resulting high-resolution stills become invaluable resources for cataloguing artefacts, creating detailed site maps, and preserving a visual record of underwater cultural heritage that may undergo changes over time (Figure 5). These high-quality photographs not only serve as a comprehensive documentation tool for archaeological research but also contribute to public engagement by providing visually stunning glimpses into Malta's maritime history. Exhibitions, publications, and online platforms can leverage these images to share the beauty and historical significance of these submerged treasures with a wider audience.

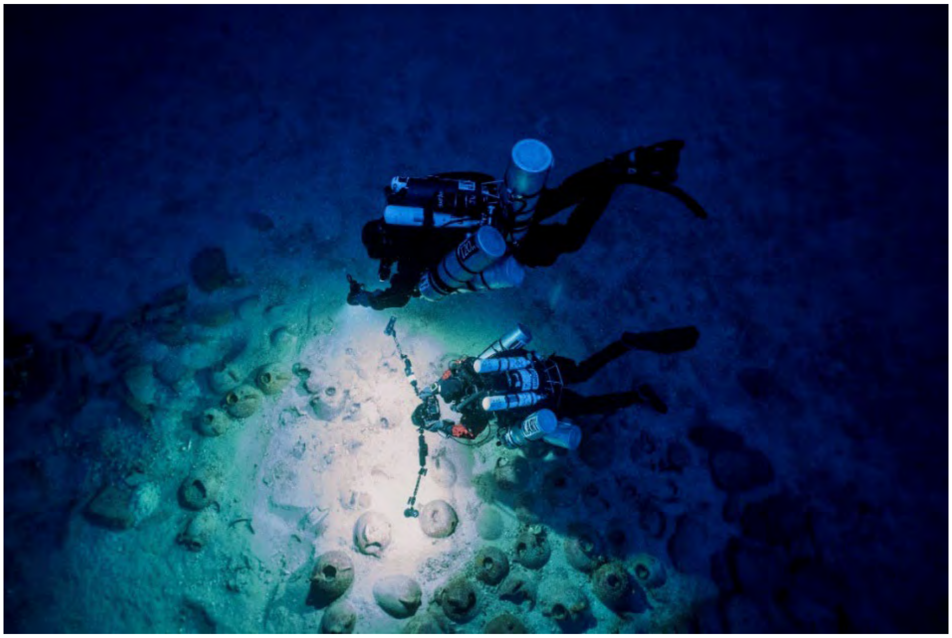

Figure 4. Rebreather divers carrying out 3D photogrammetric documentation on the Phoenician shipwreck © Dave Gration/University of Malta.

Figure 5. High-resolution photo of two lanterns on HMS Nasturtium © Dave Gration/Heritage Malta.

Rebreather diving has also revolutionized the ability to film deep shipwrecks in Malta with exceptional video quality. Traditional scuba diving equipment, limited by finite air supplies and frequent ascents, constrained the duration and quality of video recordings. Maritime archaeologists equipped with rebreathers can now navigate intricate underwater landscapes, capturing the nuances of submerged cultural heritage with remarkable clarity. The absence of bubbles, a characteristic feature of rebreathers, eliminates disturbances that could otherwise impede video quality. This silent and unobtrusive approach allows for more immersive and detailed recordings, enabling archaeologists to document the structural intricacies, artefacts, and surrounding marine life associated with deep shipwrecks. The high-resolution video footage becomes a valuable archival resource, providing a dynamic visual record that aids in subsequent analyses, public outreach, and educational initiatives. Additionally, it serves as a foundation for the creation of compelling documentaries and visual narratives that bring Malta's underwater cultural heritage to a global audience (Figure 6).

Underwater archaeology is not an overly well-funded discipline and one of the most significant advantages of rebreather technology on our projects is its impact on cost reduction. The reliance on helium, a costly resource used to mitigate the effects of nitrogen narcosis and decompression, is significantly reduced with rebreathers. The integration of rebreather diving into the toolkit of Malta's maritime archaeologists has ushered in a new era of exploration, enabling the recording of deep shipwrecks in unprecedented detail. Malta's strategic integration of rebreather diving has propelled the nation to the forefront of underwater cultural heritage management (Gambin et al. 2021a). The virtual museum, www.underwatermalta.org, stands as a testament to Malta's commitment to digital preservation and global accessibility. The innovative use of 360-degree film footage and virtual reality headsets in outreach programs has broken down barriers, making deepwater archaeological sites a tangible experience for diverse audiences (Gambin et al. 2021b). Underwater sites are no longer out of sight and out of mind but explored and experienced by thousands of individuals from diverse backgrounds. Moreover, the artefacts recovered, and imagery captured through rebreather diving have become not only educational resources but also key elements of cultural exhibitions, magazine articles, and documentaries (Figure 7). Malta's leadership in these endeavours extends beyond its shores, contributing to a global dialogue on the importance of underwater cultural heritage preservation and the role of technology in achieving this goal. The combination of technology, outreach, and storytelling underscores Malta's commitment to ensuring that its maritime history is not just preserved but shared with the global community, transcending boundaries, and fostering a deeper appreciation for the treasures that lie beneath the waves.

Figure 6. Videographer filming on the Xlendi Underwater Archaeological Park © Dave Gration/Heritage Malta.

Figure 7. The exhibition on the Phoenician shipwreck. The work carried out was greatly facilitated by the use rebreather diving technology © Heritage Malta.

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QUESTIONS AND DISCUSSION

MICHAEL RICHARDSON: Are you aware of any neolithic sites at all? Are there any known neolithic sites that have been excavated?

TIMMY GAMBIN: We have a very shallow excavation in 6 m (20 ft) for our master students. On the last day of our excavation we came across a fragment of a cranium that was dated to 3500 BC. It is one of the oldest pieces of human remains to be found underwater in central Mediterranean. The sea is full of incredible things, in both 5 m (17 ft) and 110 m (360 ft).

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The Near Future of Physiological Monitoring

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Abstract

Recent and ongoing efforts have the potential to improve physiological monitoring of divers, hopefully to improve safety. A range of physiological, performance, and environmental measures could be important to evaluate diver state. The underwater environment and existing equipment present multiple challenges in developing new monitoring capabilities. Recent efforts include the use of machine learning to evaluate breathing sounds for hypercapnia and respiratory distress; eye tracking for hypoxia, hyperoxia, hypercapnia, or narcotic impairment; functional near-infrared spectroscopy for brain function; pulse oximetry for hypoxia; ultrasound for bubble formation; and possibly electrodermal activity as an indicator of hyperoxia. The ultimate goal is to develop a compact suite of tools able to monitor as many relevant parameters as feasible. The future application aims to develop better tools to enhance research capabilities and to promote diver safety.

Keywords: eye tracking, functional near-infrared spectroscopy, pulse oximetry, ultrasound

Introduction

Ongoing efforts have the potential to improve physiological monitoring of divers and extreme environments that could become tools for research or diver feedback, depending on the developmental engineering and scientific challenges revealed by these early experiments. The overarching goal is to improve data and knowledge that can reduce the risk of morbidity and mortality in divers.

A range of physiological, performance, and environmental measures could be important to evaluate diver state. These include heart rate, oxygen and carbon dioxide concentrations, inspiratory and expiratory pressures, ventilation frequency and volumes, blood pressure, electrocardiography, temperatures, orientation, and the presence of decompression-induced bubbles.

Some data have been captured along these lines, but the research to date has often been limited by the available tools suitable for use underwater and under pressure. The underwater environment poses multiple challenges for designing research and monitoring tools, with core issues including the aquatic environment, the substantial ambient pressure range, and spatial and power constraints. We focus on examples of current research with potential applications to diving.

Breath Sounds

Developed by the Institute for Human and Machine Cognition (IHMC, Pensacola, FL, USA); funded by the US Office of Naval Research (ONR).

Current efforts focus on a machine learning algorithm to interpret respiratory measures, shown to be useful for identifying hypercapnia ($\leq 0.05\%$ carbon dioxide [CO_2] on the surface) and monitoring respiratory distress. This technology could also help monitor heart rate and signs of pulmonary barotrauma (PBT) and arterial gas embolism (AGE). It could detect other types of physiological distress, possibly even some associated with acute myocardial infarction (heart attack). The algorithm could be used on laptops or phones, connected to a microphone, and provide effective sound filters for various breathing setups. Further effort is needed to collect real-world data and test this algorithm across a range of breathing apparatus configurations. Looking beyond diving research, this technology could be used in hospital settings to monitor high-risk patients.

Eye Tracking

Developed by IHMC; funded by ONR.

This technology has a lot of potential, given that the eye is an externally accessible organ sensitive to oxygen (O_2) and CO_2 levels and has been used to indicate changes in physiological state through alteration in movement patterns. It may be useful for assessing hypoxia and hypercapnia, and potentially other conditions such as narcotic impairment. Commercially available equipment can be used as a base, with cameras facing both the eye and the environment to interpret eye movements. Measures could include eye motion and pupillary responses, and the data would optimally be coordinated with specific events and other environmental and physiological measures. Systems would have to work effectively in low light and low visibility conditions to be suitable for diving environments. Drawbacks of current systems include the bulkiness of equipment, compatibility issues with diving headgear, and calibration needs.

Functional Near-Infrared Spectroscopy (fNIRS)

Developed by Triton Systems, Inc (Chelmsford, MA, USA); funded by ONR.

This technology, used to monitor brain function, has been employed successfully in marine mammal research to study blubber blood volume and oxygen dynamics in seals. As current research tools using this technology can monitor the entire head, they could help identify critical brain areas for diving-related measurements. fNIRS has been used to measure hypoxia and could inform us further about neurological responses to adverse diving conditions. While the main problem with this technology has been adapting it to the hyperbaric environment, developers have found a way to waterproof the electrodes and make them tolerate expected pressure changes, with preliminary tests conducted at Duke University, NC, USA. Smaller versions that focus on specific regions could be developed if critical areas of the brain to be monitored are identified.

Pulse Oximetry

Funded by ONR and US Naval Sea Systems Command (NAVSEA).

Pulse oximetry is widely used to estimate hemoglobin oxygen saturation (S_pO_2) and heart rate in dry conditions and can be adapted for the aqueous environment. Pulse oximetry has been used with a rebreather (using a US Navy underwater breathing apparatus MK16 and an InnerSpace Megalodon) as a forehead sensor as an independent warning device for rebreather failure (Lance et al. 2017; 2022). This work found that it gave enough warning time to avoid loss of consciousness (80% oxygen saturation, with a minimum 40 s warning time). The particular benefit to diving research is that it seems to be more resistant to motion artifacts and false alarms at depth. However, it has been difficult to get reliable results in moving divers, and so, it currently has only 'suitable for research' status. Ongoing efforts are directed at developing a more robust solution.

Looking forward to potentially new applications, a pig study showed that O_2 saturation and time at low SpO_2 were variable, and in animals that showed no signs of decompression stress, could drop towards 80% O_2 saturation. The time spent at lower oxygen saturation levels post-dive seemed correlated with decompression sickness outcome. This raised the question, could this be an indicator of decompression stress that might be developed as a tool in the future?

Capacitive Micromachined Ultrasonic Transducers (CMUT) Wearable Diving Ultrasound

Developed by Clearsens, Inc. (Raleigh, NC, USA); funded by ONR.

This technology incorporates micromachined ultrasound, with the goal of building compact units capable of use while diving. The necessary equipment is potentially very small in comparison to current handheld ultrasound transducers, with multiple transducers fitting onto a palm-sized circuit board. CMUT, like pulse oximetry, appears to perform better at depth, which could make it very suitable for diving. The aim is to use wearable CMUT along with a bubble-detecting algorithm (developed by the University of North Carolina, Chapel Hill, NC, USA) to continually monitor for venous gas emboli. This could be useful for research purposes and has potential for operational monitoring. Determining the optimal placement and effectiveness of ultrasound probes remains on ongoing effort.

Electrodermal Activity

Developed by the University of Connecticut (Storrs, CT, USA); funded by ONR.

Skin glands open when people start to sweat, which affects the electrical resistance of the skin. This also occurs with hyperoxia. It is therefore possible that electrodermal sensors could detect skin changes related to hyperoxia. Pilot testing has been done using fingertip dermal sensors with subjects experiencing varying levels of hyperoxia. Further work is underway to assess the engineering challenges involved in using this technique in the damp or wet diving environments.

Conclusion

Technologies like breath sound analysis, fNIRS, and pulse oximetry all have the potential for automated physiological monitoring, which could benefit both diving research and safety. The ultimate goal is to develop a small set of sensors that could monitor as many relevant parameters as feasible. The potential to monitor research subjects, investigate physiology, and record and monitor vital signs in divers holds promise for enhancing research capabilities and promoting diver safety. Given that humans are not infallible, strategies to improve monitoring can enhance diver safety through the data recording and information/alarm systems.

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Blue Sky Future Closed-Circuit Rebreather Technologies

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Abstract

Challenges for divers and diving supervisors or diving safety officers include the need to rapidly and easily confirm the status of the dive team and their equipment throughout all phases of diving. This may include dives in which diving systems are being used outside of their tested envelope. They will also be aware of the need for more advanced face masks, monitoring, and display systems. Innovations are likely coming in diver tracking, head-up display systems, equipment testing for depths beyond the currently certified range, carbon dioxide scrubbing, full-face mask design, and possibly equipment to reduce the hydrostatic burden in work of breathing.

Keywords: diving equipment, EN14143, Extendair, head-up display, hypercapnia, rebreather, Sofnolime

Introduction

Technological innovation is a mainstay in rebreather system evolution. An array of technologies are in development or imagined that could enhance the safe operating range and/or minimize the challenges of use. We provide six examples where future technology could be deployed that would assist a tasked (at work) diver and materially improve either safety or operability. Some of these technologies can be considered longer term ('blue sky') developments, but others may be possible in the near future.

Sample Scenarios and Mitigation

Situation 1

Conducting scientific diving activities, some in deep water, and some for which the scientific training of the team far outweighs their diving expertise, can be extremely challenging. Scientific divers can be much more focused on scientific tasks than diving tasks, even if the latter are critical for life support. A major challenge for the diving supervisor or diving safety officer (DSO) is the need to rapidly and easily confirm the status of the dive team and their equipment throughout all phases of diving.

Human interaction is a critical step in pre-dive preparation. Fundamentally, an interactive system needs to be in place to confirm that all equipment and personnel are appropriately configured and fully functional. Where large dive teams operate, systems may be linked wirelessly to a DSO tool (eg, computer tablet) to display the status of all equipment.

Such tools could naturally expand into a 'during-the-dive' diver tracking system where real-time data can be continuously sent to the DSO. This could include a host of environmental, equipment, and diver data to protect operational integrity. Notifications and alarms could be configured to divers and surface support as appropriate. Two-way communication system (text or voice) could be used to avoid problems and/or to remedy emergent issues.

Situation 2
Underwater activity, particularly commercial and military, but sometimes scientific, can be conducted in conditions with little to no visibility. The risks increase in such operations, not only for the work complications but also for normal rebreather use, for example, if displays are difficult to read. Special consideration may also be required for effective team communication, navigation, and travel in the water column.

A development program for a Waveguide head-up display (HUD) can display complex data to divers by projecting the image forwards. This could deliver important information while allowing the diver to remain on task. This is expected to be available in the next two years.

Situation 3
The current Conformité Européenne (CE) depth limit for rebreathers is 100 m (328 ft) (EN14143 2013). A conflict exists with dives in excess of 100 m being increasingly common in technical diving.

CE test limits for human performance are set at 40 m (130 ft) with air diluent and 100 m with helium-oxygen or helium-oxygen-nitrogen mixtures. There are, though, test systems (hyperbaric human simulators) capable of testing rebreathers to 200 m which can be used to test the expanding range of operations. The physiological limits established for 40 m and 100 m evaluations should be applied to 200 m (656 ft). Testing minimums include:

- Canister endurance - addressing both cold water (4°C [39°C]) and elevated work rates (1.6 $L\cdot min^{-1}$ carbon dioxide [CO_2] generation).
- Work of breathing - evaluating both resistive and hydrostatic loads on the diver. High workloads can lead to CO_2 retention, even in properly functioning rebreathers. Hypercapnia can have adverse effects on work capacity, cognition, seizure thresholds, and decompression safety.

Situation 4
Granular style (Sofnolime™) absorbents have been the mainstay of rebreather diving since its inception. A more recent development (using the same base chemistry) is the polymer-based cartridge systems (Extendair™). The polymer systems offer advantages of reduced dusting, reduced work of breathing, and ease of replacement. They may perform less well than the granular alternatives, however, at higher workloads and greater depths.

A future option may be found in using metal organic frameworks (MOF). The scrubber capacity of such materials could potentially be regenerated by applying pressure, temperature, or vacuum after use. Historically only available in a powder form they are now being developed in a granular format. Successful trials have been conducted at depth and at varying temperatures.

Situation 5
Full-face masks have been available to divers for decades. Primarily developed for commercial and military diving, there is also interest for recreational and scientific applications, both for the possibility of voice communications and to minimize the possibility of losing a mouthpiece.

The loss of a mouthpiece is currently mostly mitigated by use of mouthpiece retaining ('gag') straps, devices that can help to keep the mouthpiece in place during periods of impaired consciousness. Full-face masks create a challenge for rebreather divers since, ideally, they should include an open-circuit bailout valve (BOV). This can be achieved by allowing the breathing system element to be separated from the visual element (mask) without flooding the latter. At least one full-face mask (Kirby Morgan KM48) has an oral section that can be removed without compromising the visual portion. This can be configured to include a BOV.

The current recommendation for full-face mask use with rebreathers is to employ a bite mouthpiece to reduce the deadspace for CO_2 accumulation. This creates an issue when trying to talk into a microphone and for jaw strain on long dives.

There is currently development work ongoing by several companies to improve full-face masks. The efforts could lead to better vision, nutrition, and communication interfaces.

Situation 6

Currently available rebreather systems are being used beyond their tested depth limits, often without a full appreciation of the implications of the activity.

The expansion of the operational depth range requires further development of breathing circuits to ensure acceptable low levels of work of breathing. The work of breathing associated with any rebreather is heavily influenced by two elements. The resistive element is primarily influenced by flow restrictions in the circuit. This is a feature of the component design. The hydrostatic element is primarily influenced by the position of the counterlungs in relation to the diver's lungs and the diver's position in the water. The resistive circuit can be improved by increasing the internal volume of components combined with a reduction in the resistance to flow. The hydrostatic effect can be altered by the counterlung position and shape/size.

Trials have been conducted using counterlung vests which reduce the hydrostatic effect. Designed correctly, this type of system could virtually remove the hydrostatic element. This would significantly reduce the peak breathing pressures experienced by the diver. There are no known commercially available systems.

Conclusion

Rebreather performance and diver safety are inextricably linked. Thoughtful improvements in the technology can help to promote diver safety. Rebreather data management and display can play a major role. Data-rich HUDs can improve communication and safety. A clear understanding of performance envelopes and limitations is important for both approval and decisions to use equipment. Remaining within the performance limits of a rebreather will reduce the life threat. Rebreather manufacturers should be asked for performance data. The next generation of full-face mask needs to be designed to improve safety, reduce fatigue, and enhance operability. Finally, there is room for improvement in rebreather design with regards to work of breathing.

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QUESTIONS AND DISCUSSION

OSKAR FRÅNBERG: We have been diving Interspiro masks in the Swedish Navy for quite some time. We have always used a oronasal mask and have found through quite a few tests of CO_2 and deadspace that it is fine. What you need to have is a stiff enough oronasal mask so you do not get the dynamic expansion. Appropriate design allows for verbal communication at the same time.

KEVIN GURR: So you are saying the elastance of the oronasal part is key. You need that to be as rigid as possible.

OSKAR FRÅNBERG: Exactly. But not so rigid that it does not seal.

KEVIN GURR: So that is obviously the compromise. I know people that have done work with very soft, very elastin materials and they have had folding issues (and others) with them.

OSKAR FRÅNBERG: As another issue, we are often focusing on the oxygen sensors and of course surviving. But I think we are still not there when it comes to the ergonomics of the breathing circuit. A design which has been long lasting in Sweden is the bellow weights on the hinged bellow. If you have it backmounted it will increase the pressure to the lung centroid or vice-versa if you have it chestmounted. I have experimented with the French DC55 design and it works perfectly with that as well. But another issue is increasing inertia. When you add inertia into the picture you basically cancel out the elastic component.

KEVIN GURR: Interesting. We should talk a bit more about the mask thing. Thank you.

MARK CANEY: One example described visibility dropping virtually to zero. We have all been there. Could you use something like ultrasound or light detection and ranging (LiDAR) to effectively see when there is no visibility?

KEVIN GURR: That technology does exist in military circles. There is a way to look through the muck fundamentally. There are HUDs that allow you to do that.

DAN REYNOLDS: In response to the last question, there is a device you can already buy called the Darkwater Vision. It employs infrared, which does not go very far through water, but effectively further than anything else. On a different topic, I was delighted to see the alternative scrubbers mentioned. Metal organic framework was considered before, but I thought they were extremely sensitive to water. I wonder if that problem has been fixed to make it a practical option at this point.

KEVIN GURR: As far as I can tell from all the testing work that I have seen out of the States, they appear to have got over that. It is probably worth reading the research again.

DAN REYNOLDS: That is fantastic stuff. On the full-face mask thing as well, the other attraction to me of the no-bite full-face mask is that you have no resistance from the tiny gap between your teeth. I have to thank Nick Bailey for allowing me to do this experiment, to put a simple mouthpiece and a pair of dentures on a machine to measure how much resistance is derived, which is pretty much as big as the entire rebreather, if not more.

KEVIN GURR: In your design what sort of percentage gain have you got by, in effect, removing that element?

DAN REYNOLDS: I could not tell you off the top of my head, but I would be happy to discuss it later. It does remove a choke point in the system.

GARETH LOCK: You talked about work of breathing. Something that Tim Clements picked up for his presentation about 18 months ago for the CE side of rebreather testing is that you have a standard mannequin size when it comes to testing of work of breathing. Is an expansion of effort needed to take into account the human variability in body size and lung centroid position?

KEVIN GURR: That is a really good question. I do not have enough information to say yes or no, but Gavin Anthony can help out. The standard has been around for a while but, as you say, everyone is at least slightly different. What is more important when you are actually doing the test is how you put the rebreather on the mannequin. You can see a massive difference in the values by not fitting it correctly.

GAVIN ANTHONY: I am not going to get into a major discussion over CE of this stage. What I can say is that does requires a standard size mannequin, but the bit in the standard most people miss is that the manufacturer has to define the distance from the suprasternal notch to the counterlung on their equipment, and it is tested that way. So the actual mannequin and the testing will be modified to fit the numbers which are declared by the manufacturer.

KEVIN GURR: That is a very valid point. The manufacturer does have to specify all this as part of the CE testing program. It is down to the manufacturers when testing. Differences in body size will have some real-world impact, but the bigger impact is probably the way the rebreather is worn. You can picture the student with a rebreather floating off his back wondering why he cannot breathe.

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Advanced Telemedicine in Adverse Environments

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Abstract

Most remote scuba diving related medical emergencies are, at best, managed by a telephone or radio interview without any real-time physiological data evaluation by the attending/assisting physician. We evaluated a remote monitoring system able to provide real-time physiological and environmental information from remote areas by dedicated devices compatible with extreme environmental conditions and specific algorithms allowing remote management of injuries or illnesses, based on advanced bidirectional telemedicine techniques. We evaluated the data capture in a small variety of controlled and open water environments. A total of 10 expert scuba divers were investigated during a single dive in six different conditions. A t-shirt with integrated sensors to capture electrocardiographic information, respiratory rate, and posture was worn by divers first lying down on an examination bed and then under drysuits in different diving conditions. The data were streamed to a remote control center where two electronic engineers assessed signal quality and two emergency medicine specialists assessed the data for possible artifacts (physiological incongruity). We did not find statistically significant differences in signal reception and physiological congruity between the control group and the six different investigated diving conditions. We believe this system can improve diving safety and diving emergencies management.

Keywords: breathing rate, extreme environment, heart rate, scuba diving, telemedicine

Introduction

The popularity of extreme sport and activities in remotes areas is steadily increasing together with the number of participants and related diseases (Trout et al. 2015). Among them, scuba diving, implying the most hostile adverse conditions as to difficulty in signal transmission and the impossibility for normal devices to work underwater, could be the core test of the project because the effort made for underwater testing can be easily transferred to any other extreme environment. Currently most emergencies occurring in remote areas are, at best, managed by a telephone interview without any real-time physiological data evaluation by the attending physician. This assistance modality shows evident weaknesses:

1. It is based exclusively on a telephone contact.
2. There are no automatic mechanisms to intercept and prevent critical situations.
3. It is impossible to send automatic alarms in case of need.
4. All the health information is collected by telephone interview without any "real" physiological data obtained by the patient.

A telemonitoring system could provide real-time physiological and environmental information from remote areas through the development and "accuracy testing" of dedicated "extreme environment compatible" devices and algorithms allowing accurate remote management of injuries or illnesses, based on advanced bidirectional telemedicine techniques. This approach could provide important physiological and environmental information through medical wearable devices. Wearable devices can be defined as smart electronic devices (electronic devices with micro-controllers) that are worn close to the surface of the skin, where they detect, analyze, and transmit information on signals such as vital signs (eg, heart rate, breathing rate, oxygen saturation), and/or environmental data and can also allow immediate feedback to the subject (Duking et al. 2016). Wearable devices are already revolutionizing medicine through mobile and digital health systems enabling continuous health monitoring outside clinics or hospitals (telemedicine).

Furthermore, prolonged and/or intense physical activity may lead to chronic fatigue, overtraining and negative health effects (Halson 2014; Masoudi Alavi et al. 2014), and this effect can have greater importance for athletic performance in extreme environments. For this reason, wearable devices are useful noninvasive tools to monitor biological markers (Halson 2014), analyze and transmit physiological and environmental data from subjects engaging in sports or activities in remote environments, potentially allowing immediate biofeedback in case of accident and permitting remote assistance by delocalized medical teams. Among the great variety of relevant physical parameters, heart rate is one of the most important: this parameter can be split in heart rate during exercise (HRex), heart rate during recovery (HRR), and heart rate variability (HRV) (Buchheit 2014; Plews et al. 2014). Another important aspect of physical activity in extreme conditions is temperature variation that can be associated to hyperthermia or hypothermia (Armstrong et al. 2007; Fudge et al. 2015), and oxygen saturation estimated by pulse oximetry (SpO_2) that is often linked to performance (Siegler et al. 2007). At altitude and in scuba diving this value can be very important and help to predict acute mountain sickness or decompression sickness (Basnyat 2014). Our project aimed at testing wearable devices to record and send real-time data wirelessly from the subject to a dedicated remote medical control center. The wearable monitoring systems (worn under drysuits) were based on smart garments, textile sensors, electronic devices, and software to monitor electrocardiography (ECG), respiratory rate, S_pO_2, and body position. All data were available in real-time through a dedicated application allowing direct transmission from a smart phone to a control center, using, when underwater, dedicated devices, including acoustic modems.

The purpose of this paper is to show the results of our approach and the use of wearable physiological and environmental monitoring devices in the underwater realm.

Methods

Subjects and Diving Procedures

The study was conducted in accordance with the Helsinki Declaration and was approved by the ethics committee of Università degli Studi di Milano, Italy (authorization number 37/17).

All divers received an explanation of the study purpose, risks and benefits, were familiarized with the experimental protocol, and provided written, informed consent before the experiment. No diver performed any compressed gas diving or breath-hold diving during the 30 days before the experiment.

Materials and Protocol

We organized six tests, with increasing environmental difficulties and depth and preceded by an identical test in a controlled room, repeated three times (control).

In particular, we effected one test with divers lying down on an examination bed, three dives at shallow depth (10 m [33 ft]), one indoor and two outdoor, and three at increasing depth (40, 60, and 75 m [131, 197, and 246 ft]), two indoor and one outdoor.

In all cases divers wore a drysuit and dived (or laid on the bed) for 60 min minimum, exceeded only to respect mandatory decompression time.

A t-shirt with sensors to record ECG, respiratory rate and posture (Comftech srl Milano Italy) was worn by each diver under a drysuit. The ECG, posture, and respiratory rhythm signals were acquired by an electronic device, equipped with an electronic board, a microcontroller, and a low energy Bluetooth transceiver. The ECG signal was acquired through three textile electrodes, processed and digitally filtered by the microcontroller. Respiratory rate was measured by a strain gauge placed inside the t-shirt. Posture was determined by a triaxial accelerometer, with the signal quantifying gravitational acceleration.

The wearables recorded 128 measures per second, one every 7.8 ms, ECG data were transmitted at every recording (7.8 ms), respiratory rate and heart rate every second, and body position only when parameters changed. Data packages were sent every 10 s to a dedicated device called "Dive Sense" which was positioned outside the drysuit and able to wirelessly send data to the surface through an acoustic modem.

The acoustic modem exploited the reverse piezoelectric effect (Lippmann effect): if a piezoelectric material is stimulated by an electrical source, it deforms elastically and produces a vibration. This electrical stimulation induced a vibration at a frequency ranging from 24 kHz to 32 kHz, which allowed the modem to send data. The acoustic modem consisted of a microcontroller circuit and a medium voltage generator (about 200 V) used to vibrate a ring made of piezoelectric material. The maximum achievable data rate was estimated to be 463 $\text{bits}\cdot\text{s}^{-1}$ with a range up to 2 km. The modulation used was a binary phase-shift keying two-phase (BPSK). At the surface the signal is received by a dedicated device called "Boa," using global system mobile (GSM) general packet radio service (GPRS) or satellite connection to send data to a dedicated web portal called "DANA Health" that received real-time (streaming) wireless underwater dive and physiological data and provided the possibility to show, analyze and elaborate data.

Signal Quality Evaluation

Two electronic engineers and two emergency medicine specialists, unaware of the protocol and the nature of the received signals, sat at the dedicated center and analyzed (in streaming) the arriving data and the quality of the signal for the entire duration of the test. The two engineers were instructed to fill in a grid where to indicate correct signal reception every 30 s (yes or no), while the two medical doctors were instructed to indicate the presence of any physiological parameters inconsistency (eg, heart or respiratory rate outside normal physiological possible ranges) or possible artifacts every 30 s.

Statistical Analysis

Data are presented as the mean±standard deviation for parametric data and median and range for non-parametric data after the D'Agostino and Pearson normality test to assume a Gaussian distribution. Differences between control group and the different diving conditions were evaluated with Chi-square tests, with $p<0.05$ accepted as the threshold to reject the null hypothesis.

Results

A total of 10 expert scuba divers from different groups including military special task force divers belonging to Gruppo di Intervento Speciale of Italian Carabinieri were investigated during a single dive in seven different diving conditions.

Diver tests were done in seven different locations:

1. In the Y-40 swimming pool (Montegrotto Terme, Italy) in an isolated room.
2. In the Y-40 swimming pool in the 10 m (33 ft) depth area.
3. In the Venice lagoon, at 10 m depth.
4. At Elba Island, at 10 m depth.
5. In Y-40 swimming pool, 40 m (131 ft) depth at the bottom.
6. In the Deep Dive Dubai pool (Dubai, UAE), 60 m (197 ft) depth, at the bottom.
7. In Sicily, at 75 m (246 ft) depth.

During all the tests signals were properly recorded and sent, all the steps of the protocol were respected, and the data were constantly available - through streaming - at the remote medical control center. As shown in Figures 1 and 2, we did not find statistically significant differences in signal reception and physiological congruity between the control group and the six different investigated diving conditions. When also adding the received diving data and comparing to the control group no significant differences were found. Concerning signal reception, and considering the double rating, only 55 signals (110/2) out of a total of 720 recordings were not received in streaming while regarding physiological congruity only (36/2) 18 data were considered as inconsistent.

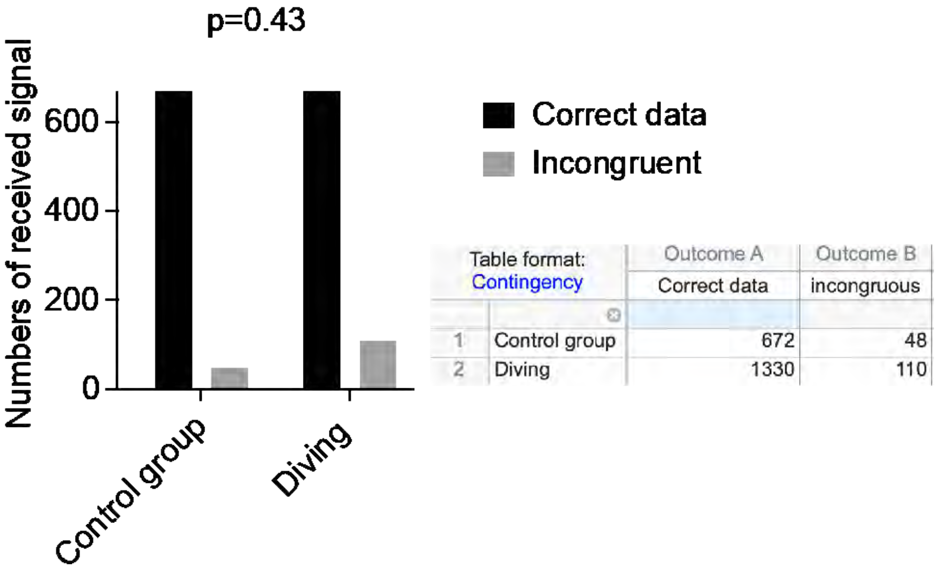

Table format: Contingency	Outcome A Correct data	Outcome B incongruous
1 Control group	672	48
2 Diving	1330	110

Figure 1. Signal reception between the control group and the six different investigated diving conditions.

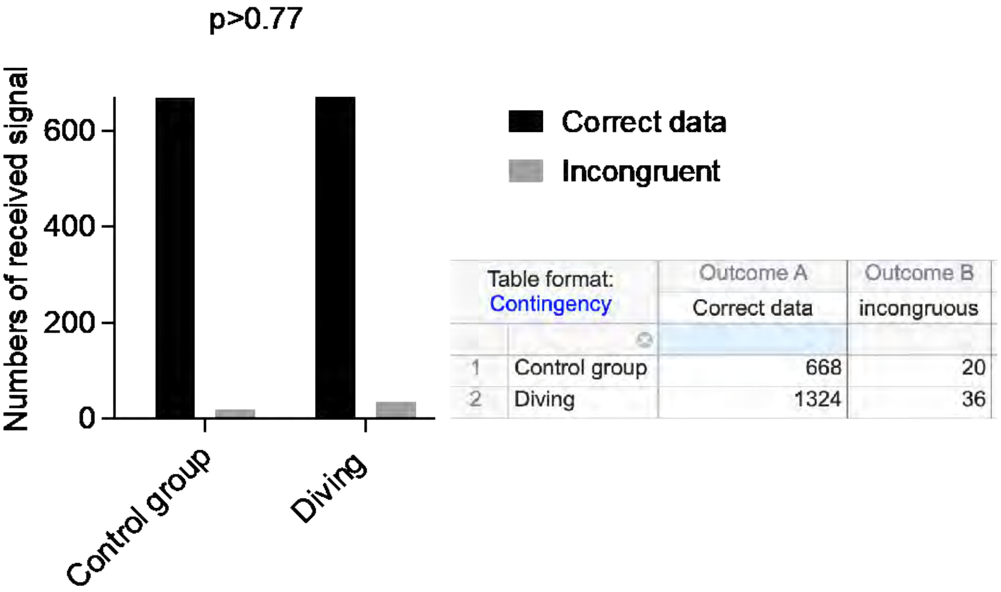

Table format: Contingency	Outcome A Correct data	Outcome B incongruous
1 Control group	668	20
2 Diving	1324	36

Figure 2. Physiological congruity between the control group and the six different investigated diving conditions

Discussion

Our preliminary data reflect a high accuracy in the streaming transmission of physiological and environmental data recorded during scuba diving and sent to the control center with four different devices. Data were recorded by wearable devices characterized by textile sensor (first step), sent to an underwater device called Dive Sense (second step) transmitting to the surface by an acoustic modem, where data were received by a "Boa" (third step) that finally sent data by GSM or satellite connection to a web portal (fourth step) allowing for real-time physiological data analysis by a dedicated medical control center with immediate feedback to the diver. Despite the difficulty to manage data in such a complex context (water) and to use four different devices to guarantee data transmission from depth to surface and from there to the dedicated web portal, data constantly and regularly arrived to the final web portal. Only 8% of data (monitored in 10-s packages) did not arrive, similar to the 7% unreceived data when recording in a dedicated room with divers lying on a bed and the four devices all positioned close together with ease of transmission. Also, the physiological data, heart rate, respiratory rate, and body position, as evaluated by the two medical doctors, showed discrepancies only in 3% of packages, indicating the possibility to use real-time underwater data transmission to manage accidents occurring in adverse/remote environments where victims cannot be reached rapidly.

This approach may open a new path to support advanced telemedicine for sport activities in extreme areas and could:

- Improve a better differential diagnosis in case of diving injuries, even if they happen in hostile environments and in the absence of medically trained individuals on site.
- Improve the management of diving emergencies needing immediate treatment for both medical evacuation to a hyperbaric facility and cost optimization.
- Reduce the numbers of diagnostic errors due to potentially incorrect information provided by bystanders.
- Reduce serious consequences of any delay in proper diagnosis by improving rescue management and first aid quality.
- Reduce fatal outcomes and disabling sequelae of decompression illness by a quick and more correct diagnosis.
- Reduce the delay of appropriate treatment.
- Reduce social and legal costs of improper diagnosis.

The evolution of this service, enhanced by real-time data collection of physiological parameters transmitted by innovative telemedicine protocols will enable more sophisticated analyses, customized medical care, and therefore an even more efficient and valuable service as perceived by divers as well as by participants in extreme activities and involved healthcare personnel.

It is well known that the greatest limit of the current emergency medical services assistance in remote areas is due to the fact that the entire emergency can be initially handled only counting on information communicated by telephone. Our innovative solution relies on the greater bandwidth use of satellite networks, allowing for worldwide information also in case of poor GSM coverage and this can really open a new era in diving and remote emergency management.

Limitations

There were limitations in this preliminary study. The sample size was limited, some of the dives were made in a controlled pool environment, and testing was limited to sensor arrays worn under drysuits.

Conclusion

Our system could help to better manage diving remote emergencies using wearable devices while underwater and receiving data (in streaming) at a dedicated control center. Our preliminary work showed no statistically significant differences in signal reception and physiological congruity between the control groups and the six different investigated diving conditions, and no substantial loss of data compared to the control group. We believe that the technology holds promise for real-time physiological monitoring of the immersed diver.

Acknowledgments

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QUESTIONS AND DISCUSSION

ATTENDEE: If you could integrate that with a rebreather and have the oxygen and other gas mix for the support crew, that will be really handy.

ALESSANDRO MARRONI: You will be happy soon. We are also in contact with a group that is conducting activity studies that are very well connected to incoming potential oxygen toxicity. The textile sensors are also chemical sensors so they can be used also to analyze sweat and to analyze electrical signals.

WINSTON WALKER: Have you identified any physiological parameters that immediately precede the onset of DCS?

ALESSANDRO MARRONI: Yes. But this is the ongoing study so I am not ready yet to anticipate anything that could be proven wrong. This is what we believe and we feel is there now, but studies are ongoing. There are parameters that obviously can be related. Some are physiological, electrical, and these are relatively easy to capture with these sort of modalities. Other are biochemical, blood-related, and a little more difficult. We are studying on these question marks, and we hope to give answers as soon as possible. But for the moment, we are quite happy to have a tool that can get the signals.

ALEJANDRO GARBINO: Going back to the initial analysis when you looked at surface gradient factors as a risk for DCS, were you able to see if there is any value in looking at the maximum gradient factor throughout the dive to see if during the decompression there is a peak that exceeds the surface?

ALESSANDRO MARRONI: This is a very intriguing question, especially if you compare it to one of the most recent publications by a Belgian group of military drivers talking about how to manage the low with respect to the high and so on. The answer to your specific question is not yet. We are focusing on what also our Belgian colleagues focused on in their paper. We are focusing on how you come out of the water. Obviously, there are many ways you can come out with the same supersaturation gradient and/or the same bubble level. And that is very much dependent on how you want to ascend, how much time you want to spend at any given depth, and so on. But for sure, the way you calculate your economy of ascent or decompression will have an influence eventually on the level of risk that you have when you surface, but also on how you spend the time during the ascent.

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The Use of Hydrogen in Deep Technical Diving, and a Case Report

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Abstract

Diving to great depth requires knowledge and technology to overcome a variety of obstacles stemming from physical, technological, and physiological barriers. A major issue is the increase in gas density at depth, which can cause respiratory impairment and carbon dioxide retention in divers. As technical divers now approach the limits of what is safely possible with helium-based breathing gases, there is renewed interest in the use of hydrogen as a breathing gas. This article reviews the barriers to safe deep diving, the history and scientific basis for hydrogen diving, and describes a single closed-circuit rebreather dive to 230 m (755 ft) in a freshwater cave in New Zealand.

Keywords: closed-circuit, deep diving, gas density, hydrogen, rebreather

Introduction

From the first documented forays beneath the ocean surface, humans have held a desire to go deeper. In the commercial sector, the need for oil and gas led to the development of saturation diving to improve productivity, and the adoption of helium-based breathing gases to overcome the challenges of inert gas narcosis and high gas density. Scientific and military divers pushing deeper adopted these gases for the same reasons. And, of course, recreational ("technical") divers wanting to explore deep shipwrecks, reefs, or flooded caves, soon followed suit.

Across these disciplines, mixtures of oxygen and helium (heliox) and oxygen, helium, and nitrogen (trimix) became effective tools for deep diving. In technical diving operations "deep" can be considered greater than 100 msw (328 fsw), in commercial saturation diving operations, greater than 200 msw (656 fsw). The commercial saturation sector has safely managed deep diving due to the ability to support slow, controlled compression-decompression cycles in monitored, pressurized habitats. The benefits of increased levels of diver observation, communications, low equipment breathing resistance, and the ability to heat both the divers' suits and breathing gases are pivotal. These additional resources and technologies add a large safety margin compared to a free-swimming technical diver.

Despite the theoretical limitations imposed on technical divers, the depth of exploration has been steadily increasing. Since the 1990s the average depth of the 10 deepest shipwreck dives has increased from 122 to 176 msw (max 236 mfw) (400 to 577 fsw; max 774 ffw) (Menduno 2018; 2019). In the 10 deepest caves dived since 2000, the average depth (adjusting for altitude) increased from 230 to 284 mfw (max 286 mfw) (755 to 932 fsw; max 938 ffw) (Menduno and Gomes 2021). Dives in the range of 200 to 250 m (656 to 820 ft), whilst still cutting edge, are no longer unheard of. Such dives, however, are pushing up against physiological and technological boundaries in the technical diving sector. The reasons for this include:

1. Increasing gas density at depth produces an increased risk of CO_2 retention in the diver. This can result from factors including an increased work of breathing, a reduced ability for the diver to perform work, and lessened efficacy of rebreather CO_2 scrubbers.

2. High gas density can have predictable impacts on the ability to operate buoyancy devices, drysuit inflators and rebreather gas supplies.
3. Increased gas density and the use of gases with high thermal conductivity and high specific heat, can cause increased heat loss and "cold stress," especially in the respiratory tree (Jammes et al. 1988).
4. Long exposures increase the risk of oxygen toxicity (both pulmonary and central nervous system).
5. Rapid compression rates to depths as shallow as 130 m (427 ft) can generate symptoms of high-pressure nervous syndrome (HPNS) (Bennett and Rostain 2003).
6. The use of inert gases such as nitrogen to ameliorate HPNS, will increase gas density and may produce narcosis.
7. Decompression schedules used at these depths are extrapolated from shallower, evidence-based algorithms. Partly for this reason, the risk of decompression sickness (DCS) may increase with diving depth (Doolette et al. 2018), and the consequences of omitted decompression are more serious.
8. As most of these dives are being performed on closed-circuit rebreathers (CCR), emergency "bailout" breathing supplies become both complex and expensive based on open-circuit and/or rebreather solutions.
9. Diving equipment manufacturers generally neither test nor warranty equipment for these depths.

In 2020 the author (RH) and team performed a CCR dive to 245 mfw (804 ffw) in the Pearse Resurgence, New Zealand. The Pearse is a Vauclusian spring with a constant water temperature of 6-7°C (43-45°F). Using a diluent gas of trimix 4% oxygen, 91% helium and 5% nitrogen (Tx 4/91), RH and dive buddy Craig Challen (CC) experienced minor HPNS symptoms but no subjective concerns with work of breathing or elevated CO_2. Decompression using a series of four habitats starting at 40 mfw (141 ffw) was uneventful. Despite the straightforward nature of the dive, with a PO_2 of 1.3 atm at depth, the estimated density of the breathing gas approached 7.4 $g \cdot L^{-1}$. It has become accepted that the risk of CO_2 retention begins to rise sharply when breathing gas density is higher than 6.2 $g \cdot L^{-1}$ (Anthony and Mitchell 2016).

With this in mind, the risks of further exploration in the cave appeared to be increasing, and so the author began researching the concept of hydrogen diving on CCR. Coincidentally, around the same time, a think tank on exactly this topic was being established by Michael Menduno. That group began meeting and discussing the hypothetical issues surrounding the operationalization of hydrogen in deep technical dives. The group contained a wealth of experience, including scientists and engineers from the Compagnie Maritime d'Expertises (COMEX) HYDRA series and from the Naval Medical Research Institute (NMRI), who investigated biochemical decompression following hydrogen diving, as well as members from the Swedish Naval Research Group and current-day researchers from the Navy Experimental Diving Unit (NEDU). Also in the group was a diving medicine expert with an active research interest in rebreather diving, and two experienced deep technical divers (RH included). The information discussed within the group heavily informed the author's risk-benefit analysis of the dive that would eventually follow.

Brief History on the Use of Hydrogen in Diving

The history of hydrogen as a breathing gas for diving is rich and fascinating. Most importantly, it has built a solid basis for understanding some of the engineering and physiological issues faced by those who wish to use it.

Hydrogen, with an atomic number of 1, was identified by physicist Henry Cavendish in 1766. It is flammable in the range of mixtures containing 4-96% oxygen, and at close to stoichiometric mixtures, it is highly explosive. Hydrogen is the lightest gas, with a density approximately half that of helium (Table 1). Lavoisier is credited with first exposing animals to an atmosphere rich in hydrogen 235 years ago (Seguin and Lavoisier 1789), and the first chamber-based human experiments were conducted in 1941 (Case and Haldane 1941).

Table 1. Important physicochemical properties of the main diving gases (Bennett and Rostain 2003

	Atomic Weight	Density at STPD ($g \cdot L^{-1}$)	Specific Heat ($J \cdot [kgK]^{-1}$)	Thermal conductivity ($W \cdot [m^oC]^{-1}$)
Nitrogen	14.01	1.251	1039	0.026
Helium	4.00	0.179	5193	0.157
Hydrogen	1.01	0.089	14310	0.182

STPD - standard temperature and pressure dry

Arnie Zetterström

Hydrogen is the most abundant element in the universe, a fact that did not escape the Swedish Navy in the early days of World War II. At the time, the United States had the largest natural reserves of the finite resource that is helium. An embargo was placed on the export of helium from the United States due to its use in barrage balloons, and so the Swedes began researching alternatives to helium for their deep diving operations. Methane (CH_4) and hydrogen (H_2) were the options considered. A young and daring civilian named Arnie Zetterström, who had a flair for engineering and problem-solving, began working with the Swedish Navy on solving the issues of hydrogen diving (Gardette et al. 1988).

Between 1943 and 1945, Zetterström performed six ocean dives in the Baltic Sea, culminating in a dive to 160 msw (525 fsw) from the HSwMS Belos. He wore a mask inside his standard diving dress so precise gas mixtures could be delivered to him. Once at sufficient depth (30 msw [100 fsw]) to safely breathe 4% oxygen in hydrogen (hydrox 4/96), he would switch to that mixture via an intermediate nitrox mixture of 4% oxygen 96% nitrogen in order to lower the risk of breathing an explosive gas mixture. No account of the sensations experienced during these dramatic switches has been found. He did comment that at 160 m (525 fsw), the hydrox felt like breathing air at 40 msw (130 fsw), and that he felt colder than usual (sent by Morse code).

The final dive was successfully performed to a depth of 160 msw (525 fsw), completing an audacious and highly courageous series. Sadly, this last dive ended in disaster when a tender on the Belos accidentally hauled Zetterström directly to the surface where he died from fulminant DCS and hypoxia. Arnie Zetterström is remembered for not only these extraordinary dives, but for his major contribution to a variety of diving technologies which have stood the test of time. The Swedish Navy would not revisit hydrogen diving for many years.

Interestingly, the main factor that drove Zetterström to test hydrogen as a dive gas (limited helium supply), has now returned as this finite global resource has become increasingly precious and costly.

COMEX and the HYDRA Series

A more systematic study of hydrox began in the latter part of the 1960s in the United States. Ralph Brauer began saturation exposures using hydrogen-helium-oxygen mixtures (hydreliox) on animals, apparently without ill effect. Edel performed hydrox chamber dives on himself and others to 7.0 ATA before moving to animal experiments at much greater pressures. In 1968, in France, COMEX began a series of experiments known as HYDRA, to test all facets of hydrox and hydreliox diving (Brauer 1987) (Table 2).

COMEX had been investigating deep diving for many years. Between 1968 and 1972 the PHYSALIE series of chamber dives using helium-based mixtures saw simulated dives progress to 610 m (2000 ft). In parallel, real ocean helium dives in 1967 (IDEFIX 100 msw [330 fsw]) culminated in a remarkable 501 msw (1644 fsw) excursion in 1977 (JANUS IV). However, the JANUS VI dive using trimix resulted in the use of a gas with a density of 10.5 g·L^{-1}.

Table 2. COMEX HYDRA dives (Brauer 1987; Gardette et al. 1988, 1993, Delauze et al. 2006)

HYDRA mission	Year	Description	Major conclusions
1	1968	Brief hydrox bell dive at 250 msw (820 fsw) by René Veyrunes.	Diver was too cold to stay on the hydrox for more than a few minutes. High incidence of DCS in hydrox build-up dives.
2	1970	Baboon chamber dives 200, 300, 500, and 675 msw (656, 984, 1640, and 2215 fsw).	Severe HPNS at 675 m (2215 ft) but no lasting ill effects
3	1983	Ocean hydrox dives between 71 and 91 msw (233 and 299 fsw).	First successful human bounce dives since Zetterstrom, with brief period of hydrox breathing at depth. Also delivered a series of mice experiments to 600 m (1969 ft) with hydrox.
4	1983	Chamber wet and dry hydrox dives to 120, 150, 180, 240, and 300 msw (394, 492, 591, 787, and 984 fsw).	Pressure reversal of H_2 narcosis possibly seen at increasing depths (at similar or higher PH_2). No biochemical effects of hydrogen breathing. Hydrox diving may be limited to 160 msw (525 fsw) due to narcosis.
5	1985	Chamber hydrox saturation 450 msw (1476 fsw).	No HPNS or arthralgia, subjectively easier to breathe, no digestive issues. Isobaric supersaturation and bubbling noted on ascent after switching back to helium.
6	1986	Chamber hydreliox human saturation to 520 m (1706 ft). Mouse saturation to 201 ATA.	Increasing workloads were better tolerated and pipe puzzle test performance was better than with trimix. No HPNS or arthralgia, good breathing comfort.
7	1987	Hydrox saturation to 260 m for diver selection for HYDRA 8.	Slow dehydrogenation avoided isobaric supersaturation (no Doppler bubbles).
8	1988	508 m (1667 ft) offshore hydreliox ocean saturation. Working dives.	Demonstrated same operational efficiency as heliox diving to 250 msw (820 fsw). A new world record.
9	1989	73-day hydrox chamber exposure to study long-term effects.	No ill effects. Narcosis was too significant at 300 msw (984 fsw).
10	1992	Chamber hydreliox dive to a record 701 msw (2300 fsw) (Theo Mavrostomos).	The divers suffered no ventilatory impairment, no arthralgia and only mild HPNS. Minor narcosis with PH_2 of 20 bar.
11	1994	Chamber dives to 350 m (1148 ft).	Studying gas switching for narcosis and counter-diffusion "He IN/H_2 OUT."
12	1996	Offshore heliox and hydreliox dives to 210 msw (689 fsw).	Gas switching mastered, hydrogen diving improved efficiency and working capacity compared to heliox.

The COMEX HYDRA dives were designed to reveal any physiological and technical problems whilst showcasing the advantages of using hydrogen beyond 300 msw (660 fsw) depth. The record depths in the ocean (508 msw [1667 fsw] HYDRA 8) and in a chamber (701 m [2300 ft] HYDRA 10) remain unsurpassed. It is worth delving further into some of the important findings revealed during this dive series. The potential for narcosis and the effect on HPNS were of particular interest. Pioneers like Peter Bennett, Xavier Fructus, and Ralph Brauer elucidated the features of HPNS, dysbaric osteonecrosis, and the effects of gas density on working divers (they had set a maximum of 9.0 g·L^{-1} for their experiments).

Brauer believed that hydrogen was likely to be four times as narcotic as nitrogen but by the end of the series this was revised to two to four times *less* narcotic than nitrogen. A maximum PH_2 of 20-25 bar was recommended for slow compressions. The subjective quality of hydrogen narcosis was likened by one diver to hallucinogenic substances like lysergic acid diethylamide, whereas the effects of nitrogen were always considered to be more like that of alcohol. Those comparisons were subsequently disputed.

The advantages of hydrogen were clear, as the dual benefits of reducing the symptoms of HPNS (and compression arthralgia) whilst lowering gas density were demonstrated. Psychomotor and psychometric tests conducted during HYDRA 4 and 5, as well as those by the Swedish Defence Research Institute in 1983, concluded that hydrogen's narcotic potential was approximately one-fifth that of nitrogen and that a PH_2 of 24.5 bar (98% hydrogen at 240 msw [787 fsw]) could be tolerated in simulated chamber dives. A safe dive depth limit of 200 msw (656 fsw) for hydrox was recommended. The possibility of a pressure reversal of hydrogen narcosis at greater depths was raised. The greater than \$30 million^{US} investment made by COMEX on its HYDRA program proved invaluable and was best summarized by their statement that they had "improved diver efficiency, better working capacity, avoided intravascular bubbling on Doppler, improved HPNS, avoided narcosis and mastered the technology!" (Delauze et al. 2006).

After the COMEX dives were complete, the economics of very deep saturation diving did not warrant further testing, in part due to the developing technologies in remote operated vehicles and robotics which are increasingly being used in the offshore oil and gas industries. The last recorded hydrogen dive was in 2012, reported by Swedish biomedical engineer **Åke Larsson. Larsson and his team completed a single open-circuit hydrox dive to 42 mfw (138 ffw) in a quarry. This "Hydrox Project" was conducted in association with the Swedish Diving Historical Society to recreate and pay homage to Arnie** Zetterström's 40 m (131 ft) dive.

Decompression Strategies

The data set for decompressing from hydrogen-based saturation dives had become substantial through the work of COMEX and others. But to translate that to the bounce diving being performed by technical divers would mean essentially going back to square one. Very small numbers of H_2 bounce dives have been performed by individuals like Zetterström, Fife, Edel, and Larsson (Col William Fife developed the first decompression tables for hydrogen dives, subsequently used by COMEX). Certainly, the numbers are insufficient to draw any conclusions, and, in fact, the dives experienced a high incidence of DCS. The experience with helium-based mixes is much more extensive at least to a depth of 100 msw (328 fsw), so further technical dives using hydrogen should use these data as a starting point for experimentation.

Biochemical Decompression

Andreas Fahlman, Susan Kayar and other workers from the Naval Medical Research Center in Maryland performed some extraordinary work in the late 1990s. They found that by introducing a hydrogen metabolising bacterium (*Methanobrevibacter smithii*) into the intestinal flora of pigs they could lower the incidence of DCS after provocative dives. The bacteria were "methanogens," which combined hydrogen with CO_2 to produce methane and water. This "biochemical decompression" removed sufficient inert gas to lower DCS rates by up to 50%. Kayar earned the nickname "Queen of Farts" for her dedication to measuring the methane content of swine flatus (Fahlman et al. 2001; Kayar and Fahlman 2001). The research has not been translated to human trials and hence is currently not helpful for use in technical diving.

Deep Diving and the Utilization of Hydrogen as a Breathing Gas

As technical divers proceed beyond 200 m (656 ft) depth, the limitations of helium based breathing gases become more apparent. Rapid compression rates can produce symptoms of HPNS in as little as 130 m (427 ft). To counteract this, a trimix of oxygen-helium-nitrogen is standard, with the narcotic gas nitrogen keeping symptoms like hand tremors at an acceptable level. With Gavin Anthony's data showing the inflection for increasing respiratory impairment noted at a gas density above 6.0 $g \cdot L^{-1}$ (Anthony and Mitchell 2016), it is very difficult to use trimix with consistent safety beyond 250 m (820 ft). Heliox would provide acceptable gas density down to 300 m (984 ft), but HPNS would be disabling. Hydrogen offers the obvious solution.

A hydrogen/helium/oxygen mix of 30%/67%/3% at 300 m (984 ft) depth:
1. Does not support combustion
2. Provides a gas density of 5.55 $g \cdot L^{-1}$
3. Gives a PH_2 of <10 bar (minimal narcosis)
4. Should be protective against HPNS

But numerous issues remain for the technical diver:
1. Hydreliox use has never been reported with a closed-circuit rebreather
2. Decompression strategies for deep hydreliox bounce diving are untested
3. Technical divers do not actively heat their breathing gas, so the high thermal conductivity and specific heat of hydrogen could generate thermal stress in the respiratory system, especially as gas density or work rates (and hence respiratory minute volumes) increase
4. Techniques to operationalize hydrogen in deep rebreather diving have not been described.

Case report – A Closed-Circuit Rebreather Dive to 230 mfw (755 ffw) Utilizing Hydreliox Diluent

Dive Goals

To trial breathing a hydrogen containing mixture during a deep technical rebreather dive with the following goals.
- To learn whether hydrogen could be safely handled by technical divers in a remote location
- To use hydrogen in sufficient molar percent to assess the following potential impacts:
    a. Ability of the diver to do gas switches at 200 mfw (656 ffw) on descent and ascent, and maintain a non-flammable F_IO_2 (<0.04) in the loop throughout the high-risk portion of the dive.
    b. Subjective respiratory cooling.
    c. Subjective narcosis and HPNS.
    d. Safe decompression, assuming that hydrogen would behave similarly to the trimix gas with respect to the planned ascent profile.
    e. Subjective change in gas density.

Preparation

Before the trip, the ISC Megalodon® (DiveCAN® electronics) was tested in a swimming pool (no diver attached initially) by incrementally adding oxygen to the loop pre-filled with 100% hydrogen. The diluent cylinder was filled by transfilling from the high purity hydrogen cylinder (in Australia and New Zealand D and G sized cylinders come filled to only 13.7 MPa [1990 psi]). An adapter was made for a DIN – bullnose left hand thread to achieve this.

Oxygen addition occurred in the first instance by manual addition with the rebreather electronics switched off. Once it was estimated that the loop contained between 30-60% oxygen in hydrogen, the counterlungs were vigorously manipulated to mix the gas and to elicit any possible static discharge in the low humidity environment within them. The rebreather head was lightly affixed and not clamped in place to limit containment of any blast in case of explosion. Encouraged by this success, the electronics were switched on and oxygen addition commenced via the solenoid valve. The loop was again manipulated and then finally breathed at PO_2 levels between 0.2 and 0.7 atm.

With this (nerve wracking but necessary) testing complete, it appeared that with very limited testing under provocative conditions, no ignition source was seen within the unit.

Dive Plan

The initial goal of combining exploration beyond the previous limit at 245 m (804 ft) with the use of hydrogen was revised to a hydrogen dive to 230 m (755 ft) due to other expedition factors. In addition, a new cave line would need to be reinstalled from 185 m to 230 m (607 ft to 755 ft) depth, so it was decided that RH would utilize the hydrogen diluent, and CC would dive with trimix. CC would run the reel and act as a control and observer.

Both divers used twin Megalodon CCRs with one unit as the primary unit and the second as a bailout rebreather (with the integrity of the latter intermittently checked during descent).

- The divers used the diluent trimix 4/90 in both loops.
- CC maintained a setpoint of 1.3 atm throughout the dive.
- RH used a setpoint of 0.7 atm on descent and during ascent back to 150 m (492 ft), and of a setpoint of 1.3 atm otherwise. Diluent to the primary loop was changed to 100% hydrogen via a switch block at 200 m (656 ft) on descent, then back to trimix 4/90 at 200 m (656 ft) on ascent. Practice using the extra hydrogen cylinder and switch block procedure was conducted during three preceding dives >150 mfw (492 ffw) by RH.
- On reaching 200 m (656 ft) on ascent, RH would flush/exchange one generous breath of the hydrogen containing loop gas with fresh trimix 4/90 every 10 m (33 ft) of ascent until 150 m (492 ft). At 150 m, a full loop flush would be performed and the setpoint changed to 1.3 atm for the remainder of the decompression. It was calculated that sufficient hydrogen would be eliminated at that stage to safely increase the F_IO_2 above 4%.

It was previously modelled that a dive to 200 m (656 ft) using heliox 5/95, and a subsequent swap to 100% hydrogen would generate a final loop content of approximately 3% oxygen, 66% helium, and 31% hydrogen at 300 m (984 ft). This would give a final gas density of ~5.8 $g \cdot L^{-1}$ and a PH_2 of ~10.5 bar.

Given the revised (shallower) depth, RH decided to introduce some extra hydrogen into the loop between 200 and 230 m (656 and 755 ft) to increase the likelihood that some valid observations could be made.

Dive Execution

February 14, 2023. The dive went extremely well during the descent phase and return to the first habitat at 28 m (92 ft). The first cautious introduction of H_2 was performed after the gas switch at 200 m (656 ft), then the descent was recommenced (Table 3). Thereafter, in addition to the predictable inflow of H_2 via the automatic diluent valve (ADV), several additional manual additions of hydrogen were performed. The dive was turned at 231 m (758 ft) at 26 min runtime, 2 min before the allocated maximum turn time. At 200 m (656 ft) during the ascent, the switch block was changed back to trimix (with buddy confirmation) and the loop flushing protocol was followed without difficulty. The setpoint was increased to 1.3 atm at 150 m (492 ft) after the final loop flush. The difference between decompression obligations between the two divers (one with a lower setpoint at depth) was negligible as predicted by the standard decompression algorithms used.

At 28 m (92 ft) the two divers entered the first habitat and the twin backmount units were taken to the surface by the support team (see computer download Figure 1).

- Dive start: 0740 h
- Divers surface: 2139 h
- Total runtime: 13h 38 min

Table 3. RH dive data points

Depth (mfw / ffw)	Runtime (min)	PO_2 (atm)	Notes
116 / 381	7	0.7	
120 / 394	9	0.7	
200 / 656	18	0.7	H_2 switched on
230 / 755	25	0.7	
200 / 656	27	0.7	H_2 switched off
150 / 492	35	1.3	PO_2 change to 1.3 atm

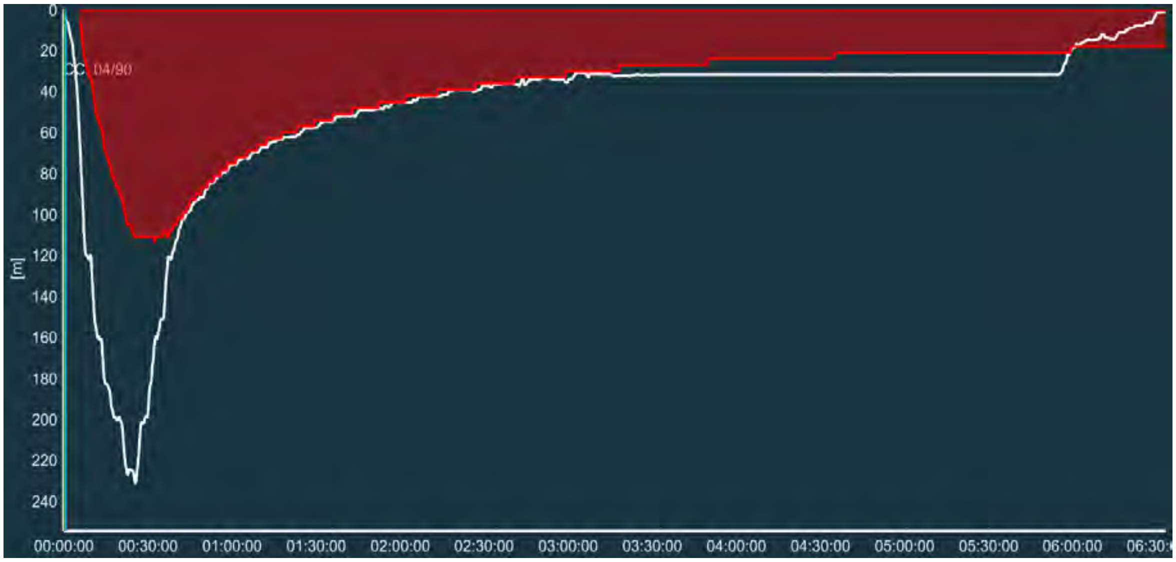

Figure 1. Computer download from the Shearwater NERD2 on Harris' CCR

Practical Observations

It is difficult to make many assertions following a single dive beyond 200 m (656 ft) utilizing hydrogen-based breathing gas in an electronic closed-circuit rebreather. However, the dive offers a degree of reassurance for further study and testing. Dr David Doolette did make the astute observation that one thing we have shown is "*that the odds of survival have been demonstrated to be greater than zero.*" This is a salient point that should be remembered by anyone who chooses to pursue this path.

Using the pre- and post-dive hydrogen cylinder pressures and considering the estimated rebreather loop volume and author's approximate tidal volume, a final predicted hydrogen fraction at 230 m (755 ft) was ≤38%. Predictably, the author could not detect any subjective change in gas density between 200 and 230 mfw (656 and 755 ffw). The calculated gas density at 200 mfw breathing trimix 4/90 PO_2 0.7 atm was 5.6 $g \cdot L^{-1}$. Had the dive continued on trimix, this would have increased to 6.4 $g \cdot L^{-1}$ at 230 mfw (or 6.8 $g \cdot L^{-1}$ with a PO_2 of 1.3 atm). Using 30% hydrogen at 230 mfw density would be approximately 5.1 $g \cdot L^{-1}$. Hence no *subjective* change during descent from 200 m would be expected (5.6 →5.1 $g \cdot L^{-1}$).

No subjective sensation of cold was noted with the hydrogen diluent, but it was introduced slowly into a closed system and the author was extremely careful to avoid work or anything that would increase respiratory minute volume. Open-circuit bailout onto hydreliox or even trimix would likely have a very different effect.

No subjective sensation of narcosis was felt, although the author did feel surprisingly calm at 230 m (755 ffw), and the HPNS tremors that commenced at ~180 mfw (590 ffw) rapidly ceased after switching to the hydrogen diluent.

A final point to be made is that there were almost certainly times during the dive when the fractional concentration of oxygen in contact with hydrogen (either close to the solenoid or more widely throughout the gas path) was above 4%. During ascent, the solenoid would be firing to maintain a PO_2 of 0.7 atm, and at depths shallower than 160 m (525 ft), that equates to an F_IO_2 higher than the desirable maximum. The steps taken to clear hydrogen from the loop during ascent were a compromise between doing it too quickly (risking complications of isobaric counterdiffusion) and too slowly (risking an explosive mixture). The author was reassured by the pool testing and by the high humidity in the breathing loop during the dive, which should diminish the risk of static discharge. Enthusiasts should familiarize themselves with the concepts of minimum ignition energy (MIE) for hydrogen and triboelectricity to inform their own risk tolerance.

With those declarations made and remembering that n=1, it is reasonable to state the following:

- H_2 can be decanted and boosted
- H_2 and CCR diving may be compatible
- Introducing 100% H_2 on descent is possible
- The introduction of 100% H_2 did not appear to produce a significant or dangerous drop in the rebreather loop oxygen levels
- A single decompression dive was successful (no DCS)
- A low setpoint on descent and at depth (to maintain a loop oxygen fraction of <4%) did not practically affect total dive time according to the standard decompression algorithms used
- A strategy to reintroduce a high PO_2 on ascent is possible
- HPNS and narcotic impacts were subjectively favorable (F_IH_2 ~0.3)

Conclusion

It is exciting to consider that the utilization of hydrogen in deep technical diving may open up the next realm of underwater exploration, perhaps at depths between 250 and 300 m (820 and 984 ft) depth. Further cautious testing to develop and expand our knowledge is required and any explorers who consider adopting the technique should make themselves fully cognizant of the risks.

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CONSENSUS STATEMENTS

Simon J. Mitchell, Neal W. Pollock

The consensus statements generated in this meeting are presented below. They were also published with some additional accompanying text in the peer-reviewed literature:

> Mitchell SJ, Pollock NW. Rebreather Forum Four consensus statements. Diving Hyperb Med. 2023 June 30; 53(2): 142-6. DOI: 10.28920/dhm53.2.142-146. PMID: 37365132.

Following the precedent set in Rebreather Forum 3 (Mitchell 2014) the final half day of the meeting was dedicated to discussion of a series of consensus statements intended to reflect widely supported opinion of participants. The statements were drafted by the authors (SJM and NWP) during the course of the meeting, and were explicitly designed to be confluent with important messages emerging from presentations and any subsequent discussion. The statements do not purport to be the only important messages to emerge from the forum; the authors focused on matters that seemed important, widely supported and relatively non-controversial, and that would therefore lend themselves to meaningful consensus.

The statements were presented one by one to a plenary session of participants and discussion was invited. The amount of discussion was variable with some statements attracting little, and others requiring more debate and wordsmithing which was performed live. As is the case with sessions of this nature some degree of directive chairmanship was required in order to work through the list of statements within the allocated time. For this reason discussion of some statements had to be truncated but there was substantial discussion of all statements that emerged as controversial for any reason. For transparency, a transcript of the discussion will be presented in the forum proceedings (edited to correct grammar and eliminate extraneous comments, but retaining the spirit and intent of the original dialogue). At the end of discussion of each statement a show of hands was taken to gauge agreement and disagreement with the statement. It was announced prospectively that a clear majority of participants would need to agree for a statement to make the published list. Ultimately, after discussion and rewording where necessary all draft statements were accepted; most unanimously and never with more than 5-10% in disagreement.

The 28 statements are presented in thematic areas designated 'safety,' 'research,' 'operational issues,' 'education and training,' and 'engineering.' The authors acknowledge that some of these statements seem relevant to multiple themes. Most are self-explanatory, but some are accompanied by contextualizing narrative from the authors where necessary.

THEMATIC AREA 'SAFETY'

Accident Data

Analysis of contemporary rebreather accident data indicates a continued need for integrated effort to reduce the rates of injury, morbidity, and mortality associated with rebreather diving.

Cardiac Health Surveillance

The forum endorses the principle of periodic cardiac health surveillance for all rebreather divers with an emphasis on targeted annual or biennial evaluation for divers older than 45 years even in apparent good health.

> *Contextualizing narrative: The forum resolved that this statement should be accompanied by citation of relevant supportive medical literature. Various studies have identified the importance of cardiac events as the disabling injury in recreational diving fatalities (Denoble et al. 2008; Lippman and Taylor 2020) and an expert consensus guideline for cardiac evaluation of divers was recently published (Jepson et al. 2020).*

Accident Analysis

The analysis of accident, incident, and injury data from rebreather incidents should consider wider contextual elements and error-producing conditions and not just immediate contributory factors.

Solo Diving

The forum recognizes that solo diving may increase the likelihood of a fatality in the event of a rebreather diving incident.

Pre-Entry Checklists

The forum strongly advocates the use of a pre-entry checklist (in a check and response format if practicable) administered just prior to water entry. This should be a brief checklist addressing contextually relevant critical safety items such as "rebreather switched on," "oxygen cylinder on," "diluent cylinder on," "wing/buoyancy device/drysuit inflation connected and working."

THEMATIC AREA 'RESEARCH'

Training and Sales Data

The forum strongly endorses continued collection of anonymized rebreather diver training and rebreather unit sales data by the Divers Alert Network (DAN) Research Department as an adjunct to interpreting diver accident statistics.

Mishap and Near-Miss Reporting

The forum advocates self-reporting of diving mishaps and near-misses, and reporting of fatalities, to the DAN diving incident reporting system.

> *Contextualizing narrative: The DAN diving incident reporting system was nominated in this statement because of its high visibility, global scope, and accessibility for divers anywhere in the world. However, the forum also acknowledged the value of national or regional systems of relevant data collection and analysis (such as that run by the British Sub-Aqua Club [BSAC]) and also advocates for maintenance of diver reporting to such systems. Data sharing between DAN and regional groups was also discussed and was supported.*

End-Tidal CO_2 Monitoring

The forum identifies as a research priority/goal the development of capnography and accurate end-tidal CO_2 monitoring for rebreathers.

Regenerating CO_2 Absorption Technology

The forum identifies as a research priority the development of regenerating CO_2 absorption technologies.

Full-Face Masks

In relation to a documented Rebreather Forum 3 research priority, the forum recognizes the emergence of data pertaining to the efficacy of full-face masks in preventing water aspiration in unconscious subjects (van Waart et al. 2020). This strengthens the argument for considering their use in scenarios associated with an elevated risk of oxygen toxicity such as in-water recompression.

Real-Time Physiological Monitoring

The forum endorses ongoing research into strategies for real-time diver physiological monitoring.

THEMATIC AREA 'OPERATIONAL ISSUES'

Bailout Rebreathers

The forum identifies as a priority/goal the development and documentation of practices and/or monitoring for optimizing bailout rebreather use.

Mouthpiece Retaining Straps

The forum recognizes the use of correctly deployed mouthpiece retaining straps as a strategy for avoiding loss of the mouthpiece and minimization of water aspiration in the event of loss of consciousness underwater.

Bailout Valves

The forum recognizes the potential advantage of a bailout valve for transitioning from closed- to open-circuit in the event of hypercapnia or other events requiring bailout; this advantage requires a high performance open-circuit breathing system.

Mixed Mode Diving

The forum recognizes mixed mode diving as a legitimate buddy option in dives of appropriate scope but recommends a mixed mode briefing, and pre-establishment of strategies for gas sharing.

> *Contextualizing narrative: 'Mixed mode' in this context refers to divers using different underwater breathing apparatus types working as a buddy pair, for example, and open-circuit diver diving with a rebreather diver.*

Mixed Platform Diving

The forum recognizes mixed platform diving as a legitimate buddy option and recommends at least a mixed platform briefing with emphasis on emergency procedures.

> *Contextualizing narrative: 'Mixed platform' in this context refers to divers using different brands or models of the same underwater breathing apparatus type working as a buddy pair, for example, two divers using different brands of rebreather.*

Bailout Rebreather Symmetry

The forum recognizes symmetric (same rebreather unit) or asymmetric (different rebreather unit) multiple rebreather systems as options for an alternative breathing or bailout system.

> *Contextualizing narrative: 'Symmetric' in this context refers to multiple rebreathers of the same make and type, and 'asymmetric' refers to multiple rebreathers of different makes or types.*

Head-up Display

The forum recommends the display of safety-critical information such as loop oxygen status on a head-up display.

Expedition Standard Operating Procedures and Emergency Action Plan Documentation

The forum endorses the compilation of a contextually tailored and detailed dive plan/standard operating procedures document and emergency action plan prior to rebreather diving expeditions.

Emergency Preparedness

The forum endorses the importance of emergency preparedness including a validated emergency action plan, oxygen supplies, access to appropriate medical support with adequate medical supplies, and evacuation plans during rebreather diving expeditions, particularly to remote locations.

In-Water Recompression

The forum recognizes the recent medical endorsement of emergency in-water recompression of selected divers by appropriately equipped teams trained in oxygen decompression (Doolette and Mitchell 2018; Mitchell et al. 2018).

THEMATIC AREA 'EDUCATION AND TRAINING'

Manufacturer-Training Agency Coordination

The forum recognizes the challenges for training agencies in maintaining confluence between course content/availability and emergence of new rebreather technologies. The forum endorses close liaison between training agencies and manufacturers (including factory trainers) to share information about emerging technologies and manufacturer expectations on training approaches using their platforms.

Knowledge Gap Targets

The forum identifies the following as common knowledge gaps that constitute educational opportunities for rebreather instructors and leaders to address:

- Predispositions, symptoms, and frequency of immersion pulmonary edema
- Increasing risk of deeper dives executed perfectly on the same decompression algorithm (ie, these are not iso-risk exposures)
- Scope of variability in venous gas emboli counts in individual divers serially performing identical dives and the associated implications for interpretation of individual monitoring of venous gas emboli post-dive
- The difference between CO_2 inhalation and hypoventilation as the two mechanisms of hypercapnia in rebreather diving.
- Correct management of ingestion/inhalation of caustic scrubber byproduct (ie, a 'caustic cocktail')
- Functional characteristics of CO_2 scrubbers

> *Contextualizing narrative: It is emphasized that this list is not intended to define all relevant knowledge gaps. Rather, it contains items that emerged as obvious educational opportunities in the various presentations and discussion at Rebreather Forum 4.*

Diver Retraining/Updating

The forum recognizes the potential for skill and knowledge degradation over time or during periods of diving inactivity and encourages training agency initiatives to promote continuing education and training, refresher options, and/or recertification as appropriate.

THEMATIC AREA 'ENGINEERING'

Oxygen Sensor Replacement Warning

The forum recommends that manufacturers consider incorporating oxygen sensor replacement warnings in rebreather operating systems.

> *Contextualizing narrative: The context in which this discussion took place was that these warnings would be based on elapsed time since sensor manufacture.*

Gas Density Warning

The forum recommends that rebreather manufacturers consider incorporating gas density displays and/or alarms in the user interface.

> *Contextualizing narrative: The discussion around this statement included strong advocacy for viewing gas density as a dive planning and operational concern that requires careful consideration. Reference was made to recently published data identifying an inspired density threshold of 6 $g \cdot L^{-1}$*

beyond which the risk of CO_2 retention rises significantly, especially during exercise (Anthony and Mitchell 2016).

Orientation Monitoring

The forum identifies optimally positioned accelerometers or inclinometers within rebreathers as an opportunity for capturing diver trim and movement data that could be used for training, performance, and forensic evaluation.

Inspired CO_2 Monitoring

The forum recognizes the potential safety advantage of inhale side CO_2 or scrubber monitors, but acknowledges that they may fail to detect some causes of hypercapnia.

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CONSENSUS DISCUSSION (EDITED)

SIMON MITCHELL (moderator): The plan this afternoon is to work through a series of consensus statements. We have been listening to all the presentations over the 2.5 days, and have tried to identify themes or topics that reflect the mood of the meeting. We compiled these into a series of high level, nongranular statements that reflect a consensus of the participants in the room. I will read out those statements momentarily, and the rest of the day will be dedicated to working through them to ensure that we have reached a consensus, modifying them if necessary, and compiling a final list of product from the meeting.

Many of the statements we have put together are fairly noncontroversial statements of the obvious. And you might ask, why are you doing that? We have found in this type of meeting that it is good to have a series of statements at either the beginning or end of the proceedings document that a reader can review to get a general sense of the key points that came out of the meeting. The edited discussion will provide further insight into agreement and conflict.

We will start by reading the compiled statements to appreciate the whole of our starting point before we discuss specifics. There may be no discussion on some, and much more on others. Our goal will be to revise, remove, and/or replace statements that we can then ratify as a reasonable reflection of the collective thought. The discussion here may be particularly important for topics in which there was insufficient time after the presentation for questions or debate.

The draft consensus statements are loosely grouped under four thematic titles. The first is safety, with only statement under that title, "*Analysis of contemporary rebreather accident data indicates a continued need for integrated effort to reduce the rates of morbidity and mortality associated with rebreather diving.*" In other words, we think there are too many accidents and we would like to reduce them. Fairly bland, but that is an overarching statement that captures the sense that we know we still have problems.

On to research, "*The forum strongly endorses continued accumulation of anonymized and protected rebreather diver training and unit sales data by the Divers Alert Network as an adjunct to interpreting diver accident statistics.*" In other words, the type of data that Frauke presented that are valuable in providing a quasi-denominator for interpreting the accidents.

Also in research, "*The forum advocates reporting of diving mishaps and fatalities to the DAN diving incident reporting system.*" In order to interpret accident rates, we need to know the accidents that occur.

The next is slightly more granular, "*The reporting on oxygen toxicity incidents to the DAN diving incident reporting system is endorsed as particularly important for answering questions relating to optimizing* PO_2 *setpoints in different phases of the dive.*" PO_2 is something a lot of rebreather divers discuss, what do I have my setpoint at when I am on the bottom and I am doing hard work? What do I bump it up to if I do bump it up during decompression? This sort of discussion would be informed by knowing more about when oxygen toxicity occurred.

Also under research, "*The forum identifies as a research priority or goal the development of capnography and accurate end-tidal* CO_2 *monitoring for rebreathers*." That came out of my presentation. And related, "*The forum identifies as a research priority the development of new regenerating* CO_2 *absorption technologies.*" This harks back to a research priority that was documented in RF3 proceedings. It did not really come out here so we thought it was important to put it in as something that the forum has at least partially achieved.

"*In relation to a documented RF3 research priority, the forum recognizes the emergence of data pertaining to the efficacy of full-face masks in preventing water aspiration in unconscious subjects*." This strengthens the argument for considering their use in scenarios associated with an elevated risk of oxygen toxicity such as in-water recompression. That comes from when we asked for data on efficacy of full-face masks in protecting the airway back at RF3. No one really expected we were going to have that kind of data. And then Thailand happened. No ethics committee was ever going to allow us to make people unconscious, put a full-face mask on them, and see if they survived underwater for a period of time. And that is exactly what Richard Harris and his colleagues did in Thailand.

"*The forum identifies as a research priority or goal the development and documentation of practices and/or monitoring for ensuring bailout rebreather integrity*." This came out in Andy Pitkin's presentation. And more research, "*The forum endorses ongoing research into strategies for real time diver physiological monitoring such as breath sounds, automated Doppler, eye tracking, fNIRS, pulse oximetry and electrodermal measurements*." We could also add avatar-like strategies into that statement.

Moving on from research to education and training. The pace of change in rebreather technology is a massive challenge. "*The forum recognizes the challenges for training agencies in maintaining confluence between course content and availability and the emergence of new rebreather technologies. Therefore, the forum endorses close liaison between training agencies and manufacturers, including factory trainers, to share information about emerging technologies and manufacturer expectations on training approaches using their platforms*." It is wordy but it seemed important to identify that challenge.

Over the course of various discussions there were three or four items that came out as what we wanted to call knowledge gaps. Some are things that we suspect that some rebreather divers, and even some instructors, may not really understand. These are opportunities for knowledge improvement. "*The forum identifies the following as potential education knowledge gaps that constitute educational opportunities for rebreather instructions. Predisposition symptoms and frequency of immersion pulmonary edema, the fact that deeper dives executed perfectly on the same schedule are not iso-risk.*" In other words risk increases with depth. Some of these come from David Doolette's talk. "*The scope of variability in VGE counts in individual divers serially performing identical dives and the associated implications for interpretation of individual monitoring of VGE post-dive.*" That was a very important point. That kind of interpretation is very challenging because individual divers can produce very different results across identical dives. And, finally, "*The difference between CO_2 inhalation and hypoventilation is the two mechanisms of hypercapnia in rebreather diving.*" Most rebreather divers know that we can inhale CO_2 if the scrubber fails. Lots of rebreather divers do not appreciate that that is not the only pathway for hypercapnia. Hypercapnia and hypoventilation is probably just as, if not more, important.

Education and training. "*The forum recognizes the potential for skill and knowledge degradation over time or during periods of diving inactivity and encourages training agency initiatives to promote continuing education, certification refresher options, or recertification if appropriate.*"

Now we move on to engineering. "*The forum recommends that manufacturers consider incorporating cell replacement warning systems in rebreather operating systems*." And, "*The forum recommends that manufacturers consider incorporating gas density displays and/or alarms in rebreather operating systems*." These do exist in some rebreathers, but it is something that all manufacturers might like to consider. Still engineering. "*The forum endorses the use of mouthpiece retaining straps as a strategy for avoiding loss of the mouthpiece and minimization of water aspiration in the event of loss of consciousness underwater.*" That came from Pete Mesley's presentation. Still engineering. "*The forum identifies the use of accelerometers or inclinometers in rebreather heads as an opportunity for capturing body trim and movement data that could be used for training, performance and forensic evaluation*."

Moving onto the theme of operational. "*The forum recognizes the potential advantage of a bailout valve for transitioning from closed- to open-circuit in the event of a hypercapnic event; this advantage requires breathing performance of a high quality open-circuit second stage.*" In other words, it is probably not going to help you that much if you bail out onto something where the work of breathing is really high.

Staying with operational, "*The forum endorses mixed mode diving as a legitimate buddy option in dives of appropriate scope, but recommends a mixed mode briefing and pre-establishment of strategies for gas sharing.*" That comes from Mauritius Bell's presentation. Similarly, "*The forum recognizes the advantages of common platform diving but endorses mixed platform diving as a legitimate buddy option and recommends a mixed platform briefing with emphasis on emergency procedures*."

Staying with operational. "*The forum recognizes symmetric, same unit, or asymmetric, different unit, bailout rebreather systems as legitimate options for backup gas supply in the event of primary rebreather failure*." Also, "*The forum strongly advocates the use of a pre-dive checklist in a check and response format if practicable administered just prior to water entry. This should be a brief checklist addressing contextually relevant critical safety items such as rebreather switch on, oxygen cylinder on, diluent cylinder on, drysuit inflation connected and working*." Also, "*The forum recommends the display of safety critical information such as loop oxygen status on a heads-up display*." Also, "*The forum endorses the compilation of a contextually tailored and detailed dive plan document prior to diving expeditions*." The last came from Richie Kohler's talk.

Staying with operational. "*The forum endorses the importance of emergency preparedness, including oxygen supplies, emergency medical technician or medical support with adequate medical supplies and evacuation plans during rebreather diving operations particularly for expeditions to remote locations*." This is where the issue of in-water recompression came up. This came from Richie Kohler's talk. One of his comments was that this is very controversial within the medical profession. I want to tell you it is less controversial now that the concept of in-water recompression by appropriate divers has been endorsed by an expert group convened specifically to address this issue in the early management of decompression sickness. It is not that controversial anymore. We introduced the concept of in-water recompression and endorsed it for appropriate divers in a journal article last year. So, "*The forum recognizes the recent medical endorsement of in-water recompression of selective patients by appropriately equipped divers who are trained in oxygen decompression*." I will make a few more comments about that. The idea is not to relitigate what those documents say about selection of divers and what sort of appropriate training. It is just to make people aware that the medical profession have somewhat moderated their views on this, in fact, substantially moderated their views.

Finally, "*The forum endorses the principle of periodic health surveillance for all technical divers with an emphasis on targeted annual or biannual cardiac health evaluation for divers older than 45 years. The nature of such evaluation should be based on assessment of the individual's risk factor by primary care physicians*."

MICHAEL MENDUNO: I would like to offer one thing that was discussed.

SIMON MITCHELL: We will do that at the end. There may be things that some of you are thinking that are not on there that you think should be statements. When we have worked through these we will solicit additional ideas.

GARETH LOCK: The question was under safety and when it comes to the surveillance data, incidence data and such like, it is looking at context in error producing conditions. But you have said we will discuss that later on.

SIMON MITCHELL: We are going to work through these statements. Remember that they are high level statements. Any one of these things you could probably run an entire conference on. The idea is not to capture everything in these statements. We are open to adding useful detail if it can be done reasonably.

GARETH LOCK: The bit then was most of what we talk about in surveillance was physiology-based as opposed to context-based so it is looking at the error-producing conditions that lead to those events, not just the physiology itself.

SIMON MITCHELL: What I suggest you do is craft a statement that you think would satisfy your concern and communicate that to us during the break.

The point of this reading was to let you know what is coming. You can think about what we have and what we may have missed. We want obvious pitfalls or problems to be pointed out to us.

"Analysis of contemporary rebreather accident data indicates a continued need for integrated effort to reduce the rates of morbidity and mortality associated with rebreather diving."

SIMON MITCHELL: Is there anyone who disagrees with this statement?

DOMINIC HOUSIAUX: I suggest that we add the word "injury" as well as morbidity and mortality.

SIMON MITCHELL: Morbidity includes injury, but if that word is opaque --

DOMINIC HOUSIAUX: That is kind of my point. Morbidity is not particularly intelligible to people outside this room.

SIMON MITCHELL: I guess the question is does injury capture all morbidity? It probably does. I would be happy with that. I take the point that morbidity is something of a medical jargon term. Does anyone object to that statement as it is currently written? Good. We will move on.

JACEK KOT: Where is the decompression sickness at the moment if you the leave the injury and the mortality. Morbidity was better. If we want to be explanatory, we should do injury, morbidity and mortality, just taking into account that readers are not necessarily highly sophisticated English speakers.

SIMON MITCHELL: Decompression illness is a form of injury, but I get your point. Is there anybody who disagrees with this statement? We will fix these up.

JOE RYAN: Is there an acceptable level of injury or a level you cannot go below? Because that would provide some context to the statement.

SIMON MITCHELL: It does, but I think trying to define that would be an impossible task. If I go back to the statement, "there is an implicit." So contemporary rebreather accident data. When we heard from Frauke Tillmans that her current evaluation of those data suggested that rebreather diving is still substantially more risky than open-circuit diving. And I think we all accept that that is a situation that we are not happy with. But I do not personally think that trying to define an acceptable level of injury or death associated with rebreather diving is going to serve us very well. This is a high level statement simply saying that we are not happy with where we are.

ALESSANDRO MARRONI: Just how about incidents?

SIMON MITCHELL: I think there is a big focus on mortality in rebreather diving. That is one of the problems with it. I agree "incidents" would be an all-capturing thing. I think that injury, morbidity and mortality it is slightly more granular.

We need to establish a protocol now. When we start to get bogged down I will ask for a show of hands. All those who agree with this statement, put their hands up. Those who disagree? That is a clear majority in favor so we will move on.

"The forum strongly endorses continued accumulation of anonymized and protected rebreather diver training and unit sales data by the Divers Alert Network as an adjunct to interpreting diver accident statistics."

Frauke Tillmans was able to acquire from eight training agencies and multiple rebreather manufacturers with the exception of two. The "anonymized and protected" wording is very intentional to emphasize the fact that this is going into a database that is managed by an ethical and highly respected group with Frauke at the lead. And this is going to be used as an adjunct to interpreting diver accident statistics. Is there anyone who thinks we should not gather these data? Is there anyone that thinks this statement is poorly worded?

DAVID DOOLETTE: The word "unit" is very vague. I mean, I think probably everyone here knows what is being talked about. Maybe "rebreather."

SIMON MITCHELL: We will put "and rebreather unit sales." Fair enough.

ARLINDO SERRAO: Divers Alert Network (DAN) is doing a tremendous job, but including the reference to DAN might dissuade other insurance companies that also are in the market and that could be great sources for obtaining more information.

SIMON MITCHELL: The point here, Arlindo, is that we are not really interested in information from insurance companies. We are interested in information from rebreather training organizations and manufacturers. And we have been trying to get this information for years. And somehow, after all this time, Frauke has managed to do it. So what that tells me is these agencies trust her, and that is why it is worded the same way. This is maintenance of a program that she is established.

FRAUKE TILLMANS: Two points. The training data was, in fact, collected by the Rebreather Training Council (RTC). That just as a statement. But DAN is perceived as this big insurance agency, and, yes, we do offer insurance, but I would like to make the statement that DAN is more. It is mission driven and it is, in this case, predominantly research. And the research department is completely separated from anything that has to do with insurance. So if "DAN research department" would settle the difficulty I would be happy with it.

MICHAEL MENDUNO: Yes. I think it should be clarified that the data were from the RTC. It was their initiative and they shared the data with Frauke and others. They should be the group continuing to do so.

SIMON MITCHELL: Rather than try to wordsmith that in real time, I will make a note to include RTC in the data collection statement. Given that we do that, is there anyone else who objects to the statement?

LAURA MARRONI: I want to add, and I am sure that Frauke would agree, that DAN commits to make this data transmissions publicly available and not to use it for any commercial purposes.

SIMON MITCHELL: I do not think we need to capture that in this statement. I think that that is implicit in their modus operandi and it is also implied by anonymized and protected wording of the statement.

ATTENDEE: I do not want to wordsmith everything, but instead of "accumulation," it should be more about the verbiage to provide the data to DAN rather than saying they should accumulate it. Because it is nice for DAN to try to accumulate it, but I think the forum wants to state that manufacturers and training agencies should be providing actively that data to DAN, RTC, etc.

SIMON MITCHELL: I think that is implied in the statement. What word would you use instead of "accumulation"?

ATTENDEE: "Providing the data."

SIMON MITCHELL: What about "collection?" I do not think it makes much difference, but I think we are splitting hairs here. The idea is we want the data collection to continue, with the training agencies and the rebreather manufacturers providing the data. That is the key thing.

MICHAEL MENDUNO: One of the things from Rebreather Forum 3 (RF3) that we discussed is the importance of these aspirational statements. I am just wondering when we finally get it hashed out, will it have a little more teeth so we do not have to go, yes, it would be great if we did this, but does an action plan follow somewhere else?

SIMON MITCHELL: We have no authority to order these. Many of these statements are worded quite deliberately so that training agencies or the manufacturers do not feel that we are telling them to do something. We can only endorse it as a group; we cannot dictate efforts.

GAVIN ANTHONY: I think you have a slight conflict in the statement. The one thing you want from the data is a denominator. Without that, it is useless. And, yet, you have "protected." I think that you have to define "protected" or reword it accordingly.

SIMON MITCHELL: What if we take out "protected" and leave "anonymized."

GAVIN ANTHONY: That would work.

SIMON MITCHELL: The key thing is that the training agencies and the rebreather manufacturers need to feel that no one is going to know their business numbers.

ATTENDEE: Maybe "protected, confidential" just to make them sure.

SIMON MITCHELL: I think that would be getting back into the territory that Gavin is concerned about, that the data are not being used. I think "anonymized" is going to cover it. All those in favor of this statement? All those against the statement? A couple. That is a clear majority in favor.

"The forum advocates reporting of diving mishaps and fatalities to the DAN diving incident reporting system."

NICK CUNNINGHAM: While DAN is doing a job, it is not necessarily the trusted body within all the communities for that type of reporting. The nature of experience reporting is it needs to go to that community's trusted body. By limiting it to DAN, I think we are doing the community a disservice.

SIMON MITCHELL: The problem is that DAN has a high profile system. Anyone can find it easily.

NICK CUNNINGHAM: I am saying remove the reference to DAN. I would leave it at "diving incident reporting systems."

SIMON MITCHELL: Correct me if I am wrong, Frauke, but you have the DAN diving incident reporting system that can easily be found in Google searches. What we want here, Nick, is something that people can find easily. They will know how to do it. I think that naming what is arguably the world's highest profile incident collection system is reasonable and there is no intended insult or exclusion to other potential reporting systems. And I think having a name in there that corresponds to something that is easily searchable and you can go to it is probably an advantage. If we just have a blank statement saying, report your incidents, people wonder well, how would I do that?

ATTENDEE: Should it be exclusively DAN incident reporting systems or could we add wording that says "and similar?"

SIMON MITCHELL: It is not intended to be exclusive. But I do think having the bulk of it in one place is helpful. How are we going to benefit from having little chunks of data? I think tasking a group that has well established expertise in doing this is a valuable thing to do.

DAVID DOOLETTE: I agree with you, Simon, that the idea of having it collected at one point is really important. So maybe just deal with this as a footnote you can wordsmith later saying "other reporting agencies who would funnel their data to DAN" or something like that. We cannot solve it now.

SIMON MITCHELL: No, we cannot. What I am going to say here, Nick, no exclusivity implied. We will make a footnote to this statement along the lines of, "No exclusivity implied. And linkages between DAN and other reporting systems."

CHARLES ROBERSON: I wanted to change "reporting" to "self-reporting," but that obviously does not work with fatalities. It will be important to include a self-reporting element. People may not want their buddies or their divemasters reporting on their incidents.

SIMON MITCHELL: If we put "self-reporting," we immediately run into the problem that you just identified, Charlie. I think the intent is pretty clear. And I do not think we are going to have an epidemic of people reporting on behalf of others. Just out of interest, Frauke, does that happen? Do you get a lot of that?

FRAUKE TILLMANS: We do.

SIMON MITCHELL: Would we want to discourage that?

FRAUKE TILLMANS: I would not.

SIMON MITCHELL: I do not think we want to discourage it.

ALEJANDRO GARBINO: Can we add "near misses" too?

SIMON MITCHELL: Okay. I am all for clarity with "near misses." There is no harm in it.

DOMINIC ROBINSON: As some know, we probably have one of the longest lasting incident reporting systems in the world so I feel that I need to speak up on the point made by Nick. The problem with asking people to report incidents twice is that they rarely do that. What I think we should be doing is encouraging communications between major systems. I agree that DAN is probably the best group to do that, but I would support the point made earlier that we should be encouraging the reporting and then collaboration.

SIMON MITCHELL: There is going to be a footnote. It will something like, "The existence of national data collection systems or non-DAN systems is acknowledged and this statement is in no way intended to discourage reporting to those systems and that communication between DAN and other collection groups would be an appropriate goal."

DOMINIC ROBINSON: Thank you very much.

FRAUKE TILLMANS: I would like to add that this system is designed for anonymous and confidential reporting, in that whatever is coming out of that is the raw data that goes into a database. Then if the reporting person agrees this can be put into a report published on the website in an anonymized form.

SIMON MITCHELL: That is great. Thanks.

JACEK KOT: I add assuring the proper identification of the person. It can be done in an anonymous way that is disconnected from a person and from the insurance part of DAN. So I concur with what Frauke said, but I would like to see this in the text.

SIMON MITCHELL: What you are saying, Jacek, is "The forum advocates reporting of diving mishaps, near misses and fatalities to the DAN incident reporting system by individuals whose names will be recorded." That sounds like a very odd thing for me to write.

JACEK KOT: No. I mean, ensuring proper identification of people or ensuring anonymization.

SIMON MITCHELL: Why do not we leave that. We just heard that that system, that already exists. That is the modus operandi of the group that we are advocating that they report to. So why do we need to specify it in this statement? That is what happens; right, Frauke?

FRAUKE TILLMANS: Yes.

ALESSANDRO MARRONI: Just to specify what Jacek was asking, the European part of the DAN database already complies with the general diver protection directive (GDPR) in Europe. We do have the obligation to de-identify and anonymize whatever comes in in a non-anonymous way. So what Jacek was saying is what we do.

SIMON MITCHELL: I am sure that is true. And the message here is for the divers to understand this. It is not intended to be a description for the receiving agencies, which already have their processes in place. We have just heard from DAN America and DAN Europe how they operate.

PETER GERMONPRE: Could we consider adding that we recommend self-reporting. Because, as you know, in a blame free society admitting to one's mistakes and stupidity is actually encouraged. While it is obviously not self-reporting for fatalities, I would add that self-reporting is encouraged because it does not actually put the blame on anybody.

SIMON MITCHELL: How do we get around the issue of fatalities if I put "self-reporting" in here?

There are several options, but what we could do is make a note to wordsmith this to distinguish between self-reporting of mishaps and near misses and reporting of fatalities. Neal and I are pretty good at doing this kind of thing.

[Break for lunch]

"The reporting on oxygen toxicity incidents to the DAN diving incident reporting system is endorsed as particularly important for answering questions relating to optimizing PO_2 setpoints in different phases of the dive."

SIMON MITCHELL: It was pointed out that there may be too much granularity in this statement. We want all diving mishaps, near misses and fatalities. So this will be ditched to speed things up a little bit.

"The forum identifies as a research priority or goal the development of capnography and accurate end-tidal CO_2 monitoring for rebreathers."

Remember that was what we use in the operating room that gives you inspired and expired CO_2 in the same display so that that would translate into being able to monitor our scrubber and any scrubber breakthrough and the CO_2 levels in the divers themselves. So that is the accurate end-tidal CO_2 monitoring for rebreathers. Okay then. Who agrees with this statement? Who disagrees with it? Nobody. So we can lock that one in.

"The forum identifies as a research priority the development of new regenerating CO_2 absorption technologies."

This was one of the blue sky ambitions that was articulated in the presentation by Phil Short and Kev Gurr. It was one of the things they brought up that had the most practical relevance to us as end users. Any issues?

GAVIN ANTHONY: Remove the word "new."

SIMON MITCHELL: Fair enough. It is adapting them into our environment.

We will take a vote on this one. Who agrees? Who disagrees? Another one locked in.

"In relation to a documented RF3 research priority, the forum recognizes the emergence of data pertaining to the efficacy of full-face masks in preventing water aspiration in unconscious subjects."

This addresses what I talked about earlier that since RF3 identified it as an explicit research priority statement about the utility of full-face masks in protecting the airway in an unconscious diver. I look back on that and I wonder what we were on when we generated that statement because it was never likely we were going to get data and then, of course, we did because a group of our colleagues were forced into it in Thailand and had no other options. We now have 13 data points where children were kept deeply unconscious through anesthetic. By the way, a detailed description of the anesthetic that Harry gave is in a published report, available on PubMed Central as a free download. It was good to close this loop because, you know, when we make these statements, it is great if we can come back five years later or 10 years later and say, hey, we have done it. This strengthens the argument. Does not say you must. "*It strengthens the argument for considering their use in scenarios associated with an elevated risk of oxygen toxicity such as in-water recompression.*" Where I think we all agree is that someone who has just completed a technical dive and developed symptoms and then goes back in the water on 100% oxygen, that is a higher risk than the technical dive itself. Does anyone disagree with this statement? Terrific. Those who agree with it? And those who disagree? Very good. That is good. All right.

> [van Waart H, Harris RJ, Gant N, Vrijdag XC, Challen CJ, Lawthaweesawat C, Mitchell SJ. Deep anaesthesia: the Thailand cave rescue and its implications for management of the unconscious diver underwater. Diving Hyperb Med. 2020; 50(2): 121-9. DOI: 10.28920/dhm50.2.121-129.]

"The forum identifies as a research priority or goal the development and documentation of practices and/or monitoring."

So either things that the diver can do or "monitoring for ensuring bailout rebreather integrity." Now, this is just an acknowledgment of the fact that at this meeting we have heard that there is an increase in the prevalence of the use of bailout rebreathers as opposed to open-circuit bailout, and that a common issue is how the divers ensure that the loop in their secondary rebreather maintains integrity, it is breathable during a descent and a period of time at the bottom and the ascent, for that matter. This came out of Andy's presentation. Is there anyone who thinks this is not correctly worded or disagrees with it? This is an aspirational goal, what we would like to see in guidelines. As people get more experience with it, hopefully, that will emerge.

AUGUSTO FEDERICI: I think it is just more than this. We need protocols to use the bailout rebreather more than just being sure of the integrity of the loop because there is not much out there about protocols, how to use it, how to switch from one unit to the other. I can keep going on for an hour about this.

SIMON MITCHELL: I totally agree with you. Everything you just articulated is captured in the wording "the development and documentation of practices." That is exactly what you are asking for. We cannot get more granular than that. What we cannot do is come up with a micro-list of everything we would want to see. This is a broad-brush statement saying, we would like to have protocols, guidelines, development and documentation of practices I think covers off what you are asking for.

AUGUSTO FEDERICI: And classes, courses.

SIMON MITCHELL: At the moment -- well, I am calling it a research priority. Actually, one question I would like to ask you, Andy, is do you think this is research or do you think this is training and education? What would you call it? I can easily reclassify the slide, just put it in the other section.

ANDY PITKIN: My feeling is that it should be under the practice section, the operational section.

SIMON MITCHELL: Operational. Yes, in retrospect and listening to what Augusto was saying, I agree.

ANDY PITKIN: And maybe take out the word "research" from the sentence.

SIMON MITCHELL: Because it is hardly research. Agreed. Thank you.

MATT JEVON: Whether it changes the wording or not, but over the last three years myself and someone from Divesoft have written a specialty in bailout rebreather that is been accredited by Technical Diving International (TDI). The procedures, processes, and protocols are contained within there. They are up for critique, feedback, amendment, improvement, et cetera. Anything that is out first has room for improvement. There is something out there, but it is generic, not unit specific.

SIMON MITCHELL: I suggest that we add "documentation and optimization." In other words, we are refining what you have done. You said yourself that there is room for improvement in everything.

RICHARD HARRIS: I think in terms of what was said previously, the issue is the final four words, "for ensuring rebreather integrity." That is just a small part of it. It is more about defining definitions, scope of use, practices, and procedures.

SIMON MITCHELL: Okay. We can replace it with, "optimizing bailout rebreather use." Better?

MARK POWELL: As long as Matt has no objections as the author, I have no objections including those bailout rebreather standards in the proceedings as a strawman for people to have a look at.

SIMON MITCHELL: Would it be possible to provide us with a website link to those proceedings so they can be downloaded?

MARK POWELL: Yes, I can, as long as Matt has no objections.
[https://swt.ie/wp-content/uploads/2024/08/TDI-Diver-Standards_Bailout_CCR_Diver.pdf]

KEVIN GURR: You may need some kind of electromechanical development to do this safely, as a part of this. I would not take out "development."

SIMON MITCHELL: I have not taken out "development." Development and documentation. All right. We can vote on this one. Everyone who agrees with this statement? Anyone who disagrees with it? That is a clear majority so we can call it a consensus. Very good.

"The forum endorses ongoing research into strategies for real time diver physiological monitoring such as breath sounds, automated Doppler, eye tracking, fNIRS, pulse oximetry and electrodermal measurements."

This is a reflection of the presentation from Rachel this morning. Does anyone disagree with the statement?

PETER GERMONPRE: I would not put a list of things to encourage. I think most data we could get would be useful.

SIMON MITCHELL: I am surprised you have not checked that out, actually, Peter. You have done trampolines, dark chocolate, saunas, and vibration. I am happy to take the examples out. Then it becomes a very aspirational statement. Does anyone disagree with this statement?

TIM INGLIS: I do not know. Right now there is no consensus on gradient factors. They have inertia-based recommendations, inertia-based defaults, that no one is comfortable saying everyone should dive this so I feel like something that is a bit more descriptive of how this would impact decompression strategies or what the main factors should do.

SIMON MITCHELL: Not all of these are designed to impact decompression strategies. I think this is a bit more broad-brushed than that. Remember, too, that we are trying to capture things here that were at least to some extent the topic of discussion at this forum. And as much as I am interested in default gradient factors and Shearwater computers and have been engaged in some conversations with Tyler about that, it was not something that we discussed here. I think keeping it as broad as possible is probably the right way to go. Who agrees with this statement? Who disagrees? Okay. Accepted.

"The forum recognizes the challenges for training agencies in maintaining confluence between course content availability and emergence of new rebreather technologies. Therefore, the forum endorses close liaison between training agencies and manufacturers, including factory trainers to share information about emerging technologies and manufacturer expectations on training approaches using their platforms."

This is an interesting one. It was not something that was front of mind for me, and I really learned something when the guys started talking about this because it makes perfect sense. It must be a massive challenge for training agency people to keep up with the technological revolution. I am happy to take any comments on this, but in particular anything from any of the three training agencies? Have I got this wrong? Have I misinterpreted what you were saying? Because I thought this was an important message in your presentation. Paul, do you want to make any comments about this?

PAUL TOOMER: No. You have got it spot on.

SIMON MITCHELL: Does anyone disagree with this? Okay. Excellent. We can vote on this. I know what the vote shows, but we just want to go through the motions of this. All those who agree with it? Does anyone disagree? Cool. We will lock that one in.

We will do the next separately to avoid getting into a real mess because different speakers might have things to say about different points. These were things that we thought constituted potential knowledge gaps in the way the instructors teach things or in the way that rebreather divers perceive things. It is not an exhaustive list. This is some of the ones that fell out of the discussions that we had here. So you could extend this list, I get that. But these are things that we picked up on. And if people think that it is wrong to just pick up on these things, we can delete it altogether, but I actually think that would be a shame because I think these are quite important topics.

"The forum identifies the following as potential education/knowledge gaps that constitute educational opportunities for rebreather instructors, both for their own knowledge and the knowledge of their students -- the relationship between PO2 setpoint and oxygen toxicity risk; the predispositions, symptoms, frequency of immersion pulmonary edema; whether deeper dives executed perfectly on the same schedule are iso-risk (or if risk increases with depth; scope and cause of variability in venous gas emboli (VGE) counts in individual divers serially performing identical dives and the associated implications for utility of individual monitoring of VGE post-dive; and an appreciation of the difference between the two mechanisms of hypercapnia in rebreather diving (CO_2 inhalation and hypoventilation)."

Immersion pulmonary edema is emerging as a more and more common problem or at least a more widely recognized problem. Does anyone think that that is not something that rebreather divers should be aware of? And it is quite common in rebreather divers probably because of static lung load issues in relation to rebreathers, possibly work of breathing. We are still not to the bottom of that yet. Does anyone disagree with that being a potential knowledge gap?

JACEK KOT: I would like to ask why this is a so short list of topics. That is why I would like to present, for example, that those topics which have been discussed during Rebreather Forum 4. And to the second point, deeper dives executed perfectly on the same schedule are not iso-risk so it is not clear. I would prefer, "the extrapolation of the knowledge and algorithms from shallower or shorter dives into the deeper and longer dives is inappropriate because it increases the risk."

SIMON MITCHELL: That is the second point. Jacek, we are not writing a textbook here. We are identifying ideas. Most people in this room should understand what iso-risk means. I get it, there is a bit of jargon in there. Anyway, we are on the first point. Look, to Jacek's first comment though, why are we identifying -- I thought I addressed that, but obviously, not well enough. These were things that fell out of the discussion here that we noticed. If you are going to be uncomfortable with identifying these things without standing here all afternoon talking about the other things we could add to this list, then I will just delete it.

JACEK KOT: You explained this, but it is not explained in the text. This is my only point.

SIMON MITCHELL: I see what you are talking about. Yes, I get it. So what we are going to need is an addition to that stem explaining why we have chosen these things. I have got you now. Sorry, Jacek, I misinterpreted what you were saying.

PETER GERMONPRE: Jacek voiced a little bit of my concern. I think dismissed actually reflects the fact that rebreather divers have maybe an insufficient knowledge of deep diving physiology as a whole. And immersion pulmonary edema, the risk of decompression in these deep extreme dives, the VGE thing, the CO_2 thing, I think these are all items that could be maybe summarized at the top as saying, we encourage rebreather diver training agencies to incorporate a large number of physiological teaching in their training programs. Because I am not sure -- I am not a rebreather diver yet, but I am not sure what is in the training manuals about diving physiology.

SIMON MITCHELL: I think all of these things are in there to some extent, but some of them are not particularly well perceived. These were items that at some point in the last three days popped out as potential items of relatively widespread misunderstanding or lack of knowledge. Once again, if we are uncomfortable with identifying these as examples, or people are going to want to continually add to the list, I will just delete it. Neal, do you want to make a comment about that?

NEAL POLLOCK: I think they should stay. They did come up. They are points of misunderstanding. It would be way too vague to just say they should add more about physiology in the training documentation. I think this does reflect what was discussed here.

SIMON MITCHELL: If we refine that stem to make it very clear that this is not an exhaustive list, but it were things that came up during the discussion at RF4, would that make things better for you, Peter? Okay. Thank you. Does anyone else have any comments to make about this?

ATTENDEE: I just wanted to suggest on the first sentence that you move "potential education" because "knowledge gaps" and then you say "education" later. It would just make it simpler to read. "Knowledge gaps that constitute educational opportunities."

SIMON MITCHELL: Fair enough. That is better wording.

DAVID DOOLETTE: Are we moving on to specific points now?

SIMON MITCHELL: Okay. Let us take some of the specific points.

DAVID DOOLETTE: So on the deeper dives I would at least change "schedule" to "algorithm" because it implies that.

SIMON MITCHELL: You are right.

KEVIN GURR: Is this the right place to add something on scrubbers, on canisters? I really did feel like that came out in some of the discussions and there is definitely a knowledge gap on how they function.

SIMON MITCHELL: We could add that. I do not think it is in education and training. Well, look, I do not want to open the floodgates here; okay. What do you think, Neal?

NEAL POLLOCK: Yes to the addition.

SIMON MITCHELL: We will add it. "*Function of CO_2 scrubbers.*" Does anyone else have any comments they want to make about this slide? All right. Who agrees with this slide? Who disagrees with it? We will call that a consensus.

"The forum recognizes the potential for skill and knowledge degradation over time or during periods of diving inactivity and encourages training agency initiatives to promote continuing education."

This came up in discussion rather than as part of a lecture, but it is a recurring theme at many meetings we go to and it was discussed here. It is fairly bland but an important thing "refresher options" or "recertification if appropriate."

Would anyone disagree with any of this or think that it is not worded appropriately?

JACEK KOT: Should it be "continuing education and training?"

SIMON MITCHELL: Fair enough. We will add the word "training."

TRAVIS KERSTING: I would like to figure out a way to add that training agencies or manufacturers have the right to remove an instructor who has done something that is unsafe. So if they are outside of their education and training credentials or they have not gone through their refresher, that it be a thing that we can not necessarily publicly ostracize. We should be able to advertise that these people are no longer an instructor for us.

NEAL POLLOCK: I think that is a departure from the current topic. And it is not something that we discussed. I am not sure that is a good add-on at this point.

PAUL TOOMER: We spoke about the training and education platforms. All the training agencies certainly within the RTC have protocols that we can use to remove instructors. You do not need to take this burden on yourselves. We have those protocols in place so we have your back.

ATTENDEE: And many of us publish those too.

SIMON MITCHELL: I think we have a reasonable sense that we would not add that to this part of the consensus. I think we will leave that one, Travis, if that is okay. It is a different topic. I agree with Neal. Does anyone else disagree? We can vote on this. Those who agree with this statement as it is worded and those who do not? Okay. Cool. Thank you.

"The forum recommends that manufacturers consider incorporating cell replacement warning systems in rebreather operating systems."

We are on to engineering now. We may need some wordsmithing, but essentially you in some way tell your rebreather when the cells are changed and it warns you. This is not a directive. It is a recommendation that manufacturers consider it.

RICHARD PYLE: The only thing is wordsmithing of the word "cell." That is a common usage word to imply oxygen sensor. It kind of implies galvanic oxygen sensor. I would go with more explicit "oxygen sensor."

SIMON MITCHELL: You are right. We can vote on it with the proposed changes. All those who agree with it? Accepted.

"The forum recommends that manufacturers consider incorporating gas density displays and/or allowance in rebreather operating systems."

This is based on the data that Gavin Anthony published. Does anyone want to comment on that? Does anyone think that that is an inappropriate statement or it is not worded correctly?

> [Anthony G, Mitchell SJ. Respiratory physiology of rebreather diving. In: Pollock NW, Sellers SH, Godfrey JM, eds. Rebreathers and Scientific Diving. Proceedings of NPS/NOAA/DAN/AAUS June 16-19, 2015 Workshop. Wrigley Marine Science Center, Catalina Island, CA; 2016; 66-76.]

KEVIN GURR: Just a comment about potential misnomer. Fundamentally, it is not the gas density that is the issue. It is the resistive effort within that product design.

SIMON MITCHELL: Both are important. Gavin's data was unit independent. It was across a lot of platforms and it reasonably clearly showed that it was a significant infliction of risk once you got beyond 6 $g \cdot L^{-1}$, irrespective of what rebreather it was you were diving on.

KEVIN GURR: I am not saying that is not important. The two are kind if inextricably linked.

SIMON MITCHELL: I think what we are addressing here is the gas density issue, which is an independently proven risk factor so why not consider having an alarm for it. Gavin, did you want to respond to that comment?

GAVIN ANTHONY: Basically, almost to reiterate what Simon said, the base data was over multiple platforms, open-circuit and closed-circuit, all sorts of gases, and all sorts of depths. The data pointed to this threshold as important.

A lot of it is what is inside us. I think this as it stands is okay. As soon as you put the resistance or the equipment on the outside, it just gets worse.

SIMON MITCHELL: Yes, but we cannot incorporate an alarm for that.

ALEJANDRO GARBINO: I think, technically speaking, you mean interface, not operating systems for rebreather. Because operating system has a different technical context.

SIMON MITCHELL: No, you are right. Thank you. User interface?

ALEJANDRO GARBINO: Just interface.

SIMON MITCHELL: Interface. Sure.

MANFRED THORELL: I have a question regarding this. When you plan the dive, you can know what gas density you will be exposed to. So is this an idea of catching up bad dive planning, or why is it important to display the value in real time?

SIMON MITCHELL: That is a fair comment. My unit has a gas density alarm in it, and it went off on a dive that I was on recently because I went too deep with the gas that I had. And what that reminded me to do was not work hard and not go any deeper than I had to. So, you are right. You can plan for these things, but I do not see any harm in having a monitor and alarm. This is just an advocacy for consideration. It is not a strong recommendation.

OSKAR FRÅNBERG: I do recognize the internal resistance and the gas density issues, but all the resistances or breathing impediments are additive, the elastins, the inertia, and the resistance. So these should then be some kind of display or maximum operating depth that would be unit specific; right.

SIMON MITCHELL: Did you hear what Gavin said, Oskar? It is an independently proven risk factor irrespective of what platform you are on. It is independently proven. Have you seen the data?

OSKAR FRÅNBERG: Yes, I have. I am just saying that internal resistance is also added to the other resistances, which combines into a complete burden.

SIMON MITCHELL: But how would you measure that in a rebreather?

OSKAR FRÅNBERG: Well, that would be measured already in the standard procedures; right?

SIMON MITCHELL: I do not think the standard procedures would account for every dive, every configuration, every depth, every gas density, and every attitude in the water. I think you are asking a little bit much. I would be interested to hear what a manufacturer thinks of the idea, but nobody has it.

OSKAR FRÅNBERG: To the forum, I want to stress if you go into the European rebreather the limits we see are absolute maximums and I think it is worth pointing out that it is well worth to try to lower those hydrostatic imbalance and resistance and everything beyond the levels that is in the standards.

SIMON MITCHELL: There is no objection to that concept, but we are talking about an independently proven risk factor for CO_2 retention that you can monitor and that you could put in an alarm because some rebreather manufacturers have already done it. Your point is not invalid, of course it is not.

OSKAR FRÅNBERG: It is better with this than without, but I would like to stress the other points.

SIMON MITCHELL: We understand that.

DAVID DOOLETTE: So if this is in general breathing resistance and that is the issue we have a number that you guys have published, should we be saying that, otherwise, Kevin Gurr and I are going to be arguing over beers that I have a 4 $g \cdot L^{-1}$ rebreather and he has an 8 $g \cdot L^{-1}$ rebreather. Is it going to become a competition as to where you set your alarm. I am not sure I see a whole lot of use for this.

SIMON MITCHELL: I have no objection to including the 6 $g \cdot L^{-1}$ threshold, but I would prefer to leave it general. It is not like the rebreather manufacturers do not know what we are talking about here. Are you suggesting we incorporate gas density displays and/or alarms if gas density exceeds 6.2 $g \cdot L^{-1}$?

DAVID DOOLETTE: I am saying I am not sure I see the use in the statement unless we do something prescriptive. I agree with that you should be diving to what your testing is for resistive effort.

SIMON MITCHELL: Plan your dive, dive your plan.

NEAL POLLOCK: And we know that does not always happen,

RICHARD PYLE: My reading of that recommendation is that it is for the manufacturers to take into consideration gas density, among potentially other factors, in real time situations and whether or not a diver may be approaching some sort of limit. As far as I am concerned, that wording is fine because it is up to the manufacturer to decide where those alarms trigger. They are the ones that are going to incorporate all their data on their breathing loop in particular. That is why I would advocate not putting a particular number on density in there. You can list gas density because that may be a big factor and that is the thing that your rebreather can easily measure in real time and therefore trigger an alarm, but how that alarm algorithm works is something the manufacturer would have to incorporate all those other parameters that contribute to breathing resistance. I will comment on the dive planning thing because Neal looked at me in his talk about dive planning and a video that some of you may be familiar with. It involves cold water on deep dives in the tropics and certain language. The funniest part of that video to me is the line that says, "How deep are we going to go? I do not know." My friends are always great at dive planning. I think the people in the room who do real exploration know the way they dive plan is to set a maximum depth that they feel comfortable going to. That is not always the depth they go to on a dive. If the fish are at 60 m (197 ft) and I was prepared to go to 120 m (394 ft), I will still stop at 60 m. So just as a comment on the dive planning operation, we were prepared gas density-wise, mixture-wise to go to as deep as we went. We just did not know we were going to go to our maximum depth on that dive.

SIMON MITCHELL: Great comment. Thank you. I think we are all aware of the issues that are relevant to this statement.

MICHAEL MENDUNO: I would like to two possible additions that were discussed, loop pressures and a moisture sensors.

SIMON MITCHELL: I do not remember either of those, to be perfectly honest with you. Let us just park there. We are discussing this statement. You can vote it in or vote it out.

JOE RYAN: I am not a manufacturer and do not have anything to do with any manufacturers, but if I was a manufacturer, I would be a bit concerned about this in terms of liability issues. Is that something that we are pressuring them on?

SIMON MITCHELL: No. We are saying that we ask them to consider incorporating a gas density display. It does not mean that they have to and I do not think it introduces any liability if they do not. I am not a lawyer, of course, but we as a user group are allowed to articulate aspirational goals. I think most manufacturers would be on fairly safe ground given that most of them currently do not have these things so there is ample precedent for not having one.

We will vote on this. If you do not like it, vote against it. If it is a close call, we will get rid of it. Who is in favor of this statement? Who is not? It is a small minority who do not like it so we have an accept consensus.

"The forum recognizes the use of mouthpiece retaining straps as a strategy for avoiding loss of the mouthpiece and minimization of the water aspiration in the event of loss of consciousness underwater."

This is a topic that raises great passion, particularly amongst people who do not use mouthpiece retaining devices. This is not a directive. It simply recognizes that this is something that may contribute to those goals, loss of the mouthpiece and preventing loss of the mouthpiece and minimizing water inspiration.

This is controversial. There are no strong data in support of mouthpiece retaining devices in achieving these goals, as you might well imagine. No one is going to get an ethics approval to render people unconscious with mouthpiece retaining devices underwater. We are never going to have that. There is one paper that was published around the time of the last rebreather forum by the French group. They reported on military rebreather diver accidents over a 20-year period in France. There were 54 loss of consciousness events, with three diver deaths. They were all wearing the Draeger mouthpiece retaining device. Now, as a diving physician who has seen a few loss of consciousness events in my time in the water, I would expect that if you have 54 loss of consciousness events even when people have buddies, you will expect more than three of them to drown.

[Gempp E, Louge P, Blatteau JE, Hugon M. Descriptive epidemiology of 153 diving injuries with rebreathers among French military divers from 1979 to 2009. Mil Med. 2011;176(4):446-50. DOI: 10.7205/milmed-d-10-00420. PMID: 21539168.]

I think there is a pretty strong circumstantial case that mouthpiece retaining devices made a difference in those situations. They do come with their disadvantages, although I think they are more imagined than real. I wear one all the time. I would not go diving without one. But if you want to vote this out, that is fine. The other piece of evidence I would offer you is that they passed the sort of biological sense test. In other words, it is a device that holds the mouthpiece in your mouth. The properly designed ones have a flange that seal around the lips and full the flange in against the lips to create a seal. I have tried dislodging it and making it incompetent actively and I struggled to do it. So I am a believer, but I know that a lot of people are not. Just bear in mind this is a fairly low level statement. It is putting it out there that they probably will help with these things, but it is not a directive. We removed the word "endorses" for exactly that reason because endorses is slightly stronger.

GARETH LOCK: The question I have is if we recognize this as a split between use and non-use, would a question actually to find out why people do not use them and then we can address that. That statement stays the same. We recognize the use of it. But, actually, we want to improve the safety one way or the other is one of the barriers to use of the mouthpiece retaining straps.

SIMON MITCHELL: I agree that would be a very good thing to do, but that is not our goal here. We as a group need to decide if we should recognize that these devices are likely to achieve these goals. That is the statement that we are considering. I do not disagree with you, Gareth. In fact, I think a few people have made attempts in regard. Paul Haynes wrote a paper about this a few years ago. He addressed some of those issues. It was not based on data. It was based on anecdote and discussions he had had with other divers. Usually the case for not using them is that I have never used one and I do not like the idea of it.

[Haynes P. Increasing the probability of surviving loss of consciousness underwater when using a rebreather. Diving Hyperb Med. 2016;46(4):253-9. PMID: 27966205.]

CHARLIE ROBERSON: I think as written it is weak enough to be kind of pointless. If it is going to go as written, we should just delete it. If there is evidence to strengthen it, then let us strengthen it, but I would say it should probably be re-categorized into a research category, and we should reword it to encourage further research and data.

SIMON MITCHELL: Problem is, Charlie, how would you go about researching this? It is easy to say and actually is what we did in the last rebreather forum. And I remember reflecting that it was pretty stupid. Because how would we go about researching the efficacy when we cannot ethically do so.

ANDY PITKIN: I would like to say that just because we cannot see how we can do it now does not mean that somebody could not think of a way to do it ethically in the future. Given that the question is still open, that we do not have the data, I do not think we should assume that it is going to be unethical to obtain that data in the future.

SIMON MITCHELL: Fair enough. I will bring you back to this point though. It was identified as a research priority 10 years ago and we have seen nothing except that French paper, which was published around the time of the last rebreather forum but was not discussed at the meeting. So I am presenting that paper as novel evidence in the rebreather forum today. We actually have not advanced from where we were 10 years ago. It is retrospective data, not prospective or experimental data, and we still have challenges in getting more data. I accept your point, but 10 years have gone by with no progress.

CAMILO SARAIVA: I do not think that engineering is the most prominent challenge so perhaps it should be moved to operations or training.

SIMON MITCHELL: I think you are right.

NEAL POLLOCK: I agree. I think it should be operational. Even if it is weak, we would be ignoring the issue completely by deleting it. I think it is a very relevant, even if it is a soft statement.

SIMON MITCHELL: Who else wants to talk about it? We will take a bit of discussion on it.

MARK CANEY: As you have said, there is a paper that is pretty convincing, effectively new since RF3. There is also a good reason why all of the rebreathers that want to pass CE have to have some kind of retaining strap or the equivalent. So, yes, there is enough evidence in my mind to make it worthwhile saying this. We are not saying everybody must have one, but we are saying it is probably a good idea.

SIMON MITCHELL: I think that was what was in the back of the minds of Neal and I when we wrote this. Pete had it in his presentation, and it is meaningful to keep it in front of the community. It is saying that these things exist and they might well enhance safety. The best currently available evidence, albeit limited, suggests that they may help is how I would phrase it.

GABRIELE PAPARO: I would like to stress the importance of the correct use of the retainer because I think that someone may think that just hanging around the neck is enough. I am referring to Pete Mesley's presentation when he said that it is very easy to remove it. Actually, if you use correctly, it is very tight on your mouth and effective. Otherwise, it is not effective. So it is important to add, in my opinion, a correct use of the retainer strap.

NEAL POLLOCK: That could load the text.

SIMON MITCHELL: Well, we can add, "correctly deployed."

MICHAEL MENDUNO: My question was on CE. It is to meet CE standards that you have to include one of these with a rebreather. My question was in the ISO standards for training -- we do not have this in the ISO standards for training, just for equipment; correct?

MARK CANEY: In the ISO standard it has wording to the effect that where a mouthpiece retaining strap is fitted, you must show them how to use it.

CHAUNCEY CHAPMAN: About 10 years ago I tried to buy 150 retaining straps from Draeger and they refused to sell them to the company I worked for. There has been an important change in mouthpiece retaining straps in the last couple of months. Lombardi Undersea produces and sells a mouthpiece retaining strap for $25. I suggest that you change your "recognizes" to "encourages" and add a statement that training agencies need to develop a training program for mouthpiece retaining straps, and just get over it.

SIMON MITCHELL: I personally do not have a major objection to your idea, but I suspect that what that will do, Chauncey, is create barriers to getting this through as a consensus statement of this forum, and I would rather have it there in this form than not have it there at all.

RICHARD PYLE: I am a little more intimidated by suggesting this be changed, but what I want to do is come back to the research question. Maybe instead of moving this, you could add another point to the research section that data gathering processes, whether the risks of the fatalities or the accidents, include as a specific piece of information to record in such incidents whether or not a retaining strap was used so we can start building a denominator on its actual use in the field and maybe eventually be able to extract correlations between incidents and outcomes and whether or not they use it. The point is I do not think anyone is recording that particular piece of information in incidents. That should be a specific piece of information that gets captured in incident reporting.

SIMON MITCHELL: We will find a way of finessing that into a footnote. What you are suggesting, Richard, is that we, essentially, repeat the French study within our own population.

RACHEL LANCE: I do not have any qualms about your wording. I am just standing up to say that while it would be unethical to intentionally cause our subjects to lose consciousness underwater, we could test the opposite. We could test if the straps do active harm by putting rebreather divers, trained rebreather divers, into a scenario where we induce a failure. I do that all the time, induce failures and then see how they react and see if there is a difference in responsiveness or the ability to adapt to the failure in such a way that it makes a difference to predict survival.

SIMON MITCHELL: That is a good suggestion, if slightly tangential to the statement. Andy, I saw you nodding to Richard's suggestion. What that is going to produce is data similar to that which we already have from the French. You are sitting there saying, that is not very strong. It will have a bit more ecological validity, I get that, but it is going to be similarly weak data. I think it is still a good idea, but it is not going to definitively answer the question.

JENNY LORD: You said about the lack of knowledge so surely this pushes it into the educational area. You said earlier about the knowledge gaps. Does it not fit quite well in there?

SIMON MITCHELL: I think it is more than a knowledge gap. I think this is a philosophical kind of operational question. There are the users and the non-users. I think most people are aware of them. You could identify knowledge of that French study as a knowledge gap, but I do not really think that gag straps per se fit into that category. I think probably operational is correct. But we will finesse a statement with Richard's idea.

AUGUSTO FEDERICI: If I am right, I believe that we all now have a retaining strap in our bag. Why do not you ask the audience, are you willing to try it in your next dive or not?

SIMON MITCHELL: I do not think it is as simple as that. One of the things I often say, Augusto, is that if people have not used one and they are making judgments on that basis, then they actually should try one.

AUGUSTO FEDERICI: Now they have one in their bag so they can try it.

SIMON MITCHELL: I am not sure that is the one I would recommend they use, to be perfectly honest. The design is quite subtle and it is important.

JARROD JABLONSKI: I would say that there are a lot of things that we could litigate and many of us might not even have the right experience base, multiple rebreathers, different configurations, lots of things that we could talk about. I am comfortable with the simple version because it is hard to argue with. I would only say that one problem is a tiny fraction of the people in this room seem to be using these straps, and we are saying that this is endorsed or recognized by a body that is not even using them, much less in a position to advocate for their use. So, for me at least, the endorsing component helps, but if the body politic is not even using them, it is a weaker position to make comments from.

SIMON MITCHELL: Yes, of course, I get that Jarrod. We are asking people to make a judgment on the basis of no experience, but we have talked a little bit about the evidence and the biological plausibility of it as a strategy. I think people can maybe make their minds up on that basis.

KEVIN GURR: You say it requires use of a strap. Should not we encourage rather than recognize?

SIMON MITCHELL: That could make some people in this room quite uncomfortable. And I think I said before to Chauncey's comment, I would rather have this in here in its present form than not have it in here at all. It was actually "encourages," but I have had quite a lot of feedback on this that would tip the balance for a substantial proportion of the audience not wanting this statement, and I actually think this statement is quite important. I think we will take a vote on this.

ATTENDEE: Can we vote for options, either recognizes or encourages?

SIMON MITCHELL: I do not think it materially changes the message, which is that these things are here, the weight of evidence that we currently have, albeit weak as it is, suggests that they may be beneficial. I think that is the fundamental message. I think messing with that word is going to create problems for the group. The statement as it is written in the proceedings will carry some weight and it imparts a message. I think changing that word will create more problems than it solves. We can vote on this. Who agrees with this statement? Who disagrees? There are a few disagrees but we have an overwhelming majority in favor. Thank you. That was a really good discussion and exactly the sort of thing that is healthy to have.

"*The forum identifies the use of accelerometers and inclinometers in rebreather heads as an opportunity for capturing body trim and movement data that could be used for training, performance and forensic evaluation.*"

I have not seen this in real life use. I do not even know if this is a thing from an engineering point of view, but there are a few engineers in this room who can comment on it.

OSKAR FRÅNBERG: I personally use this in forensic investigations, and it is a very good measure to have. I would take out "rebreather heads" because I think that could be up to the manufacturers.

SIMON MITCHELL: What about "in rebreathers." just out of interest, does any rebreather have this? Poseidon has it, okay.

RICHARD PYLE: The reason for the rebreather head is we actually carry three of them on every dive, one in each of the two handsets. Knowing the position, that the three axes accelerometer readings of the handsets -- you may not have to say head, but you should clarify that you are talking about in a position that reflects the position of the human diver as opposed to somewhere else on the rebreather. We have almost 10 years of this data and it is important to get it right.

RACHEL LANCE: "Inclinometers in rebreathers" I would like to suggest it be "inclinometers with rebreathers" because there are a lot of lab level engineering tools to directly measure the person so that would just be a little bit more inclusive.

SIMON MITCHELL: Okay. Let us take a vote. Who agrees with this statement? Who disagrees with this statement? There was a couple of disagrees. We have an overwhelming majority in favor.

"*The forum recognizes the potential advantage of a bailout valve (BOV) for transitioning from closed to open-circuit in the event of a hypercapnic event. This advantage requires breathing performance of a high quality open-circuit second stage.*"

This one could be another interesting discussion. It is worded intentionally in much the same way as the gag strap one. This came out of Pete Mesley's presentation when he discussed what is essentially anecdotal data that several divers have remarked in the middle of hypercapnic events even when they knew they should bailout onto open-circuit and had it available. They have declined to do so because of the perception that if they took the mouthpiece out for more than a picosecond, they would drown. And, obviously, a BOV enables you to transition to open-circuit bailout without having to take the mouthpiece out. Does anyone object to this statement?

ALEJANDRO GARBINO: Being the last one in engineering and considering the fact that we have been hearing during this three days talking about human failure as one of the main responsibilities on incidents and fatalities, I would like to go back to the machinery testing or checklisting in the beginning of the dive, or the pre-dive, that could help avoid such problems.

SIMON MITCHELL: That is a different thing, though. We can do that until the cows come home, but these events are still going to occur. Obviously, we try to prevent them, but there will be hypercapnic events in rebreather diving no matter how good we get on the human factors side.

ALEJANDRO GARBINO: No, it was related to engineering. I think this is an engineering topic.

SIMON MITCHELL: If we have time at the end we will come back to things that people might want to insert into the consensus statement. I do not want to derail the discussion now by trying to create new consensus statements.

GAVIN ANTHONY: Very happy with the principle. What I would like to do is reconsider the words "in respect to breathing performance of a high quality." I can make a second stage out of gold, but it has crap holes. I think what you need to say it is a high performance open-circuit breathing system which is not just a second stage, it is the holes in the first stage.

SIMON MITCHELL: Fair enough. Yes.

VINCE FERRIS: I would say that the bailout system is a requirement regardless of whether there is a hypercapnic event. There is a lot of reasons we could bail out. I do not know that "hypercapnic events" needs to be in there.

SIMON MITCHELL: I am sympathetic to that view. The key thing is the high performance open-circuit breathing system -- so why is that there. It is there because one of the criticisms, which I acknowledge as valid, is if they are not high performance, then you may not gain anything from bailing out of a rebreather system when you are hypercapnic, particularly if the primary problem is hypoventilation rather than CO_2 breaking through the scrubber. This is one of the points about BOVs that is often made so I wanted to incorporate it. When you are likely to be hyperventilating, you need a high performance open-circuit breathing system. We could say, "*transitioning from open to closed-circuit this advantage requires a high performance open-circuit breathing system.*"

MICHAEL MENDUNO: Could we say, "in the event of a bailout."

ATTENDEE: I think we should keep hypercapnia because that is what we talked about in the forum.

SIMON MITCHELL: It is the context. I think that is probably right.

MARK CANEY: I do not disagree with that statement, but one caveat is that if you get a rebreather that has been CE-approved without a BOV, there are issues with adding it in when it is not supported by the manufacturer.

SIMON MITCHELL: Okay, that is greater detail. This is high level. What we are trying to get across is that this is a message that might encourage a diver to choose a rebreather that is manufactured with a BOV.

MARK CANEY: As I said, I do not disagree with the statement.

SIMON MITCHELL: Thanks, Mark. That is an interesting point. I had not really thought about it. Are there any other comments about this?

MICHAEL MENDUNO: You could say, "hypercapnic event and other events that might require a bailout." This would broaden it.

SIMON MITCHELL: Yes, we could.

MICHAEL MENDUNO: To Vince's point, it is relevant to other situations besides hypercapnia, though that is a primary one.

SIMON MITCHELL: How about, "in the event of hypercapnia or other events requiring bailout." I think it is implicit in all of them, but particularly hypercapnia. Thank you. We can vote on this. Who agrees with this statement? Anyone disagree? One or two disagrees but a consensus.

"The forum recognizes mixed mode diving as a legitimate buddy option in dives of appropriate scope, but recommends a mixed mode briefing and pre-establishment of strategies for gas sharing."

Does anyone disagree with this statement or want to make any comments on it?

GAVIN ANTHONY: For clarity, I think you need to footnote to define "mode" and "platform."

SIMON MITCHELL: Okay. We will add a footnote to clarify terminology later. Anyone else want to make a comment? We will vote. Those in favor? Anyone against it? Accepted.

"The forum recognizes mixed platform diving as a legitimate buddy option and recommends a mixed platform briefing with an emphasis on emergency procedures."

We will add an appropriate footnote for definition. This is happening all the time.

ALAIN NORRO: I recommend "at least a mix of platform briefing" because we in Europe ask for a little more in terms of the organization of that sort of activity.

SIMON MITCHELL: Any further comments? We can vote on it then. All those who agree with this statement? And those who disagree? Very good. Accepted.

"The forum recognizes symmetric or asymmetric bailout rebreather systems as legitimate options for backup gas supply in the event of a primary rebreather failure."

We had a whole presentation on it from Andy. A lot of people are doing it. This is an acknowledgment of what is happening, and that we as a forum, being arguably the premiere rebreather diving group in the world, agree with it. Does anyone disagree with this statement once we add a definitions footnote?

PETER GERMONPRE: If you want it to be neutral I would take out "legitimate."

SIMON MITCHELL: You are right. That is good wordsmithing.

RICHARD HARRIS: I am wondering about the terminology "symmetric" and "asymmetric." A few of us have been talking about writing some definitions. Has this definition arisen from Andy's presentation or within this conference? Is this accepted?

SIMON MITCHELL: Are they the terms you used, Andy? Yes, they are. I do not think that we need to explain them.

RICHARD HARRIS: So we are establishing definitions for this quite progressive area, which I am happy with.

JACEK KOT: I am curious what happens if there will be the failure of the secondary rebreather. I would delete the term "primary rebreather." It can simply say, "in the event of a rebreather failure" because it concerns either.

ANDY PITKIN: I think that is a valid point. There may be some situations where you do not actually designate one as the primary.

SIMON MITCHELL: "Of a rebreather failure." Nice.

CHARLES ROBERSON: I would encourage adding language at the end "where open-circuit bailout is impractical." Because, as written, we are encouraging this for all rebreather divers, and I am not sure that is appropriate.

SIMON MITCHELL: I do not get that sense. It is just an option.

CHARLES ROBERSON: It is, but it is an option, in my opinion, when open-circuit is wholly impractical. I do not think it should be your first option.

SIMON MITCHELL: There are some problems with that. If you are a rebreather diver who does a lot of deep diving and so your habitual bailout system is a bailout rebreather, and then you are going to do a shallower dive where open-circuit bailout is plausible, are you advocating that they should abandon their usual procedure in favor of carrying open-circuit just because it is possible to do so?

CHARLES ROBERSON: Absolutely.

SIMON MITCHELL: Fair enough. Andy, you are the context area expert in this. You gave the presentation.

ANDY PITKIN: Personally, I like it as it is.

SIMON MITCHELL: Harry, you are another user. What do you think of that idea? I want to give Charlie's idea a fair hearing.

RICHARD HARRIS: I see what Charlie is saying because of the almost certain increased complexity and probable increased risk of a second rebreather system. However, I think Andy's point overcomes that because we do not know how this area will develop, so keeping it simple as written is best.

SIMON MITCHELL: I think we have consensus amongst the users and can leave it. Anyone else?

MATT JEVON: When we went through the definitions for writing the course we made a distinction between dual rebreathers, where both rebreathers are in active use during the dive at different times, and bailout rebreathers, where the backup rebreather is not in use during the dive unless it is actually required in a bailout situation. That may be terminology the forum could consider. The protocols and procedures change when you are using it in dual format or bailout format.

SIMON MITCHELL: I think that would be quite difficult to capture. And I think we need a higher level statement than that. I take your point but I think we should keep it simple and not try to make that distinction here.

RICHARD PYLE: Why not just replace the word "bailout" with "multiple."

SIMON MITCHELL: "*Recognizes symmetric or asymmetric multiple rebreather systems;*" is that what you are saying?

RICHARD PYLE: Bailout is one use case for having dual loops, having more than one breathing loop with you on a dive. And so why constrain it to just one.

SIMON MITCHELL: Fair enough. That helps with the comment made before.

CAMILO SARAIVA: Can we clarify by adding "same type or same model unit."

JACEK KOT: The second rebreather system is not only a backup gas supply. It is an alternate breathing system.

SIMON MITCHELL: Shall we say "alternative gas supply?"

JACEK KOT: Not gas supply. This is a breathing system.

SIMON MITCHELL: Okay.

NEAL POLLOCK: If we are going to do that, we need to replace "rebreather failure." It is not just about failure.

MARK CANEY: The terms "rebreather type, rebreather unit and rebreather model" are defined very specifically in the ISO standards. I think we need to make sure that we are being consistent in that. For example, in the ISO standards we define type as being the principal design style such as mCCR, eCCR or SCR. The unit is the overall family, so Inspiration or Evolution. And then model is the specific model. I think we are using different terminology here.

SIMON MITCHELL: I am not sure we are. Symmetric is the same rebreather model and asymmetric is a different rebreather model.

MARK CANEY: In ISO I think it would be the unit because in the ISO standard the different models are handled exactly the same. Different units have different characteristics.

SIMON MITCHELL: Are you saying we should put "same rebreather unit?"

MARK CANEY: I think unit was the right term.

SIMON MITCHELL: If that is how it is handled in the ISO standard, then maybe we should go that way. Fair enough. This sentence had a good thrashing. It is very humbling writing statements and then presenting them to 200 people.

MICHAEL MENDUNO: I am going to vote for it anyway, but it seems this was a whole discussion about bailout. Yes, there are other alternatives, but it feels like the word bailout should be in there. "For rebreather bailout and/or alternative."

SIMON MITCHELL: I can put "breathing or bailout."

MICHAEL MENDUNO: The discussion was around that.

JAKUB SIMANEK: I am very glad for this statement. I am just a little worried that it will encourage people to use the bailout system without any open-circuit option. I think that it has to be mentioned that there is a necessity for open-circuit usage when your breathing is high, especially in the case of hypercapnia. This is not the safest option and there has to be some open-circuit alternative.

SIMON MITCHELL: I would challenge that, Jakub, and say that I do not think that was how it was presented by Andy.

ANDY PITKIN: I think that this is a different issue that I did not cover in my talk, but a very valid one. It is not what we are talking about now.

SIMON MITCHELL: I agree. I do not think we need to introduce that level of complexity, Jakub. I think, while your point is valid, what we are identifying here is that multiple rebreather systems are options for alternate breathing or bailout systems. We are not trying to drill down into specific bailout scenarios and say, if this, then that, which is what you are doing. You are saying, if it is hypercapnic, you need open-circuit. I think this statement is okay on its own, and I think Andy agrees so we will leave it.

JAKUB SIMANEK: I understand. I still would add "while supported by open-circuit option."

SIMON MITCHELL: Do any of the dual bailout divers want to comment on this? I think it is putting quite a different flavor on this statement.

RICHARD HARRIS: I agree. Jakub's comment is completely valid and correct; however, I think that with the current statement we are introducing the rebreather community to this as a new thing that is evolving. I do not think it needs any kind of grassroots interpretation.

SIMON MITCHELL: We are not trying to put more detail around it. I think, Jakub, we will leave it. And we accept that when you teach it you might add that scenario in.

GAVIN ANTHONY: I think we need to leave the term "bailout" in here. Otherwise, you are losing the message. The other is not necessary in respect to this statement. We are using lots of terminology, and it needs defining.

SIMON MITCHELL: We will vote on this statement. Who agrees? I think that is overwhelming. Who disagrees? Good. Accepted.

"The forum strongly advocates the use of a pre-dive checklist in a check and response format if practicable."

This should be a brief checklist addressing contextually relevant critical safety items, such as "rebreather switched on, oxygen cylinder on, diluent cylinder on, drysuit inflation connected and working."

NICHOLAS BAILEY: I suggest we use "wing" or "buoyancy device" in there as well.

SIMON MITCHELL: We can say, "wing/buoyancy device/drysuit."

PETE MESLEY: Maybe change "pre-dive" to "preentry" or "prejump."

SIMON MITCHELL: I have heard prejump, preentry, pre-dive, presplash. The one that I think would make sense to just about everybody is pre-dive. What are you advocating for, Pete?

PETE MESLEY: I am happy with preentry. I understand what it means. I just want to be sure that everyone else does as well.

CHAUNCEY CHAPMAN: We use prejump; I think it is the right term for a brief checklist that can be executed in 20 seconds. It was approved by the RTC. Before we recreate the wheel, I think a good examination of what already exists would be beneficial.

SIMON MITCHELL: That is a great point. I am reluctant to name a specific checklist here. It is a well understood principle of checklist design that some degree of tailoring to contextually relevant situations is allowed and indeed encouraged. So I would not want to say what has to be used. We could cite it as an example, but we have a whole bunch of people with their own tailored prejump checklists. So as long as it meets the basic criteria of brevity with key items I would rather leave this generic instead of specific. Would anyone else like to comment?

RON WAXMAN: I think people are missing what the statement is saying. I strongly agree with the statement. Every manufacturer has a prejump built into their checklist. I believe that would be a true statement. But that would be the step at which the diver self-checks his own equipment on his own. And I think what the statement is that we are adding a third step with a buddy team because there is a response format which you do not get on a normal prejump. I think we are adding a third safety mechanism in which we do this with another person in case a step was missed in the original prejump.

SIMON MITCHELL: My argument, as someone who has some degree of expertise in human factors, is I would not be considering it as a third. I would substitute -- "if the check and response format is practicable." I would do this just before you stand up and jump off the back of the boat.

RON WAXMAN: I agree.

SIMON MITCHELL: Is there anybody else who wants to comment on this? Okay, we can vote. Who agrees with this statement? We are all pretty much in agreement. Accepted.

"The forum recommends the display of safety critical information such as loop oxygen status on a heads-up display."

Does anyone want to comment on this statement? It is a statement of the obvious. I do not think there is a single rebreather without a head-up display.

TIM INGLIS: There are certainly rebreathers out there that do not have head-up displays.

SIMON MITCHELL: That then makes the statement more important. Does anyone disagree with this? Okay. We will vote on it. Who agrees with this statement? Who disagrees? Unanimous in favor.

"The forum endorses the compilation of a contextually tailored and detailed dive plan/standard operating procedure (SOP) document prior to diving expeditions."

It is pretty noncontroversial. Comments?

RICHIE KOHLER: Can we please add "emergency action plan." Dive plan and SOP are literally the same thing and we include an emergency action plan. It is outside of it, because the dive team could be in the water and the support team has to enact the emergency action plan.

SIMON MITCHELL: All right. We will vote on this one then. Who agrees with this statement? Who disagrees? Nobody. Terrific. Accepted.

"The forum endorses the importance of emergency preparedness, including oxygen supplies, emergency medical technician or medical support with adequate medical supplies, and evacuation plans during rebreather diving operations, particularly for expeditions to remote locations."

These were the main points that I took out of your presentation, Richie. And they all make perfect sense to me. It is possible there are some important omissions that we could add in or is it so obvious that we do not need to? Any comments?

ARLINDO SERRAO: What is a rebreather diving operation?

SIMON MITCHELL: That is a reasonable question. Have you got an alternative wording? I think we all know what we are talking about. You could just say, "during rebreather diving" because this would be applicable to any rebreather dive.

ARLINDO SERRAO: I think that, for me, "operations" is not enough because of all those things you asked there if it is only for rebreather diving, anytime we go rebreather diving we have to expect that those conditions are met.

SIMON MITCHELL: I guess then "emergency medical technician or medical support with adequate medical supplies." My sense is that the focus should was on expeditions.

ATTENDEE: That is redundant.

SIMON MITCHELL: "Particularly to remote locations." Thank you. There might be a bit of wordsmithing needed here.

ALEJANDRO GARBINO: I was waiting for this to quote the emergency action plan in there. I think most of the time people have the DAN kit and some vague notion of medical support and no plan, and that was the key takeaway from the presentation.

SIMON MITCHELL: I do not have a problem putting "emergency action" plan in both of those statements.

DAVID DOOLETTE: Maybe where we are saying "emergency medical technician," it should just be access to that. I might not have a doctor where I am diving, but I would know how to find one.

SIMON MITCHELL: I get that. Actually, as I listened to you speaking, Richie, I wondered how you dealt with that issue because I know I often go on rebreather diving expeditions as the doctor and Pete Mesley goes to a lot of trouble trying to find that. Do you actually seek out an EMT or a doctor to go on your expeditions?

RICHIE KOHLER: I have a lot of friends who are either police officers, firefighters and other people that are basic life support. They may not be EMTs, but they have an advanced degree or are qualified oxygen providers. We pepper the team with people who expressly have that kind of background.

SIMON MITCHELL: Fair enough. I think what we will do is soften it slightly with David's suggestion. I do not think that changes the overall intent of it.

NICHOLAS BAILEY: I suggest adding "test the actual preparedness." Have a test of the actual process to make sure it works for when you actually arrive on the site.

SIMON MITCHELL: Where would you put that? Endorses the importance of emergency preparedness, including having a plan, having oxygen supplies.

GAVIN ANTHONY: You could say, "including a validated emergency action plan."

SIMON MITCHELL: That captures it, "Including a validated emergency action plan."

PETE MESLEY: I would also like to see the inclusions of "readily accessible recompression chamber" if you are conducting technical diving activities.

SIMON MITCHELL: No, I do not think we can put that in there.

PETE MESLEY: Yes, you can.

SIMON MITCHELL: As much as I agree with your sentiment, I do not think you can put that there. What is really accessible, and there are so many technical diving operations that take place without one. I just do not think you can say that. Our friends from the Health and Safety Executive (HSE) would probably require it, but I do not think we can say it.

DOMINIC HOUSIAUX: One of the things I am most concerned about is that we are discriminating against people with fewer resources. I would suggest that we remove "emergency medical technician" and say "access to appropriate medical support with adequate medical supplies."

SIMON MITCHELL: I agree with that.

FRAUKE TILLMANS: To the chamber discussion, I would not put that in there directly, but it is in the emergency action plan.

SIMON MITCHELL: Thank you for that. You are absolutely right. I think we are getting close.

RICHARD PYLE: To be consistent between the two paragraphs why not add the word "rebreather" in front of "diving expeditions" in the first point so that it matches the second point and also brings it into context of a rebreather diver.

SIMON MITCHELL: Very good. We can vote on this. Who agrees with this statement? Does anyone disagree with this statement? Nobody. Very good. Accepted.

The next statement found its way into our list because the topic of in-water recompression was raised by Richie, and the context of it being considered highly controversial in the medical community. I am not saying that is completely gone away, but I can tell you that a group of experts commissioned by DAN to review first aid procedures in diving situations in the field has endorsed the in-water recompression by people who are properly qualified to do it. And the reason that this statement contains a reference to "appropriately equipped divers who are trained in oxygen decompression" is that that group is us. The consensus document that I am referring to here, the paper does not endorse in-water recompression in your average recreational diver dive boat. What we do not want to see divemasters or dive controllers putting up a sign saying "in-water recompression provided here." This is something that only properly trained technical divers should be doing. That is definitely us. Since it was raised and since it was characterized as a controversy, we thought we would include this statement to raise awareness that it is been substantially legitimized for us. That paper, along with a companion paper by David and I specifically addresses the narrow subject of in-water recompression. It is all described. You will probably find it very interesting. There are protocols, advice, rationale, and evidence for its efficacy. Essentially, it is not as controversial as it has been. I do not think there is too much that is controversial about the statement. Does anyone want to disagree or question the wording?

> [Doolette DJ, Mitchell SJ. In-water recompression. Diving Hyperb Med. 2018; 48(2): 84-95. DOI: 10.28920/dhm48.2.84-95. PMID: 29888380
> Mitchell SJ, Bennett MH, Bryson P, Butler FK, Doolette DJ, Holm JR, Kot J, Lafère P. Consensus guideline: pre-hospital management of decompression illness: expert review of key principles and controversies. Diving Hyperb Med. 2018; 48(1): 45-55. PMID: 30028914.]

RICHARD PYLE: That word "recent" does not belong in that statement. Talk to Carl Edmonds. Even if you are talking about medical community, Undersea and Hyperbaric Medical Society had a workshop that included one of the recommendations as almost verbatim that kind of a statement. Yes, I agree with you it has only been relatively recent that the volume level of the dissenters in the medical community has abated, but there have been at least some in the medical community who have endorsed it as a practice by appropriately equipped divers, et cetera. So I am not sure recent is a fair word.

SIMON MITCHELL: I will get rid of it.

RICHARD PYLE: I still have the scars on my back from all the arrows so I am sensitive.

SIMON MITCHELL: That is kind of the point. Carl was considered a bit of a heretic on this issue, I get it, but he copped a lot of flack.

RICHARD PYLE: I know he did and I know I did. But when UHMS had that workshop, I saw several people who started as skeptical and ended up being less so -- that felt to me to be something of a turning point.

ATTENDEE: There was no consensus.

SIMON MITCHELL: No, there was not. It was not endorsed.

RICHARD PYLE: There was no published consensus, I agree. But I was in the room and there was a lot of changed minds that I was surprised were changed. But put the "recent" in there if you want.

SIMON MITCHELL: It is gone.

NEAL POLLOCK: I think "recent" is still appropriate because otherwise it is going to sound like you are backdating this. It is still controversial.

SIMON MITCHELL: Yes, okay. Can you live with it, Rich?

RICHARD PYLE: Sure. But then can you add the word "endorsement" if it is still controversial?

ATTENDEE: "Fairly recent."

SIMON MITCHELL: I actually think it is an accurate characterization of the issue to say that the wider acceptance by the medical community is recent. I think you would have struggled to find too many UHMS doctors who would have recommended in-water recompression on the basis of that workshop. It never really came to a proper consensus.

DAVID DOOLETTE: Why not "wider," recognizes the "wider."

SIMON MITCHELL: Instead of "recent."

NEAL POLLOCK: That would be fine.

SIMON MITCHELL: Good compromise. "Wider."

RICHIE KOHLER: Should we add "when evacuation or chamber is not readily available." I mean, it makes it sound like, hey, you know, instead of me getting on a boat or helicopter, I will just jump in the water. Is that not a better option?

SIMON MITCHELL: There are a bunch of caveats or criteria that should be met before you do it. They are in those documents. We are not trying to prescribe how you would do in-water recompression. The only reason I have mentioned one of those caveats, which is "trained in oxygen decompression" is that defines that group as us. But there is a whole bunch of them, including how far away is your chamber, is the weather okay, is the diver suitable to go back in the water, have you got the right equipment, have you got the right amount of oxygen. All those things are there, and you could argue that they should be here. But at the moment we are only really directing people to the appropriate documents.

DAVID DOOLETTE: Maybe emergency in-water recompression capture that.

SIMON MITCHELL: Emergency in-water recompression. Yes. Okay.

JACEK KOT: I have some comments on wording. First, "patients" is a relation between the victim and the doctor so I would replace "selected patients" with "selected divers."

SIMON MITCHELL: Yes, fair enough.

JACEK KOT: We also should say, "selected divers by appropriately equipped team in selected situations." Because we need a team, not divers.

SIMON MITCHELL: Fair enough.

JACEK KOT: And we can add what was previously mentioned "in selected situations," but it is not obligatory.

SIMON MITCHELL: I would prefer to leave it as the definition of what qualifies the team to be appropriate, which is the training in oxygen decompression. If we start going down the rabbit hole of defining all the things you need, that is in the paper.

ARLINDO SERRAO: I think there is some level of formality in here if you keep the reference to the paper on the body of that topic, we will be voting on something that we did not all read. So you might want to change that to a footnote or something like that.

SIMON MITCHELL: The only thing you are voting on here is that there is wider medical endorsement.

ARLINDO SERRAO: It is not the medical. It is the reference for the paper. It is in the body of one thing that we are going to vote. It is on the body. I did not read it. If you want to keep it there, I will not vote. I think it does not make sense.

SIMON MITCHELL: The reason the references are there is so people can review relevant work. This is just like providing a reference for a statement in a medical journal. I think having the references is quite important. But if you do not want to vote because you have not read the papers, that is fine.

PASQUALE LONGOBARDI: I am not against it because the two papers are published in a peer-reviewed journal. But in the previous statement we said that for expeditions the team has to produce a plan of action and medical assistance. We have 50 hyperbaric centers in Italy. You can go in hyperbaric center in less than two hours. Why should in-water recompression be used as an operational norm when there are hyperbaric centers?

SIMON MITCHELL: Well, Pasquale, if divers can get to the hyperbaric chamber within two-hours, those consensus documents say they should. If the chamber is more than two-hours, use the in-water recompression provided you have got A, B, C, D, E, F, and G. Okay, we will vote on this. Those who agree with this statement? Those who disagree? Accepted.

"The forum endorses the principle of periodic health surveillance for all technical divers with an emphasis on targeted annual or biannual cardiac health evaluation for divers older than 45 years. The nature of such evaluation should be based on assessment of the individual's risk factors by primary care physicians."

This came up in the training discussion, It has to do with the fact that a diver can have a career in recreational diving and never interface with a diving physician. The statement is confluent with current advice from the high level medical societies, particularly SPUMS and the UK Sport Diving Medical Committee. What we want is for divers to not drift away from monitoring their state of health. They do not need a diving medical every year or two years. What they should be doing is seeing their primary care physician who will assess their cardiac risk, and there are ways of doing that if you are a doctor, and taking appropriate action in terms of investigations if they are necessary. This is not too onerous. If you turn up at your doctor's office and say, I run for 10 km three times a week, I never get chest pain, I go to the gym, and I am fit, they probably will not do anything. That is a form of evaluation. But if you go to the doctor and you are overweight, have high cholesterol, and complain of chest pain intermittently when you walk upstairs, the response will be quite different.

The point here is that the doctor will be tailoring what needs to happen to your individual health status. This is an attempt to encourage divers, us, to interface with doctors on our cardiac health. This is a response to what has been said several times in these last few days that cardiac issues are the disabling injury in about 25-28% of diving fatalities. What do you see in this room? Quite a few middle-aged men in that risk group. This is an attempt to push us to do what we should be doing this anyway, irrespective of technical diving. Does anyone want to discuss this?

CAMILO SARAIVA: I want to say that I think it is very important, and, therefore, I suggest moving it to a higher position in safety instead of operation.

SIMON MITCHELL: Fair enough. Good suggestion.

NICHOLAS BAILEY: Biannual means different things to different people. Some think that means twice a year. Others say every two years.

SIMON MITCHELL: Yep.

GAVIN ANTHONY: Do we need the word "technical" in there? All divers?

SIMON MITCHELL: Well, it is all divers, that is true. In fact, if we are going to say anything, it would be rebreather divers. Neal, what do you think? Do you think we should just have divers or rebreather?

NEAL POLLOCK: I think we can take out "rebreather."

SIMON MITCHELL: Just make it "divers."

PETER GERMONPRE: I have a small issue with the primary care physicians doing an evaluation and then reassuring the diver that everything is okay. I do not think primary care physicians are necessarily well placed to do that evaluation for the diver. I see regularly that even pulmonologists or cardiologists say, you are good to go for diving while diving is a completely different physical activity than jogging and cycling. I would somewhere insert the necessity for evaluation by a diving medicine physician. Maybe not in all cases, but in some cases.

SIMON MITCHELL: I disagree with that. What we are targeting here is cardiac health. The moment you make it diving medicine physician you are taking the diver outside their normal routine of seeing their own doctor, and they are far less likely to do it on a routine basis. I think that what we are trying to target here is the substantial proportion of diving fatalities, somewhere between 20 and 30%, that may be due to cardiac events. Why does it need to be a diving medicine physician who assesses cardiac risk? Family medicine doctors do that every day of their working lives.

PETER GERMONPRE: I get that. I am not saying that it always should be a diving medicine physician, but take the example of immersion pulmonary edema. Somebody with slight overweight with a little bit of hypertension with some drugs to control that hypertension may be at a high risk for immersion pulmonary edema and the primary care physician will not know about that. I am not saying primary care physician should be taken out, but I think they must have some warning that being in generally good cardiac health does not necessarily prevent you from being at risk in diving.

SIMON MITCHELL: Would it work to put "by primary care physicians or a diving medicine physician if appropriate?"

PETER GERMONPRE: Yes. Something, in case of any abnormality evaluation, by a knowledgeable diving medicine physician is advised.

SIMON MITCHELL: I am going to have a go at defining what appropriate is, but I am going to take that offline because it will take too long right now.

MARK CANEY: Earlier you said, Simon, I think, that we can only put things in these consensus statements based on what we have discussed during this conference. So I would be inclined to put the word "rebreather divers" back because we did not discuss all divers.

SIMON MITCHELL: No, we did not. But this is a well-established truth in the diving industry, as you well know. We have spent about three or four years discussing this very thing.

MARK CANEY: Yes, I am just wondering would a nonrebreather diver look at the proceedings of Rebreather Forum 4?

SIMON MITCHELL: Probably not, no. I actually am very comfortable having "rebreather divers" in there.

RON WAXMAN: I want to reiterate a smart point made earlier. Most of us in this room over the age of 50 are probably suffering from some form of high cholesterol and high blood pressure. Half the planet is on medication. And when you go to a primary care physician, even though you are being prescribed those pills, if you are generally in good shape, they are going to say, go ahead and dive. However, I do believe those folks are still at a higher risk of a cardiac event during diving. So I support 100% the idea that it should not be a primary care physician. If we are going to look at cardiac health, it should be either a cardiologist or a cardiac specialist and/or diving physician. DAN has a list of criteria that we have to meet as fitness for diving on a stress test. And those are not tests that your primary care physician will do unless you are complaining about certain symptoms. I feel if we just get a form from a regular doctor, the number of incidents will not be reduced or very slightly.

SIMON MITCHELL: Primary care doctors look after cardiac health all the time. I think we are getting mixed up here between health surveillance, which is keeping an eye on you even when nothing has gone wrong, and what happens if you have had an event and need to be reassessed for diving. That is clearly part of the "when you go to a diving medicine physician if appropriate." But the day-to-day or year-to-year evaluation of cardiac health is the role of the primary care physician. And if we try to prescribe to us as a group -- how many of you in this room are going to go to a cardiologist every year because the Rebreather Forum 4 proceedings say you should do it? That is not going to happen. Whereas, we should all be seeing our primary care physicians, have our blood pressure taken, and those kind of things, cholesterol measured regularly. So that is the point. It is the difference between the response to an event. I think Peter Germonpre's point is valid, and we will find a way of wordsmithing that. Instead of having the words "if appropriate," it will be something like, "if the evaluation is in the context of a cardiac or diving event, then it should be a diving medicine physician." But routine healthcare is your primary care physician's role and advocating for us all to go to a cardiologist every year, it is just not going to fly and it is not actually medically appropriate.

ALEJANDRO GARBINO: I do not want to get involved in a quagmire. Can we just say something like, "based on the assessment of an individual's risk factors for diving by their physician."

SIMON MITCHELL: No. It is risk factors for diving. It is risk factors for cardiac events during diving. It is not risk factors for diving. These are not diving medicals. We are not talking diving medicals here. We are talking about monitoring this particular risk factor for fatalities during diving, which is a cardiac event. And you do not need to be a diving medicine physician to do that. But I do agree with Peter and Ron, that the response or evaluation after some kind of an event should be the province of a diving medicine physician.

RICHARD PYLE: If it is just a wordsmithing thing, cannot this be simplified by replacing "primary care physician" by a "qualified physician" or "appropriately qualified physician." Why specify specifically primary care physician? Why not leave it open to determine who the right physician is by the context of the situation. And that way you can get rid of that "or a diving medicine physician if appropriate" too. Just say, "by a qualified physician" and then leave qualified up to the beholder.

SIMON MITCHELL: We could do that. I think that it is a general principle in medicine that people should be seeing their primary care physician for this exact purpose on a regular basis. But I can tell you that in the medical world that would be considered a bit of a copout because it is not really directing people where they should go.

FRAUKE TILLMANS: I am feeling that there is a misunderstanding in the room now talking about cardiac health, which I am 100% for to keep this in here, and the recommendations that every country or association, the UHMS has a few different ideas, in Germany everything is different, and the UK handles it differently. What if we put in the statement as we had it before, but then add "this does not replace or is not a substitute for the recommendations of your organization" or something to that.

SIMON MITCHELL: I doubt very much whether there are substantial differences in beliefs around people seeing their primary care physician for cardiac health evaluation.

FRAUKE TILLMANS: I get that. I am not disagreeing with you. The cardiac health follow-up is pretty much the same everywhere around the world, but I think we should make clear that we are not talking about a diving physical.

SIMON MITCHELL: Cardiac health surveillance, that would identify the issue. It is not all medical problems. It is cardiac health that is the biggest medical factor in diving fatalities.

FRAUKE TILLMANS: I like that.

LANDON LASSITER: I think there is a disconnect here and some people are associating the specific cardiac health risk that we are looking at with general diving physicals and the general nature of diving. Aside from that, I have seen a couple comments that these should be done by a diving medicine physician. The problem with that, in some areas, is the access to a dive medicine physician. There is a very limited number in most countries. Even in a place like the US, it is not a practical option for a lot of people simply because there might not be a diving medicine physician within hundreds of miles.

SIMON MITCHELL: I agree with that. I think we are getting to a place though where we can wordsmith it to put the responsibility for routine surveillance for people who have not had any issues where it should be, which is the diver's regular doctor. But if there is been an event, like immersion pulmonary edema or a heart attack or whatever and the diver is contemplating returning to diving, that is the province of a diving medicine physician.

JACEK KOT: When concerning physicians, we are trying to prepare guidelines for worldwide recognition, however, we cannot get to this consensus even within Europe. My proposal is to put the most important part, that this physician is aware about the purpose of this evaluation. It can be the primary care physician or the diving medicine specialist. He or she can refer to another specialist. As I said, the most important is that this evaluation is done for diving purposes. So my proposal would be to a place by the physician aware about the purpose of such evaluation. Are you following me?

SIMON MITCHELL: I am following you, but you are saying this is a diving medical, which it is not. What we are trying to do here is make sure people are being monitored for their cardiac health on a regular basis.

JACEK KOT: Yes, but this cardiac evaluation must be done with knowing that this person is a diver. So this is not a general cardiac evaluation by the primary care physician.

SIMON MITCHELL: Why does that make a difference, Jacek?

JACEK KOT: Because there are specific causes concerning diving, for example, with beta blockers or some other drugs. This cardiac evaluation is preparing for deep diving operations.

SIMON MITCHELL: We could go down that road. I think the concern here is that there are too many of us who are not having regular health evaluations. And if we make this the province of a diving medicine physician, we are going to be right back in that place.

JACEK KOT: I am talking that the physician who is doing such evaluation must be aware that this is done for diving.

SIMON MITCHELL: But if they are not a diving medicine physician, how would they interpret that information?

JACEK KOT: They can defer to a diving medicine physician. Maybe you do not agree with me, but I know this problem and the long lasting concern of what does it mean to be a, "qualified physician for evaluation of a diver."

SIMON MITCHELL: This is not a diving medical. It is a routine health surveillance.

JACEK KOT: Okay. I am not pushing; just commenting. And the second point is, why we choose the 45 years? I understand that 45 years is for otherwise healthy person. So even if you do not have any diagnosed disease or symptoms or on any drugs?

SIMON MITCHELL: Forty-five years is a recognized inflection point for cardiac risk to increase, particularly in males, not so much in females. But most of us are males so I did not think we would distinguish there. I am somewhat surprised that this is such a controversial thing. If we cannot come to a consensus, I am happy to ditch it, but I think that that would be a loss. This is why cardiac issues are a problem in diving, because there are too many divers who are not being seen regularly. But the minute we make it a requirement that it is has to be a diving medicine physician, the same problem is going to occur partly for the reasons that were raised before.

JACEK KOT: Maybe I was not clear. Divers older than 45 years even if healthy.

SIMON MITCHELL: That is easy to address, "Even in apparently good health." We will find a way of capturing the times when it should be a diving medicine physician.

PASQUALE LONGOBARDI: I completely agree that the check of the cardiac health by a cardiologist is good. I completely disagree on the "by primary care physicians" because they do not know our standard. I am sure that you know that the marker that makes us a community is the level of PO_2. Primary care physicians do not know the requirements for diving. And diving medicine physician is just part of our consideration. So the first part is not enough and the second part is too much.

SIMON MITCHELL: I believe you are confusing what I am saying here with a diving medical. These are not diving medicals. This is routine.

PASQUALE LONGOBARDI: I understood. But the problem is when I receive a stress test by a cardiologist, it is very useless for me sometimes because they do not know the requirements of the diving. As Jacek said before, we give guidelines to the primary care physician how to do the test for us. Otherwise, it is useless.

GAVIN ANTHONY: One of the first things, this is not a diving medical conference. It is a rebreather forum. I propose to simplify this by removing the second sentence and replacing it with, "this is separate from any requirements for a routine diving medical."

SIMON MITCHELL: Yes, that would work. The thing that we are stuck on is who does it. So it is separate from diving medicals or medical evaluations following diving or cardiac events, which would need specialist evaluation. Does that make sense? Or is that still too complicated?

NEAL POLLOCK: It is too complicated. If you want to simplify the language above, you can say annual and biennial, the latter being the right word for every two years. This is supposed to be a high level statement.

SIMON MITCHELL: Should we just get rid of it completely?

NEAL POLLOCK: Get rid of it completely. The fundamental point is that you should be surveilled. It is getting too complicated.

SIMON MITCHELL: Okay. I am happy with that. I like it, actually.

ATTENDEE: One other thing is because you have placed a reference to a published text in one of the previous statements, why not use the ones that you published with Fred Bove on cardiac evaluation.

SIMON MITCHELL: We will add references in there. And, actually, they explain the issues we have been debating and will probably result, if consulted, in channeling the diver in the right direction. That all sounds good. Who agrees with that statement now? Anyone disagree with it? Just one. Accepted.

The next is a statement that Gareth proposed that came out of his presentation on human factors. It is essentially a way of channeling our thinking about accident analysis so we do not just focus too much on physiological and circumstantial events around the accidents themselves, but we look at additional factors that may contribute.

"Analysis of accident, incident, and injury data from rebreather incidents should consider wider contextual error producing conditions and not just proximal and physiological contributory factors."

DOMINIC HOUSIAUX: I understand what Gareth is trying to do here, but the language is arcane. I recommend, "wider contextual conditions and physiological contributing factors" to simplify.

SIMON MITCHELL: What about "wider contextual error producing conditions." What can we use instead of proximal, Gareth?

GARETH LOCK: I used proximal because it is in one of the papers that talks about the cause of death and normally proximal causes.

SIMON MITCHELL: Yes, it is always proximal causes in some way. What could we substitute for clarity?

GARETH LOCK: It is time and space that we are talking about. So "local time and space."

SIMON MITCHELL: What about "circumstantial factors"?

GARETH LOCK: "Immediate."

SIMON MITCHELL: What about "immediate circumstantial"? Does anyone disagree with this statement as it currently stands?

ANDY PITKIN: I would take out the word "physiological," not just "immediate contributory factors."

MATT JEVON: I think there are three areas that we are not really addressing in this analysis of behavior, psychological, sociological, and cultural. We have addressed medical, physiological, systems, and technology. I think we need to assess the additional factors if we are going to consider why do divers do these things and what are the processes behind their decision-making,

SIMON MITCHELL: Sure. Would you, Gareth, suggest that those issues just raised would fall into that category of wider contextual?

GARETH LOCK: It really does depend. I agree with Matt in terms of those factors. It is a question of how much detail do you want to put in here.

SIMON MITCHELL: That is right. They are intended to be high level statements. I think your key point is that we should be looking at that wider picture and not just the narrow details of the accident itself.

GARETH LOCK: Absolutely. And when I talk about system, it is all the way down from government and cultural.

SIMON MITCHELL: Right. So I think in order to convey your message, this probably stands adequately on its own, does it not?

GARETH LOCK: It does. And it needs to basically be expanded in whatever text follows on from that.

OSKAR FRÅNBERG: I completely agree with this statement, but accident investigations, especially for fatalities, are often driven by the police or authorities, and then end up in legal issues where if you contextualize too much, you might end up in speculation. So you are often forced to just state the obvious aspects of it. I would like to see some kind of "where legally appropriate" or similar.

SIMON MITCHELL: I am not sure how that would fit into this fundamental message that Gareth is trying to convey here, which is basically a caution to not be too narrowly focused on the circumstances of the accident itself, and that there is a system involved that you need to think about. I think introducing legal consideration into that might be tricky. Clearly, that will be an influence in how that plays out, but whether we need to say it here is another story.

GARETH LOCK: The point here is that it is not just about fatalities. Fatalities really invoke a lot of the legal stuff. There is a huge amount to be learned from near misses. And that should not be invoked, but we should include the context and the error producing conditions. Legal issues will be covered in my paper.

SIMON MITCHELL: Are you happy that this conveys your message?

GARETH LOCK: I am.

SIMON MITCHELL: I think we will try not to incorporate legal.

FRAUKE TILLMANS: My only suggestion to close that loop would be to add something like "where feasible."

SIMON MITCHELL: To which bit?

FRAUKE TILLMANS: At the end of the sentence.

SIMON MITCHELL: "Should" and "where feasible" kind of mean the same thing. I think we are probably overcomplicating the statement. I think we will vote on this. Who agrees with this statement? Who disagrees? There is a few abstainers and a few people not quite sure, but the majority is in favor.

The final one is an engineering statement.

"The forum recognizes the potential safety advantage of inhaled side CO_2 or scrubber monitors, but acknowledges that they will fail to detect some sources of inhaled CO_2."

This has been intentionally worded to be relatively soft. It is not a statement that rebreathers should have them. It is a statement of the potential safety advantage while acknowledging what is essentially their primary weakness.

ANDY PITKIN: I think you could change "inhaled CO_2" at the end to "hypercapnia."

SIMON MITCHELL: Yes. "Inhaled sources of CO_2 or hypercapnia." Because it specifically does not detect some sources of inhaled CO_2 or some sources of hypercapnia. That is a good addition.

CHAUNCEY CHAPMAN: They "may fail to detect."

PETER GERMONPRE: "May fail to detect some causes of hypercapnia."

SIMON MITCHELL: I am happy with that, but I think some people would like to isolate the fact that they do fail to detect some sources of inhaled CO_2. Is anyone going to put up their hand if I just make it "some sources of hypercapnia?" If no one is going to object to that, I am happy with it. "Some causes of hypercapnia." Yes. Simple. All those who agree with this statement? And those who disagree with it? Fantastic. Accepted. That brings us to the end of the prepared statements.

MICHAEL MENDUNO: This was a recommendation in the RF2 meeting on safety, "*Team diving, full-face mask, and mouth straps can impact safety*." Team diving was mentioned in several presentations here. Obviously, people solo dive. In our pre-conference survey I think 40-50% reported regular solo diving. We also know that a high percentage in fatalities involve solo diving. I would like to see if we can reach a consensus to say that solo diving increases the risk in rebreather diving. This does not mean you cannot do it. It just means we acknowledge that team diving, and this is appropriate team diving not being buddied with a random person you do not know, but having a team, it is a safety factor. I would like to see this as a consensus statement. It could be a very simple statement that that we acknowledge that either team diving can reduce risk or solo diving increases risk of rebreather diving.

RICHARD PYLE: I know of at least one incident where a diver died because he was in a team who probably would not have died if he was not in a team. I know that is a controversial statement. If you want to know the details, they are published. I do not disagree with that statement as written. I just want to caution that we do not get too far down a path of interpreting situations blindly.

GARETH LOCK: Michael Menduno and I talked about this at lunchtime.

"Solo diving reduces the resilience in the event of failure following rebreather diving."

It is about the capacity to fail safely. Solo diving reduces the resilience in the event of failure of a rebreather system. The goal is to make it useful for people about either increasing the risk margin or reducing resilience.

NEAL POLLOCK: If this is going to go in, it has to be clear language. The word "resilience" is unnecessary. "The forum recognizes" can also be added in front.

SIMON MITCHELL: You mean increases the risk?

NEAL POLLOCK: Yes.

MICHAEL MENDUNO: That we acknowledge that the risk is increased while solo diving a rebreather.

SIMON MITCHELL: Michael, you have had this discussion with Gareth. Are you comfortable with changing that back to simpler language?

MICHAEL MENDUNO: Yes. I think the point is that we acknowledge that it can or does increase one's risk. We are not telling people they cannot do it, but that there is more risk if you do it.

SIMON MITCHELL: Okay. We will go back to simpler language. So, "Increases the risk."

CAMILO SARAIVA: To increase the acceptance, instead of negative of the solo diving, it should be in the positive.

SIMON MITCHELL: Are you comfortable with that, Michael?

MICHAEL MENDUNO: Stating in the positive, that team diving -- we acknowledge that team diving can reduce the risk of rebreather diving?

NEAL POLLOCK: The problem is if you start talking team diving, do you say that a buddy pair is safer than a trio? No, this one should be in the negative. This is about solo diving. Solo diving increases the risk.

MICHAEL MENDUNO: What you said.

ANDY PITKIN: I am high risk rebreather diving the day after tomorrow. What I would like this to say is, solo diving highly increases the risk of a fatality from a rebreather incident.

SIMON MITCHELL: I think that was Gareth's resilience message. Fair enough.

ANDY PITKIN: It does not change your risk of having an incident. It changes your ability to survive it.

MICHAEL MENDUNO: I am good with that.

SIMON MITCHELL: "*The risk of a fatality in the event of a rebreather diving incident is higher*."

RICHARD PYLE: Following the practice you did on several earlier points, can you include the references to published data that shows this to be a true statement? And if no such data or published references exist, could you add the word "may" because at that point you are speculating this to be the case. I am saying this because you know a lot of my philosophy has to do with anecdote, and I get criticized for that. So I want to know the difference between points that are supported by actual published data as opposed to points that are supported by intuition and casual experience.

SIMON MITCHELL: That is a very good point.

RICHARD PYLE: I do not want to be misquoted here. I personally believe it is a true statement, but I am only looking for consistency when we make declarations to make distinctions between "may," which means we think it is probably true, and "does," which means we have evidence to support it to be true.

SIMON MITCHELL: Fair enough. Is there anyone who disagrees with that statement?

ATTENDEE: I work in risk management. My comment is that if you are looking at this from a risk perspective, you have to consider the overall risk to the team, not just to the individual in trouble. What I mean by that is that the person helping a diver who is in stress is increasing his or her risk tremendously. The overall risk to the team might not necessarily be less, but to the solo diver, the person in trouble, yes, there can be some advantage there. You need to analyze all the factors included. So what is the benefit to the person in trouble versus the risk to the person who is not in trouble trying to rescue someone from 150 m (492 ft) on a dual rebreather in a cave. If you want to do a risk analysis that you look at it from that point of view as well. Because you may end up with two dead people instead of one.

SIMON MITCHELL: I think that is a separate issue and that all is covered by the "may" wording.

MICHAEL MENDUNO: I, too, think that is a separate issue and discussion. We are just trying to make a high level statement. A rescue effort introduces its own risk, but that is a rescue. Stuff is going to happen and people are going to get into trouble.

RICHIE KOHLER: But if you are alone, you are dead. End of subject, you are dead. So there is an option for life if you are with a buddy.

GAVIN ANTHONY: Statistics have been published for the last 30 or 40 years. In the last 20 or 30 years every year it says solo diving is a higher risk.

SIMON MITCHELL: It says that, but how is the conclusion reached? Is it anecdote or is it based on accurate numerators and denominators?

GAVIN ANTHONY: It is based on analysis of the incidents, and on how many of the fatalities are solo diving compared to conventional buddy diving.

SIMON MITCHELL: So the question then is are you suggesting we get rid of "may" out of there?

ATTENDEE: No. I am suggesting that there are references that can be included.

MARTIN PARKER: I think from the people around me that it is actually the idea that solo diving increases the risk is the issue. If we just take out the word "risk" and change it to "likelihood of a fatality."

CHARLES ROBERSON: Sorry, I have to disagree with the likelihood of an event. I think we should take that out. I think team diving can prevent an event. So I think that solo diving increases the overall risk, not just the risk of a fatality in an event, because it can actually prevent an event.

SIMON MITCHELL: We can all conjure up scenarios in which all of these things would be true so we can simply say, "likelihood of incidents or fatalities."

DAVID DOOLETTE: From the point of view of a statistician, it is just simply not true. If you have two rebreather divers, you have a higher likelihood of an incident. You have got two rebreathers, more chance of one of them failing. So the whole thing is what Gareth originally said and what Andy said was that you increase the likelihood of that going bad. I like the wording we were a few minutes ago, "*the likelihood of a fatality in a rebreather diving incident*."

SIMON MITCHELL: "O*f a fatality in the event of a rebreather diving incident*." All right. Who agrees with this statement? Lots of people. Who disagrees? There are a few, but it is an overwhelming consensus.

[End of discussion.]

APPENDIX A
LIST OF ACRONYMS AND ABBREVIATIONS USED

AAUS — American Academy of Underwater Sciences
ADCI — Association of Diving Contractors International
ADV — automatic diluent valve
AGE — arterial gas embolism
ALARP — as low as reasonably practicable
ATA — atmospheres absolute
atm — atmosphere(s)
AUV — autonomous underwater vehicle
BC — buoyancy compensator
BCD — buoyancy compensating device
BOV — bailout valve
BPSK — binary phase-shift keying
BSAC — British Sub-Aqua Club
BT — breakthrough
CAUS — Canadian Association for Underwater Science
CE — Conformité Européenne
CC — closed-circuit
CCR — closed-circuit rebreather
CMAS — Confédération Mondials Des Activités Subaquatiques
CMUT — Capacitance micromachined ultrasonic transducers
CNS — central nervous system
CO_2 — carbon dioxide
COBRA — compact bailout rebreathing apparatus
COD — cause of death
COMEX — Compagnie Maritime d'Expertises (France)
CPR — cardiopulmonary resuscitation
CRM — crew resource management
CSA — Canadian Standards Association
DAN — Divers Alert Network
DCB — Diving control board
DCIEM — Defence and Civil Institute of Environmental Medicine
DCS — decompression sickness
DIN — Deutsche Industrie Norm
DNC — Diving and Naval Medicine Centre (Sweden)
DOI — digital object identifier
DP — dive plan
DPV — diver propulsion vehicle
DSO — diving safety officer
DSV — dive surface valve
EAP — emergency action plan
eCCR — electronic closed-circuit rebreather (or electronically-controlled closed-circuit rebreather)
ECG — electrocardiogram/electrocardiography
EDSP — European Scientific Diving Panel
EMT — emergency medical technician
END — equivalent narcotic depth,
EOD — explosive ordinance disposal

eSCR — electronically-controlled semiclosed-circuit rebreather
ESDP — European scientific diving panel
EMS — Emergency medical services
EUBS — European Underwater and Baromedical Society
FFESSM — Fédération Française d'Études et de Sports Sous-Marins
ffw — feet of freshwater
F_IO_2 — fraction of inspired oxygen
FFM — full-face mask
fNIRS — functional near-infrared spectroscopy
FRED — failsafe rebreather for exploration diving
fsw — feet of seawater
ft — feet
FT — factory trainer
GDPR — General Data Protection Regulation
GF — gradient factors
GPRS — general packet radio service
GPS — global positioning system
GSM — global system mobile
GUE — Global Underwater Explorers
h — hour
H_2 — hydrogen
He — helium
He-O_2 — helium-oxygen
HFACS — human factors and analysis classification system
HPNS — high-pressure nervous syndrome
HR_{ex} — exercise heart rate
HRR — recovery heart rate
HRV — heart rate variability
HSE — Health and Safety Executive
HUD — head-up display
IAND — International Association of Nitrox Divers
IANTD — International Association of Nitrox and Technical Divers
IEDCS — inner ear decompression sickness
IHMC — Institute for Human and Machine Cognition
IPAVA — intrapulmonary arteriovenous anastomoses
IP — Intermediate pressure
IPE — immersion pulmonary edema
ISO — International Standards Organization
KM — Kisman-Masurel
kPa — kilopascal
LEM-he8n25 —
LiDAR — light detection and ranging
m — meter
MAV — manual addition valve
mCCR — mechanical (manual) closed-circuit rebreather
mfw — meters or freshwater
MIE — minimum ignition energy
min — minute
MOD — maximum operating depth
MOF — metal organic frameworks
MRS — mouthpiece retaining strap

msw — meters of seawater
N_2 — nitrogen
NASA — National Aeronautics and Space Administration
NAUI — National Association of Underwater Instructors
NAVEODTECHDIV — Naval Explosive Ordnance Disposal Technology Division
NAVSEA — Naval Sea Systems Command (US)
NDIR — non-dispersive infrared
NEDU — Naval Experimental Diving Unit (US)
NMRI — National Medical Research Institute (US)
NOAA — National Oceanic and Atmospheric Administration (US)
NPS — National Park Service (US)
NSW — Naval Special Warfare (US)
NTS — non-technical skills
O_2 — oxygen
OC — open-circuit
ONR — Office of Naval Research (US)
OPRV — overpressure relief valve
OSHA — Occupational Safety and Health Administration (US)
PADI — Professional Association of Diving Instructors
PBT — pulmonary barotrauma
PCO_2 — partial pressure of carbon dioxide
P_{DCS} — probability of decompression sickness
PFO — patent foramen ovale
PH_2 — partial pressure of hydrogen
PMCID — PubMed Central identifier
PMID — PubMed identifier
PO_2 — partial pressure of oxygen
RAID — Rebreather Association of International Divers
RESA — Rebreather Education Safety Association
RF2 — Rebreather Forum 2
RF3 — Rebreather Forum 3
RF4 — Rebreather Forum 4
RGBM — reduced gradient bubble model
ROV — remote operated vehicle
RSTC — Recreational Scuba Training Council
RTC — Rebreather Training Council
s — second
SAIG — serious accident investigation guide
SCBA — self-contained breathing apparatus
SCR — semi-closed rebreather
SDV — SEAL delivery vehicle
SLS — secondary life support
SMB — surface marker buoy
SOP — standard operating procedure
SPM — simulated physical model
S_pO_2 — oxygen saturation estimated by pulse oximetry
SPUMS — South Pacific Underwater Medicine Society
SSI — Scuba Schools International
STPD — standard temperature pressure dry
TDI/SDI/ERDI — Technical Diving International/Scuba Diving International/Emergency Rescue Diving International

UBA — underwater breathing apparatus
UHMS — Undersea and Hyperbaric Medical Society
UTD — Unified Diving Team
UUV — unmanned underwater vehicle
VGE — venous gas emboli
VPM — varying permeability model
WOB — work of breathing
WRSTC — World Recreational Scuba Training Council
ZH-L16 GF — Zurich Linear 16-compartment gradient factors model

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APPENDIX C
RF4 CONFERENCE SCHEDULE
April 20-22, 2023
Valletta, Malta

Thursday, April 20

Session Chair - Neal Pollock

0900-0915	Opening remarks	
0915-0945	Overview of rebreather diving	Michael Menduno
0945-1100	Hazards in rebreather diving	Neal Pollock
1100-1130	*Break/Exhibitors*	
1130-1230	Accident review - the safety situation	Frauke Tillmans
1230-1315	Human factors in rebreather diving	Gareth Lock

Session Chair - John Clarke

1430-1530	Military diving with rebreathers	Vince Ferris/Oskar Franberg
1530-1630	Equipment options for diver safety	Pete Mesley
1630-1700	*Break/Exhibitors*	
1700-1800	Bailout strategies	Andy Pitkin
1800-1830	Mixed platform/mode diving	Mauritius Bell

Friday, April 21

Session Chair - Simon Mitchell

0830-0930	Advances in decompression theory and practice	David Doolette
0930-1030	CCR training	Mark Caney/Sean Harrison/Paul Toomer
1030-1100	*Break/Exhibitors*	
1100-1200	Developments in CCR diving/equipment	Kevin Gurr
1200-1245	Developments in CO_2 monitoring	Simon Mitchell

Session Chair - Neal Pollock

1400-1500	Demystifying scrubbers	John Clarke
1500-1600	Emergency procedures	Richie Kohler
1600-1630	*Break/Exhibitors*	
1630-1715	Thermal management	Neal Pollock
1715-1800	Use of CCRs in Malta shipwreck diving	Timmy Gambin

Saturday, April 22

Session Chair - Frauke Tillmans

0830-0900	School of diving safety and medicine	Simon Caruana
0900-1000	Near future of physiological monitoring	Rachel Lance
1000-1030	Blue sky future CCR technologies	Phil Short/Kevin Gurr
1030-1100	*Break/Exhibitors*	
1100-1200	Real time physiological diver monitoring	Alessandro Marroni
1200-1245	Priority list straw man	Simon Mitchell

Session Chair - Simon Mitchell

1400-1600	Consensus list discussion	
1600-1630	*Break/Exhibitors*	
1630-1745	Consensus statements discussion	
1745-1800	Concluding remarks	
1930-2230	Banquet / Hydrogen diving	Richard Harris

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