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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.

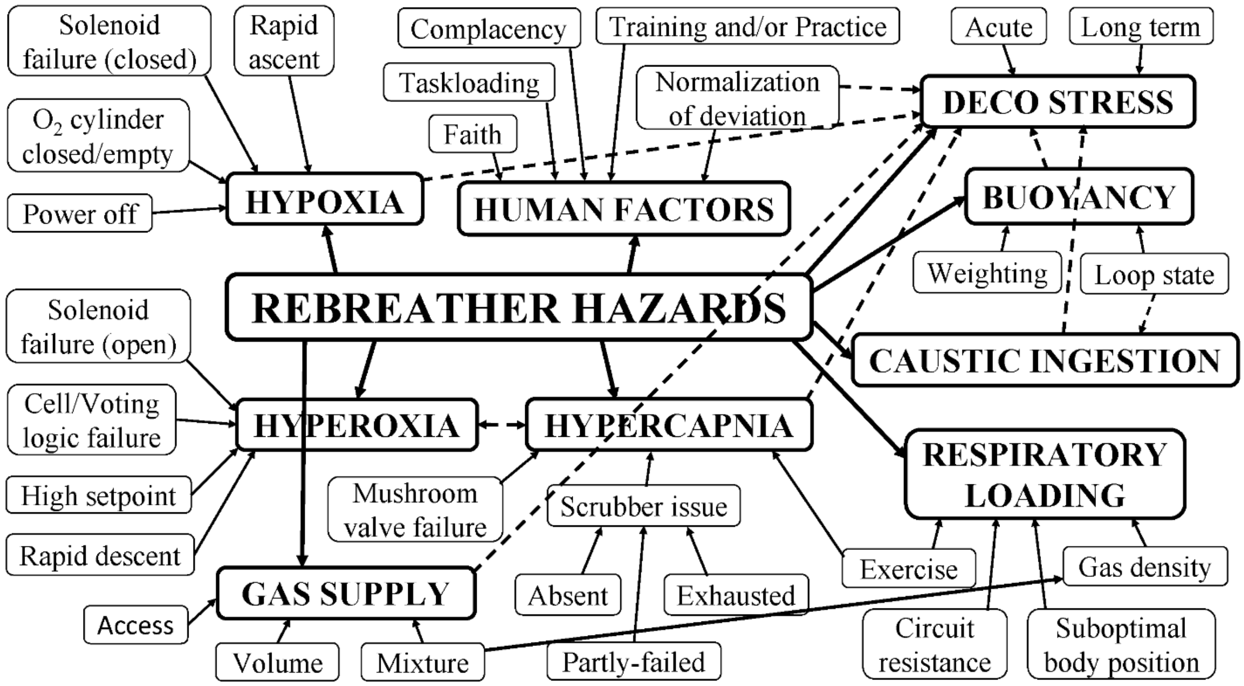

Figure 1. Summary of rebreather hazards and common or contributing factors. Primary relations between factors are indicated by solid lines; secondary relations between factors are indicated by dashed lines.

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).

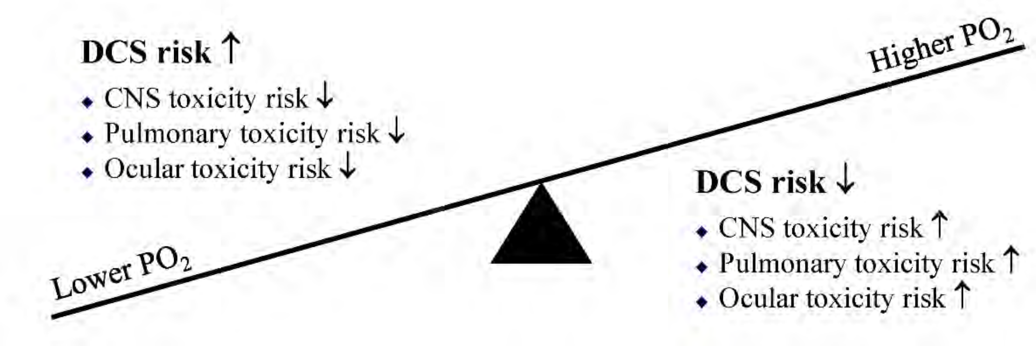

Figure 2. Risk balance schema for oxygen setpoint selection. High PO_2 offers both benefits and risks to divers. A reduction in decompression stress is balanced against an increased risk of oxygen toxicity. Acute oxygen toxicity risk climbs with PO_2 >1.4 atm. Oxygen toxicity risk is reduced by lower 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.

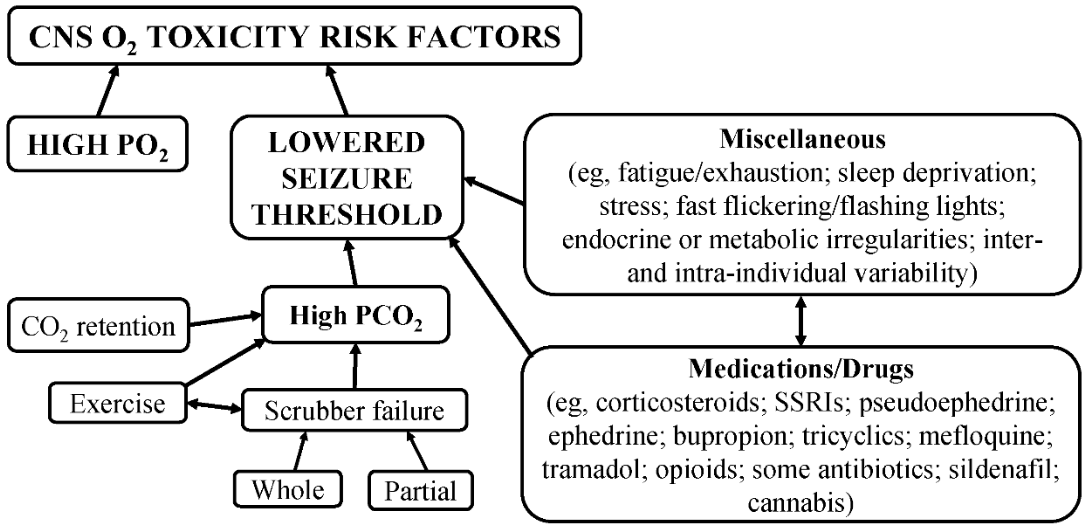

Figure 3. Central nervous system oxygen toxicity is primarily driven by elevated PO_2, but many factors can increase the risk by lowering the seizure threshold. Duration of exposure can also play an important role.

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 $g \cdot L^{-1}$) is much less dense than either nitrogen (1.251 $g \cdot L^{-1}$) or oxygen (1.428 $g \cdot L^{-1}$), 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."

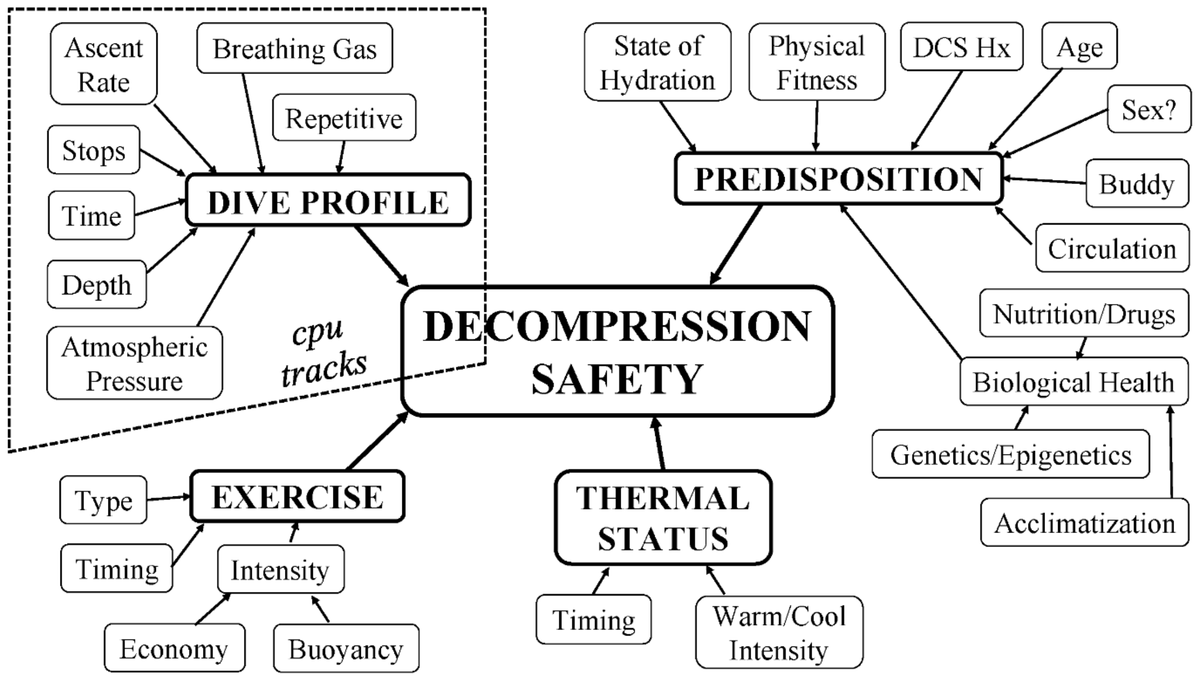

Figure 4. Factors in decompression safety. The dashed line indicates the factors tracked by dive computer algorithms. The remaining factors are not effectively captured or considered in any decompression models (Pollock 2016).

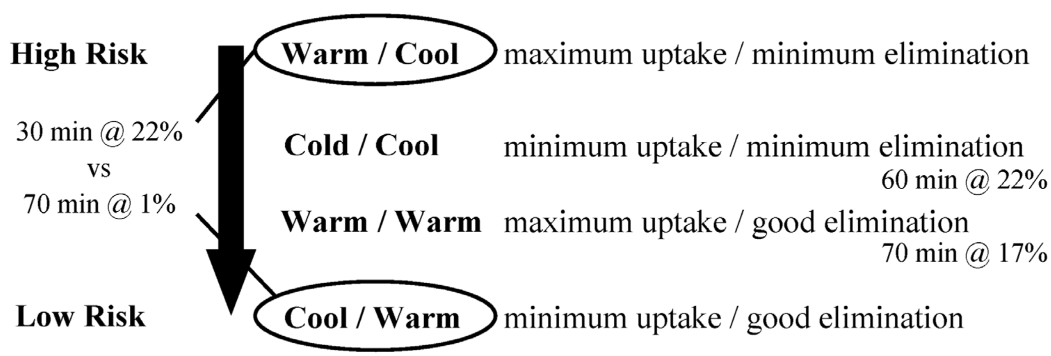

Figure 5. Thermal status and decompression stress in exercising dives to 37 msw (120 fsw) conducted in a controlled wet hyperbaric chamber. The maximum bottom times and percentage of subjects developing symptomatic DCS are presented for each of the four thermal combinations of descent/bottom and ascent/decompression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