Hypoxic loss of consciousness in air diving: two cases of mixtures made hypoxic by oxidation of the scuba diving cylinder

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Abstract

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Without an adequate supply of oxygen from the scuba apparatus, humans would not be able to dive. The air normally contained in a scuba tank is dry and free of toxic gases. The presence of liquid in the tank can cause corrosion and change the composition of the gas mixture. Various chemical reactions consume oxygen, making the mixture hypoxic. We report two cases of internal corrosion of a scuba cylinder rendering the respired gas profoundly hypoxic and causing immediate hypoxic loss of consciousness in divers.

Introduction

There are multiple factors that could cause loss of consciousness (LOC) while diving. However, in most cases of LOC, the cause remains unknown. A wide variety of reasons can be mentioned, but many such events probably result from cardiac causes (such as myocardial ischaemia, arrythmias, pulmonary edema, vasovagal syncope) with immersion and exercise as likely provocation factors. However, when LOC occurs at the surface or early during descent the question arises as to whether it was coincidental or had a causality related to the gas mixture breathed by the diver. Death due to drowning is a major risk if unconsciousness occurs underwater.

Loss of consciousness while diving is rare. Causes other than cardiac events (mentioned above) are hypoxia, toxic gas effects and arterial gas embolism. Use of rebreathers is commonly described.[1] Hypoxic accidents are also well known in the breath-hold diving community.[2,3] Immediate LOC after breathing gas from a the scuba cylinder suggests possible inappropriate composition. Loss of consciousness caused by hypoxia due to corrosion of the tank was first (and only in our opinion) described in 2008 after a diving fatality.[4] Such cases are rare.

In these two reports we describe immediate LOC after breathing air on open-circuit scuba. Case 1 is older and it was not possible to obtain patient consent for publication. The patient in case 2 consented to publication of the case history.

Case 1

The patients were a middle age adult male who was an experienced diver and his early adolescent son, also diver. Both had no medical history.

While testing new diving equipment (a buoyancy control jacket) in his swimming-pool, the father suggested his son try it with his own scuba cylinder. The cylinder gas pressure was 60 bar, which was considered enough for the test. After a few breaths from the regulator, the son suddenly lost consciousness. He was immersed with the head above the water. After removal of the regulator he quickly regained consciousness without any resuscitation measures; he had no ongoing symptoms. Then, the father, partially immersed in the pool, decided to test the new jacket. He also lost consciousness in the minute that followed. As with his son, he regained consciousness after removal of the scuba regulator a few minutes later, without any resuscitation. The two divers were checked at the hospital. Medical assessment was normal. No complications were reported.

Table 1
Analysis of gas in the scuba cylinder case 1; ppm – parts per million; VOC – volatile organic compound

Parameters	Measured values	Limit values	Measurement method
Oxygen	0.9%	20.5 to 21.5%	Electrochemical cell
Carbon dioxide	5 ppm	500 ppm	Infra red
Carbon monoxide	21 ppm	5 ppm	Infra red
Moisture	1283 mg·m^3	100 mg·m^3	Hygrometry
VOCs	607 mg·m^3	< 5 mg·m^3	Flame ionisation
Hydrogen	0.5%	0	Gas chromatography

Analysis of the gas contained in the tank was performed by a Navy specialised laboratory, LASEM (Laboratoire d'Analyse, de Surveillance et d'Expertise de la Marine), Toulon, France. Pressure in the cylinder was 25 bars and the oxygen level was almost zero. Hydrogen, carbon monoxide and volatile organic compounds were found in large quantities, outside acceptable tolerance limits. Moisture was also very elevated (Table 1).

After cutting the cylinder open, 300 ml of a brown and viscous liquid were recovered. Significant corrosion was covering the entire wall (Figure 1).

Figure 1
Internal condition of the scuba cylinder from case 1

Case 2

The patient was a 51-year-old man; an experienced dive instructor (more than 1,000 dives). While preparing to dive he noted that the cylinder pressure was only 100 bars, not enough to dive as expected. So he changed the cylinder with the 'safety scuba tank' off the boat, which contained 140 bars. Immediately after initiating descent he remembered performing a Valsalva manoeuvre after which he lost consciousness. He was retrieved unconscious by another diver, from 14 msw, without the regulator in his mouth. His buddy performed a control lift to the surface where the rescued diver was not breathing and there was pink foam around his lips. The rescuer performed mouth-to-mouth resuscitation. The rescued diver regained consciousness, and breathed again. He was evacuated to a hyperbaric facility.

Initial assessment reported tachypnoea and crackling lung sounds, a facial barotrauma with a conjunctival hyperaemia, and bilateral barotrauma of the ears and sinuses; the patient was conscious with a complete amnesia of the event. Cerebral and chest computed tomography conducted in the following hour showed diffused sinus haemorrhage, right exophthalmos caused by orbital hemorrhage, and diffuse infiltrate of the alveolar and interstitial pulmonary tissue.

The cylinder gas was analysed by LASEM (Table 2). Cylinder pressure was 185 bar; initial pressure was about 140 bar and the tank has been refilled with air after the accident. Despite this, the oxygen content was only 8%. Hydrogen and volatile organic compounds were found in large quantities, outside usual tolerance limits. Moisture was also very elevated.

Before cutting the tank open, multiple gas analyses were repeated during eight weeks, and oxygen concentration was recorded. A progressive reduction in oxygen concentration was shown (Table 3). After cutting the tank open, 250 ml of a brown and viscous liquid (with a high salinity) was recovered. Significant corrosion covered the entire wall (Figure 2).

Discussion

Aviators can experience hypoxia while flying (cockpit depressurisation, failure of supplemental oxygen systems). A variety of personal symptoms, referred to as the 'hypoxia signature' is detected by training in a hypobaric chamber among military aircrew. However, it seems very difficult for divers to detect suggestive symptoms of hypoxia in real time and perform self-rescue.[2] In these two cases, immediate loss of consciousness occurred without awareness.

Table 2
Analysis of gas in the scuba cylinder case 2; ppm – parts per million; VOC – volatile organic compound

Parameters	Measured values	Limit values	Measurement method
Oxygen	7.7%	20.5 to 21.5%	Electrochemical cell
Carbon dioxide	< 2 ppm	500 ppm	Infra red
Carbon monoxide	1.7 ppm	5 ppm	Infra red
Moisture	248 mg·m³	100 mg·m³	Hygrometry
VOCs	31 mg·m³	< 5 mg·m³	Flame ionisation
Hydrogen	1%	0	Gas chromatography

Figure 2
Internal condition of the scuba cylinder from case 2

Table 3
Oxygen fractions in the scuba cylinder from case 2 over two months of sequential oxygen content analyses

Analysis day	Oxygen fraction
1	7.68%
16	5.14%
27	4.55%
62	2.80%

Medical assessments of these three victims were normal, eliminating any medical concerns, especially cardiac disability. Biochemical etiology, and more specifically hypoxia, was suspected, and confirmed by gas analysis of residual gas in the cylinders. Hypoxic gas is defined by an inspired PO_2 less than 0.16 bars; below 0.1 bar, loss of consciousness is likely. Underwater, drowning is the main risk.

Liquid and moisture were found in the two scuba tanks. This internal contamination is abnormal. Severe corrosion of the steel tank is caused by iron oxidation with water. Many chemical reactions likely occurred but some of them are prone to consume oxygen and progressively render the 'air' (initially containing 20.92% oxygen) hypoxic.

Oxygen in contact with iron, when water is present, can lead to oxidation by sequential reactions:

$2H_2O + O_2 + 4e^- \rightarrow 4OH^-$
$Fe + 2OH^- \rightarrow Fe(OH)_2 + 2e^-$
$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3$
$2Fe(OH)_3 \rightarrow Fe_2O_3 + 3H_2O$

The global reaction leading to iron oxide, also known as rust, is:

$4\ Fe + 3O_2 + 6H_2O \rightarrow 4\ Fe(OH)_3$

The process consumes oxygen so concentration eventually tends to zero. As described, the rate of oxygen consumption is high: within two months, the oxygen concentration decreased from 7.68% to 2.80% in the cylinder. Total lack of oxygen during the incident dive seems plausible.

The corrosion process may also include a redox reaction that forms iron oxide and hydrogen according to the chemical reaction:[5]

$2Fe + 3H_2O \rightarrow Fe_2O_3 + 3H_2$

Hydrogen was identified in the cylinders in both above cases. Based on the experience of LASEM, when hydrogen is present in a steel-made scuba bottle, without any history of intentional hydrogen use, it strongly suggests an internal corrosion process.

The presence of carbon monoxide (CO) in the cylinder in case one is unexplained. Carbon dioxide combined to hydrogen can produce CO and water ($CO_2 + H_2 \rightarrow CO + H_2O$). However, carbon dioxide levels in the cylinder should have been low. It is also possible the CO detected could also be a contaminant introduced during tank filling.

Multiple chemical reactions may occur in a scuba cylinder contaminated by liquids, but the most significant result for health is the generation of a hypoxic breathing gas. In these two cases, hypoxic gas was the trigger of unconsciousness. Luckily, both cases had a happy ending with the divers being rescued by their buddy. An advanced protocol of gas/diving material analysis, usually performed by our team, allows us to explain this situation and provide preventive advice: systematic opening and inspection after water ingress and, as far as possible, a pre-dive oxygen check with a low-cost analyser before diving in case of any doubt about the internal condition of a scuba cylinder.

Conclusion

Consideration of the accident scenario plays an essential role in diving accident diagnosis. Immediate loss of consciousness without awareness at surface or during descent suggests a hypoxic breathing gas. To confirm this hypothesis, diving gas in the cylinder used by the victim must be analysed. The cylinder used by a buddy may constitute a useful reference.

In open-circuit scuba, regular maintenance and visual inspections of cylinders are key components of safe diving. Every cylinder must be carefully stored and maintained, especially those used intermittently such as safety tanks, to avoid a fatal outcome. Annual visual inspection is highly recommended.

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