Descriptive Epidemiology of 153 Diving Injuries With Rebreathers Among French Military Divers From 1979 to 2009

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4 authors, including:

Emmanuel Gempp
Sainte Anne Military Teaching Hospital

Pierre Louge
Hôpitaux Universitaires de Genève

Jean-Eric Blatteau

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Descriptive Epidemiology of 153 Diving Injuries With Rebreathers Among French Military Divers From 1979 to 2009

LTC Emmanuel Gempp, French Armed Forces Health Service, MC;*
COL Pierre Louge, French Armed Forces Health Service, MC;*
COL Jean-Eric Blatteau, French Armed Forces Health Service, MC†;
*BG Michel Hugon, French Armed Forces Health Service, MC**

ABSTRACT Introduction: Rebreathers are routinely used by military divers, which lead to specific diving injuries. At present, there are no published epidemiologic data in this field of study. Methods: Diving disorders with rebreathers used in the French army were retrospectively analyzed since 1979 using military and medical reports. Results: One hundred and fifty-three accidents have been reported, with an estimated incidence rate of 1 event per 3,500 to 4,000 dives. Gas toxicities were the main disorders (68%). Loss of consciousness was present in 54 cases, but only 3 lethal drowning were recorded. Decompression sicknesses (13%) were exclusively observed using 30 and 40% nitrox mixtures for depth greater than 35 msw. Eleven cases of immersion pulmonary edema were also noted. Conclusion: Gas toxicities are frequently encountered by French military divers using rebreathers, but the very low incidence of fatalities over 30 years can be explained by the strict application of safety diving procedures.

INTRODUCTION

Rebreather diving has become popular in the past decade and offers many advantages in comparison to open-circuit scuba diving, such as economy of gas consumption and reduction of decompression procedure by using oxygen-enriched breathing gas mixtures. However, this equipment requires specialized training and techniques more complex than scuba air diving, leading to more malfunctions and procedural errors with subsequent potential risk of drowning.

For more than 50 years, French military divers routinely use rebreather diving capabilities for their underwater operational activities and very often at the limits of their physiological conditions with respect to gas toxicity, dive duration, or the effort required. The rebreather systems used in the French army are currently all mechanically controlled devices made with nonmagnetic materials, which are selected according to the depth to be reached and the type of underwater military action. They include both closed-circuit rebreathers (CCR) and semi-closed circuit rebreathers (SCR).

CCR produce no bubbles and use pure oxygen appropriate for use at depths shallower than 7 msw due to concerns for CNS oxygen toxicity. They are worn in a prone position with a gas supply on demand mode: fresh oxygen coming from a small high-pressure cylinder is injected in the breathing bag through a flow valve to refill it when the volume of gas into the loop falls due to oxygen consumption. Exhaled breathing gases are purified by a scrubber canister that contains soda lime (Divesorb, Dräger, Luebeck, Germany), which fixes the CO_2 before the gas is returned to the breathing bag. Replacing the OXYGERS 57 (La spirotechnique, Carros, France) with the Full Range Oxygen Gas System (FROGS; Aqualung, Carros, France) in 2002 has increased the endurance of this equipment (up to 4 hours of use compared with 3 hours previously) and optimized breathing comfort.

SCR incorporate a counterlung designed as a bellows system with 2 concentric bags allowing the breathing gas to be periodically vented into the water through a relief valve in proportion to the volumetric ratio of the 2 bags (the working principle is discussed in greater detail elsewhere[1]). Additional breathing mixture is taken in from the cylinders by the contraction of the breathing bag via a flow injector that balances the gas leak. After several ventilatory cycles, the partial pressure of oxygen in the breathing bag is constant, but with a concentration in the gas mixture below that of the cylinders due to dilution of the breathing gas in the counterlung by exhaled gas. These devices operate with predefined gas mixtures that determine the maximum depth at which they can be used. The DC 55 (La spirotechnique) allows the diver to go down to 55 msw with oxygen-enriched mixtures (nitrox), and the MIXGERS (La spirotechnique) uses a trimix mixture containing 23% O_2, 37% N_2, and 40% He for deep dives between 55 and 80 msw. Both breathing apparatus were replaced in 2009 by the Complete Range Autonomous Breathing Equipment (CRABE; Aqualung), a new version of mechanically controlled device designed for the same specific tasks and capable of using nitrox or trimix gas mixtures to the same depths range.

A mixed device, the OXYMIXGERS (La spirotechnique), can be used in closed or semi-closed mode via a manual switch. The system is supplied with pure oxygen in closed mode to a depth limit of 7 msw or with nitrox 60% O_2 in semi-closed

*Department of Hyperbaric and Diving Medicine, Sainte Anne's Military Hospital, BP 20545, 83041 Toulon cedex 9, France.

†Institute of Biomedical Research in French Armed Forces, Toulon cedex 9, France.

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mode to a depth of 25 msw. It is designed exclusively for combat swimmers in their delivery submarine vehicle.

Although the number of diving fatalities increases each year with rebreathers, data regarding the source and specifics of accidents analyzed are scarce and often incomplete,[2,3] and to date, there are no published reports gathering information on the potential risks other than death. The intent of this study was, therefore, to determine the distribution of diving injuries involving rebreathers reported in French military divers over 30 years and to identify the triggering circumstances associated with the different adverse events that justify the keeping of strict safety procedures imposed by military diving regulations since many years.

MATERIALS AND METHODS

The study population consisted of French military divers certified for the use of rebreathers and divided into 2 subpopulations that are mine-clearance divers (MCD) and combat swimmers (CS). MCD (total number = 200) are trained for identifying, neutralizing, or destroying underwater explosive devices. They are qualified to work at depths of as much as 80 msw in "square" diving profiles. Nevertheless, the majority of their dives are performed with SCR using a nitrox mixture of 60% O_2 up to 25 msw for 3 hours or a nitrox mixture of 40% O_2 from 25 to 45 msw. Deep dives using nitrox 32 % O_2 between 45 and 55 msw and trimix mixture from 60 to 80 msw are relatively rare (4–8 dives per year per diver) and include extra safety precautions (support diver and decompression stops using surface-supplied oxygen). CS (total number = 100) conduct clandestine operations for counter-terrorism missions and for ground or amphibious reconnaissance purposes. They perform most of their dives at shallow depths in so-called horizontal diving profiles with CCR, but are also qualified to dive with SCR using nitrox mixtures and SCUBA air up to 60 msw.

Since 1979, each diving disorder was subject to a military and medical statutory declaration to identify potential failure equipment after careful investigation and to improve diving procedures. The information collected has given rise to a database used to produce a detailed retrospective analysis of registered cases. Each datasheet was subsequently reviewed by 1 of the authors (P.L.) to complete and update the initial declaration forms. For the purposes of this study, diving injury with rebreather was defined as a clinical adverse event that led to a hazardous behavior during diving or an emergency ascent assisted by the buddy if necessary.

The incidence rates (IR) of diving rebreather injuries were calculated using the number of injuries sustained by each population of divers as the numerator and the total number of dives performed in each subgroup over the study period as the denominator. Incidence rate ratios (IRR) were determined by dividing the rate of diving injuries in MCD by the rate in CS to quantify the increased or decreased risk of rebreather disorders associated with 1 subgroup of divers. Significant difference between IR was noted where the 95% confidence interval (95% CI) of the IRR excluded unity. The 95% CIs for rates and rate ratios were computed using standard large-sample formulas.[4]

RESULTS

Study Population and Diving Injury Incidence

Of the 362 declaration forms reported over 30 years, 153 (42%) concerned diving injuries involving a rebreather, with an average of 5 accidents per year (range 2–16). Almost two-thirds of the injured divers were MCD (69%, *n* = 106), whereas the remaining were CS (31%, *n* = 47). All subjects were men (but the advent of women as MCDs is extremely recent and only 2 women have been certified since 2006) with a mean age (SD) of 29 ± 5 years (range 20–47 years). In 76 cases (50%), the disorders took place during the intensive qualification training course that every MCD or CS candidate must complete at the diving school (Fig. 1).

The number of dives using rebreathers per year was estimated at 14,000 dives for MCD population (70 dives per year for each diver) and 5,000 dives for CS population (50 dives per year for each diver), leading to an overall incidence rate of diving rebreather injuries of 2.5 per 10,000 diver-exposures (95% CI: 2.1, 3.0) for MCD and 3.1 per 10,000 diver-exposures (95% CI: 2.2, 4.0) for CS. The IRR for MCD vs. CS was 0.8 (95% CI: 0.6, 1.1).

Distribution Frequencies of Diving Injuries

The distribution of rebreather diving-related injuries is summarized in Figures 2 and 3. Gas toxicities with a prevalence rate of 68% (*n* = 104) were the main causal factor associated with rebreather disorders. Hypercapnia during diving was listed in the majority of cases (62 out of 104, ie, 59%) and resulted in apparent breathing discomfort (air-hunger and breathlessness),

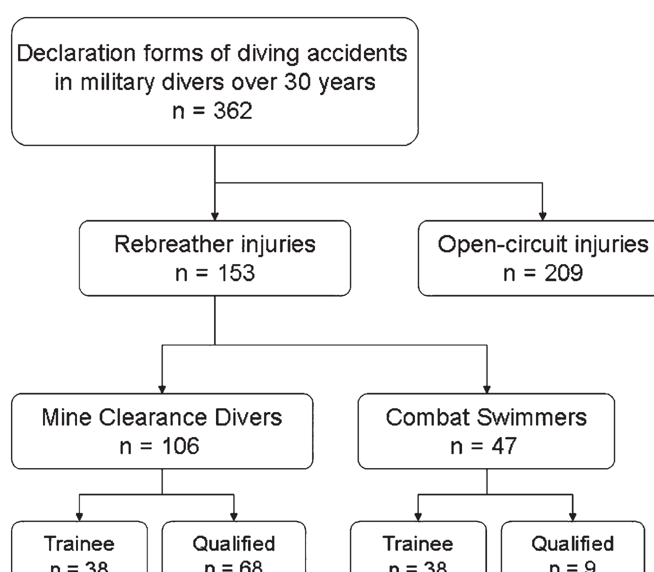

FIGURE 1. Diagram presenting the process of reviewing the declaration forms of diving accidents in French military divers from 1979 to 2009.

intense headache, and in some cases altered mental status and unconsciousness, leading to the dive being stopped and the injured diver being assisted during ascent by the buddy. CO_2 retention was determined as the common cause due to strenuous diving in 36 cases, whereas exogenous gas toxicity linked to inadequate CO_2 elimination (soda lime saturated at the end of a long dive, scrubber canister not renewed after each dive, or inoperative after water leaking into the circuit) was suspected in other cases. Acute hyperoxia was observed in 26 cases (25%) invariably revealed by a loss of consciousness followed by tonic–clonic generalized seizure, but rarely preceded by warning symptoms. This occurred either in water or on the surface, following rescue, on removing the mouthpiece. These disorders were particularly described before 2002 with the OXYGERS 57 ($n = 16$) after prolonged exposure (2–3 hours) at oxygen partial pressures, where effects of CNS oxygen toxicity are dominant (160–170 kPa) in combination with in a sustained physical exercise of fin-swimming. Some cases of acute hyperoxia were also demonstrated using the DC 55 with Nitrox 32% ($n = 2$) or the OXYMIXGERS ($n = 3$). In these cases, an equipment malfunction or human error in using the device was noted, with ventilation of hyperoxic gas mixture well beyond the oxygen exposure tolerance limit (accidental opening of the oxygen cylinder valve at 50 msw with the DC 55, gas switch from 60% O_2 to 100% O_2 at 25 msw with the OXYMIXGERS). Finally, 16 divers (15%) sustained an acute hypoxia during rebreather diving. These accidents were characterized by an insidious loss of consciousness, sometimes followed by convulsive movements and agitation with recovery of consciousness on the surface. They particularly concerned devices in which the breathing mixture became hypoxic by dilution on reaching the surface in the 0 to 15 msw depth ranges (3 cases involving the DC 55 with 32% O_2 and 5 cases involving the MIXGERS system with trimix mixture). In 6 other cases, an equipment problem with the breathing loop was identified. In 1 case, a poor rinsing of the closed-circuit breathing equipment (OXYGERS 57) was reported, and in another case the cylinders were supposed to contain a mixture with 60% O_2 but contained only nitrogen (cylinders not rinsed on return from retesting).

Overall, these gas toxicities–related disorders were predominantly observed in student divers (67 cases out 104, ie, 64%) and resulted in an impairment of consciousness in 54 cases out of 104 (52%), with 11 cases related to severe hypercapnia. Outcome was always favorable once the injured diver was rescued by his buddy to be brought back to the surface and disconnected from his breathing apparatus. However, 2 cases with moderate water aspiration were noted following a case of hypercapnia and 1 of hyperoxia. Regarding the specific disorders encountered by each sub-population of divers, the IRR for MCD vs. CS were as follows: 0.6 (95% CI: 0.3, 1.1) for hypercapnia, 0.2 (95% CI: 0.1, 0.5) for hyperoxia and 1.5 (95% CI: 0.4, 5.3) for hypoxia.

Rebreather injuries attributed to decompression sickness (DCS) were relatively rare ($n = 20$, 13%), with 17 cases of neurological DCS, 1 case presenting with inner ear DCS and 2 cases of musculoskeletal DCS. All the cases recovered without sequelae after prompt recompression with hyperbaric oxygen breathing (time to treatment less than 1 hour). They were never observed for devices using 100% O_2 or mixtures with 60% O_2. On the other hand, they were frequently documented with the DC 55 system using a mixture of 40% O_2 ($n = 17$, ie, 80% of DCS cases) used between 35 and 45 msw.

Pulmonary disorders were assigned as disabling injuries in 11 cases (7%). These symptoms characterized by dyspnea,

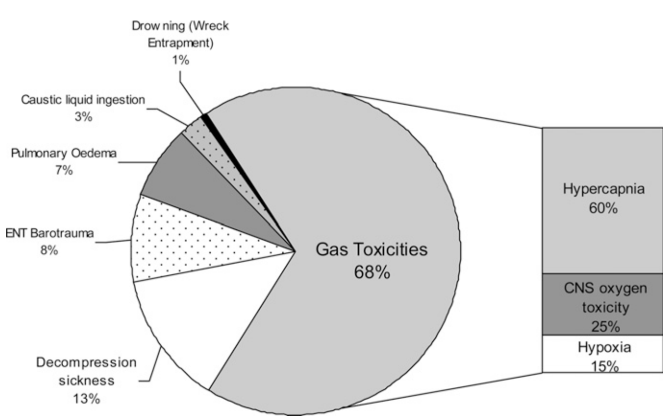

FIGURE 2. Distribution of rebreather diving-related specific disorders among the 153 injuries reported over 30 years.

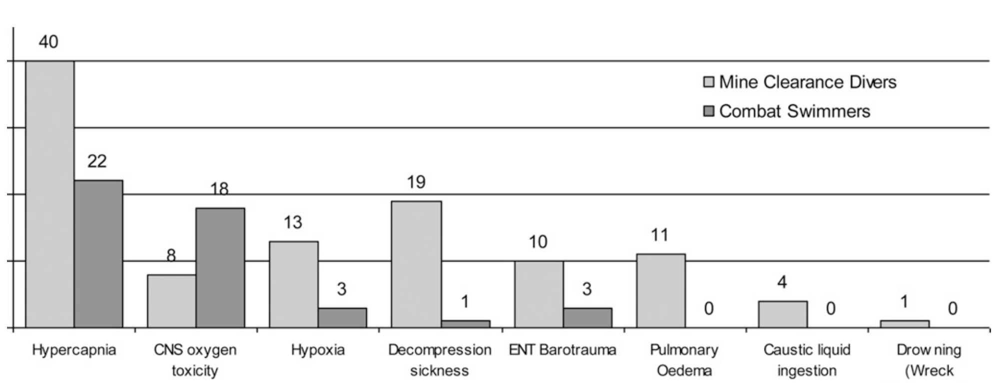

FIGURE 3. Specific disorders according to the 2 categories of French military divers using rebreathers.

cough, and expectoration of blood-tinged sputum were initially classified as pulmonary barotrauma. However, case review of the datasheets did not show a history of breath-hold or a rapid ascent during the dive, suggesting an etiology of immersion pulmonary edema. These pathologic events were predominantly associated with SCR worn on the back ($n = 10$). Only 1 case was observed in a MCD during a CCR dive to a depth of 6 msw for 10 min, but close questioning revealed that before the dive he had performed a strenuous swimming. In all cases, outcome was favorable with a complete recovery in the hours following the initial manifestations.

There were 13 cases of barotraumas involving ENT area (8%) registered in the database. They did not have any specific symptom pattern compared to scuba diving and only the most severe forms were declared. In particular, 6 cases resulted in inner ear barotrauma with cochlear and vestibular impairment, whereas an isolated rupture of tympanic membrane was cited in 4 other cases.

Finally, 4 cases of ingestion of caustic liquid (3%), a mixture of water-contaminated soda lime leading to corrosive injury of the oropharynx and/or esophagus were observed. In each case, it was due to an error in manipulating the mouthpiece with water entering the circuit.

Three fatalities were ultimately reported; these concerned 2 CS students using the OXYGERS 57 who were unable to return to the surface, caught under a barge, during an attack swim and another accident in which an MCD was trapped in a deep wreck with no visibility during a dive using a MIXGERS apparatus. CNS oxygen toxicity for the CS and insufficient gas associated with panic for the last decedent were identified as the disabling agents in post-mortem investigations.

DISCUSSION

This descriptive study is unique in analyzing the distribution of nonfatal diving injuries resulting from rebreathers in a large community of divers, hence making direct comparison with other studies difficult. The comparison of disorders among our military divers showed that the overall incidence did not differ between MCD and CS, but specific pathologic conditions were observed more in 1 of the 2 categories due to the difference in usage patterns of diving equipment. For instance, the higher rate of hyperoxia among CS can largely be explained by more dives performed with CCR using pure oxygen. Similarly, DCS cases were more identified in the category of MCD because their operational tasks imply that they dive predominantly down to 55 msw with Nitrox mixtures.

Not surprisingly, the most common diving disorders involving rebreathers were linked to gas toxicity in the majority of cases, supporting the limited quantifiable data available on rebreather fatalities investigated by root cause analysis.[3] In half of the cases, loss of consciousness occurred with the potential risk of drowning due to releasing the mouthpiece and being unable to reach the surface alone. Current diving procedures using rebreathers for military tasks in the French army do, however, ensure that these complications are exceptional, as demonstrated by the very low number of fatalities registered over 30 years. Indeed, 2 preventive measures are mandatory: (1) systematic linking of divers in pairs, so that a diver can find his buddy regardless of diving conditions (particularly if visibility is poor) and can lend assistance in the event of rescue; (2) using a strap to hold the mouthpiece in position, along with a lip guard, so that an unconscious diver can still breathe without risk of drowning. The rescuer can then concentrate on the quality of assistance and respecting the diving parameters for regaining the surface.

A great majority of these biochemical troubles were encountered by student divers in whom the intensity of physical exertion (sustained finning), difficulty to adapt breathing to the device at the start of the course, and the long duration of training dives led to an imbalance between CO_2 production and elimination with subsequent arterial CO_2 build-up. Additionally, excessive work of breathing and exercising for any length of time are prone to make a diver less tolerant to high oxygen levels,[5] and consequently, acute hyperoxia was also predominant in CS student during the initial part of their course. The association between hypercapnia and susceptibility to CNS-O_2 toxicity was ascribed mainly to the vasodilatory effect of CO_2 antagonizing the protective O_2-induced cerebral vasoconstriction,[6,7] thereby increasing delivery of O_2 to neural tissue, resulting in increased production of deleterious reactive oxygen species.

It is noteworthy that cases of carbonarcosis with loss of consciousness without any warning symptoms were relatively frequently described in our series (18% of hypercapnia cases). A possible explanation might be related to a decrease in the perception of sensation of CO_2-related symptoms because of using hyperoxic gas mixture that depresses peripheral chemoreceptors, but the inability to detect suggestive symptoms of hypercapnia by novice oxygen divers who did not experience a training period is another presumed mechanism.[8]

From 2002, the replacement of the OXYGERS 57 with the FROGS, a new generation closed-circuit rebreather, has increased soda lime capacity, with improved ergonomics and greater safety in use, leading to a reduction in cases of hypercapnia and hyperoxic seizures at the end of long dives.[9]

A further preventive measure is applied at the diving school for trainee divers who carry a higher risk of biochemical disorders: Each pair of divers is accompanied by at least 1 instructor with open circuit, down to 80 msw (use of a 2-cylinder unit with 18% O_2, 41% N_2, and 41% He between 60 and 80 msw). The students only dive in pairs on their own on the condition that they have validated the rescue procedures with this type of equipment or are marked on the surface by a buoy.

It should be noted that accidents caused by equipment failure were extremely rare (9 cases out of 153, ie, 6%), which confirms the reliability of these mechanical devices and the fact that military divers are trained in a rigorous maintenance and testing of their equipment, specifically with the conservative management of the scrubber.

Out of the whole series concerning all the rebreathers, DCS were observed only with the DC 55. Clinical presentations did not seem to differ from those encountered in air diving with a predominance of neurological DCS. It is interesting to note the absence of DCS development with the nitrox 60% O_2, which delivers high oxygen partial pressure in the 25 msw depth range. On the other hand, the nitrox 40% O_2 mixture seemed to be more hazardous with an increased propensity for DCS in dive depths between 30 and 40 msw without decompression stops provided by the decompression tables routinely used in the Navy since 1965. No DCS cases were noted for deep dives below 45 msw with nitrox 32.5% and trimix mixtures, but this was certainly linked to the protocol imposed (static dive, limited work time, and in-water decompression with oxygen), which also led to a low number of dives performed within these depth ranges. Since 2009, 2 neurological DCS with nitrox 40% have been observed with the new SCR "CRABE" during validation dives performed at the limit of physiological conditions. Analysis of PpO2 measured with a "black box" in this device allowed to highlight lower values than the theoretical values, thus requiring to change the decompression procedures with the nitrox 40% mixture. Recently, new decompression procedures with addition of oxygen during decompression stops were validated in the hyperbaric centre of the French navy (CEPHISMER).

Since recent years, there is a growing interest for the occurrence of pulmonary edema in endurance swimmers, breath-hold divers, and SCUBA divers. Various stressors have been put forward including cold water immersion, exertion, and increase in breathing resistance from diving equipment, thereby leading to increased pulmonary vascular pressures with subsequent capillary stress failure.[10,11] Conversely, pulmonary edema during rebreather diving is an uncommon disorder that has been reported once only in the literature.[12] Potential pathophysiological mechanisms that might have contributed to the development of diving-induced pulmonary edema in our military divers include the pressure difference between the lung centroid and the breathing bag of SCR positioned on the back. These could have potentiated the transmural pulmonary hydrostatic forces, hence favoring a fluid shift from the pulmonary capillaries vasculature into the alveoli. Oxygen breathing effects on systemic vascular resistance, cardiac output, and pulmonary inflammation might also promote an already existing impairment of the pulmonary blood–gas barrier.[13]

In summary, diving disorders with rebreathers in the French army are relatively common (around 1 accident per 3,500–4,000 dives) similar to the incidence of DCS with SCUBA air diving reported in the same population (estimated risk of 1 DCS event per 3,000 dives).[14] There is a distinct predominance of adverse events associated with gas toxicities, particularly in student divers. However, the diving procedures imposed by military regulations (mouthpiece strap, buddy team with link, and diving instructor with open circuit to lend assistance if necessary during training) have greatly limited life-threatening complications, ie, drowning, which are too often recorded in recreational technical diving.

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