Review article

Increasing the probability of surviving loss of consciousness underwater when using a rebreather

Paul Haynes

Abstract

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Re-circulating underwater breathing apparatus (rebreathers) have become increasingly popular amongst sport divers. In comparison to open-circuit scuba, rebreathers are complex life support equipment that incorporates many inherent failure modes and potential for human error. This individually or in combination can lead to an inappropriate breathing gas. Analysis of rebreather diving incidents suggests that inappropriate breathing gas is the most prevalent disabling agent. This can result in spontaneous loss of consciousness (LoC), water aspiration and drowning. Protecting the airway by maintaining the diver/rebreather oral interface may delay water aspiration following LoC underwater; the possibility of a successful rescue is, thus, increased. One means of protecting the airway following LoC underwater is the use of a full-face mask (FFM). However, such masks are complex and expensive; therefore, they have not been widely adopted by the sport diving community. An alternative to the FFM used extensively throughout the global military diving community is the mouthpiece retaining strap (MRS). A recent study documented 54 LoC events in military rebreather diving with only three consequent drownings; all divers were reported to be using a MRS. Even allowing for the concomitant use of a tethered diving partner system in most cases, the low number of fatalities in this large series is circumstantially supportive of the efficacy of the MRS. Despite drowning featuring as a final common pathway in the vast majority of rebreather fatalities, the MRS has not been widely adopted by the sport rebreather diving community.

Key words
Diving incidents; Drowning; Safety; Rebreathers/closed circuit; Technical diving; Unconsciousness

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Introduction

When compared to open-circuit scuba, the probability of exposure to an inappropriate breathing gas is increased when using rebreathers.[1] As a result, a serious or fatal incident is more likely when rebreather diving.[2] Inappropriate breathing gas scenarios most frequently associated with rebreather use are: (1) hypoxia, resulting from respiring an hypoxic gas; (2) hypercapnia, resulting from increased levels of inspired carbon dioxide (CO_2), or hypoventilation; (3) hyperoxia, resulting from respiring an hyperoxic gas. The sport diving community frequently refers to these maladies as the rebreather "*3H hazards*", all of which can lead to loss of consciousness (LoC) with little or no warning.[3]

The most common interface between the rebreather and the diver's respiratory system is a mouthpiece valve assembly, frequently called a dive surface valve. This human/machine interface is referred to in this paper as a 'mouthpiece' and is used in conjunction with a sport diving 'half-mask'. The mouthpiece typically requires manual operation by the diver to change from 'surface mode', which isolates the rebreather re-circulation system (breathing loop) from the environment, to 'dive mode', which allows access to the breathing loop and breathing gas.

As tone is lost from the mandibular muscles following LoC, the likely consequence is loss of airway protection as the mouthpiece/breathing loop falls from the mouth of the diver. If this occurs underwater, unless there is immediate intervention by a diving partner, the following outcomes are highly likely:

- fluid aspiration and asphyxiation;
- venting of breathing loop gas via the open mouthpiece;
- whole or partial flooding of the breathing loop;
- loss of buoyancy;
- drowning.

Although other factors (triggers) are inevitably responsible for initiating the accident, loss of airway protection and subsequent drowning is most frequently the actual cause of death (CoD). This paper examines a potential means of delaying or limiting this cycle, thus increasing the probability of surviving LoC underwater when using a rebreather.

Background

The mid-1990s saw the beginning of an upsurge in the use of rebreathers by sports divers. At that time the sport diving industry had limited rebreather experience and so, in anticipation of a growth in rebreather popularity, in 1996 the diving industry organised *Rebreather Forum Two* (RF2). The conference was organised to address the major issues

Figure 1

Triggers in open circuit and rebreather diving fatalities[5] (with permission)

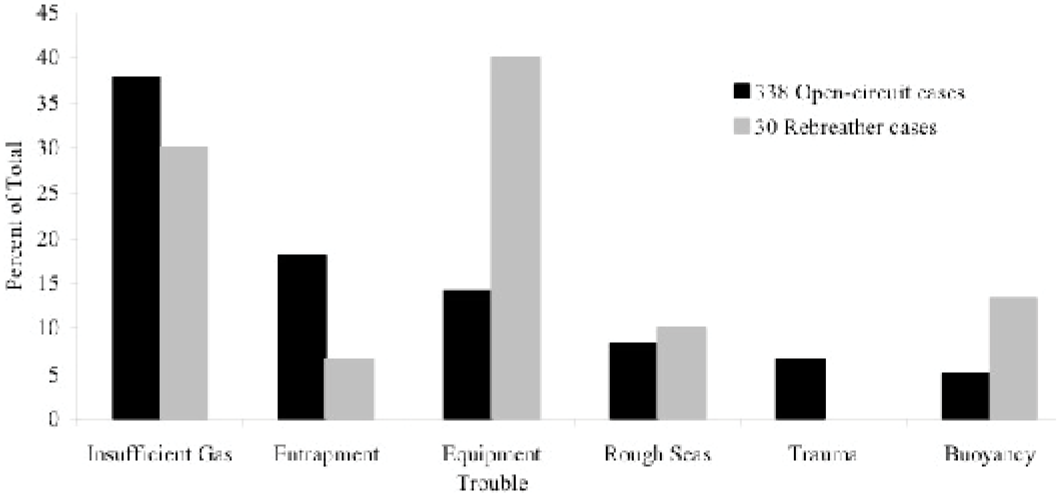


Figure 2

Disabling injuries in open circuit and rebreather diving fatalities[5] (with permission)

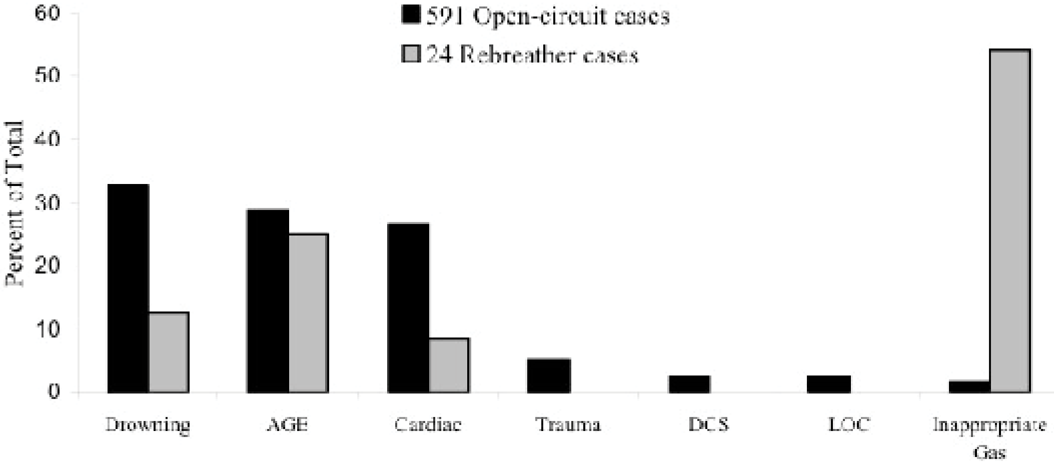
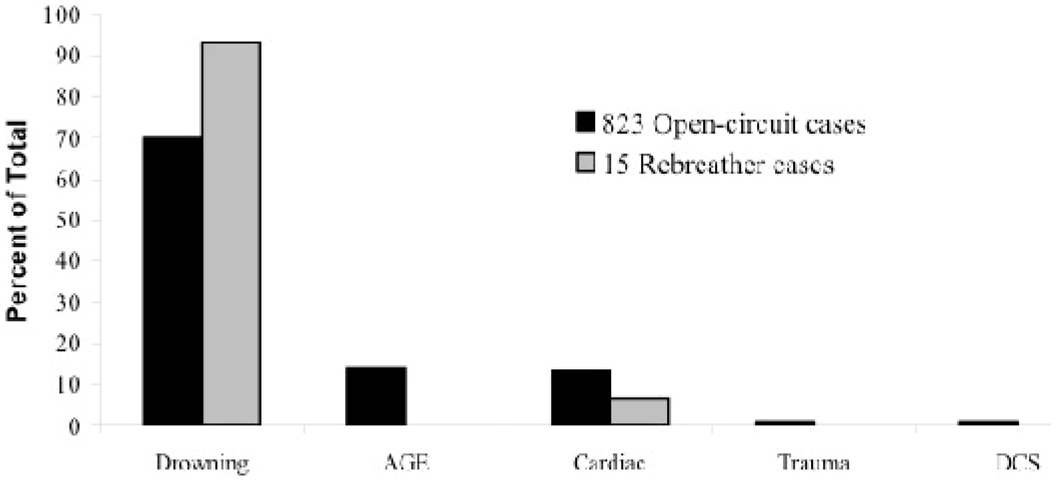


Figure 3

Causes of death in open circuit and rebreather fatalities[5] (with permission)



involved in bringing rebreather technology to the consumer market-place and was divided into working sessions to identify the key technology, safety, training and risk management issues. Drawing on the collective experience of numerous delegates from sport, military and occupational diving backgrounds, a consensus was developed in order to help shape future sport rebreather diving practice.[4]

Rebreather fatality analysis

As anticipated, sport rebreather use increased post RF2. Subsequently, with consideration of the relatively low number of rebreather sport divers, there appeared to be a disproportionately higher number of reported rebreather fatalities when compared to open-circuit scuba. As a consequence, the Divers Alert Network (DAN) conducted a study comparing sport diving open-circuit and rebreather scuba fatalities from the period 1998 to 2006.[5] Due to the difficulty in attaining comprehensive rebreather accident data specific to each fatality, in particular CoD as determined by a medical examiner (Coroner), the DAN study was restricted to a low number of rebreather fatalities (80 cases). However, study conclusions appeared to support the following related 1996 RF2 consensus points:

"*Rebreathers are much more complex than open circuit with insidious risk*."[4]

The 2007 DAN analysis concluded that of the cases studied, equipment trouble (human error or technical failure) was the trigger (something that turns an uneventful dive into an emergency) in over 40% of rebreather fatalities compared to just over 15% of open circuit fatalities (Figure 1). In addition, inappropriate breathing gas (insidious risk) was the disabling injury (something that causes death or makes drowning likely) in over 50% of rebreather cases compared to less than 5% of open-circuit cases (Figure 2).

"*Loss of consciousness presents a significant hazard when using rebreathers, likely to result in death by drowning*."[4]

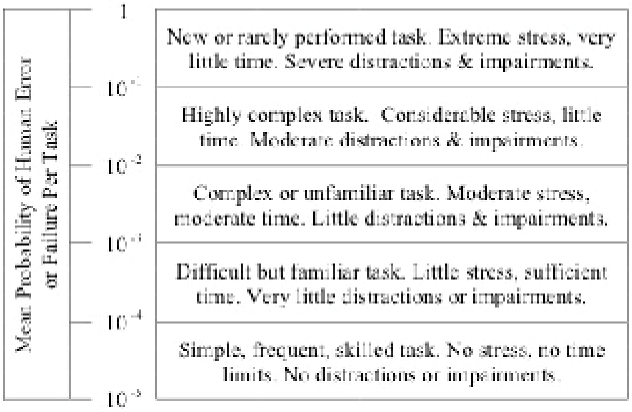
The 2007 DAN analysis concluded that in 94% of cases studied, the actual CoD, as determined by a medical examiner, was drowning (Figure 3).

In an effort to quantify rebreather diving risk, in 2013, a separate rebreather fatality study concluded that of the 181 cases analysed from between 1998 and 2010, study data suggested a four- to ten-fold increased risk of death when rebreather diving compared to open-circuit scuba diving.[2] The study also reported that a rebreather potentially has a 25-fold increased risk of component failure compared to an open-circuit manifolded twin-cylinder scuba system. Therefore, this study appears to further support the RF2 consensus statements discussed above.

Human error

Figure 4

Generic human error rates[7] (redrawn)



An incident is defined here as an unplanned event that degrades safety and culminates in equipment damage, diver injury or death. Rebreathers are complex equipment that form one element of a broader life support system that includes:

- the diver (attitude, skill set, knowledge, experience, health and fitness to dive);
- dive partner/team (attitude, skill set, knowledge, experience, health and fitness to dive);
- surface support team (attitude, skill set, knowledge, experience, emergency response protocols, emergency medical facilities);
- diving ancillary equipment (functionality and fitness for purpose);
- environmental protection equipment (functionality and fitness for purpose);
- procedural/diving methodology (appropriateness and fitness for purpose).

Rebreather incident data suggest that a frequent contributing factor is knowingly or unknowingly violating diving and/or equipment protocols as opposed to equipment malfunction.[2] This is in keeping with data from the marine oil and gas industry where approximately 80% of incidents investigated were related to human unreliability and approximately 20% were related to technical causes.[6] These figures support a widely held perception amongst the sport rebreather community that the diver is the 'weak link' in the life support system 'chain' described above.

To assist in the estimation and qualification of human error, a generic rate from experiment and simulation in the operation of nuclear power plants was developed (Figure 4).[7] If we consider an experienced rebreather diver in a benign environment, the assembly, testing, pre-dive donning and functionality confirmation (pre-breathe) procedures, all of which are essential to safe rebreather use, could be considered to fall into the fourth row of Figure 4, i.e., difficult but familiar task, little stress, sufficient time, very few distractions or impairments. The mean probability of human error or failure per task for such a scenario is between one in 1,000 events to one in 10,000 events. Thus, even under relatively benign conditions, experienced divers will occasionally make errors. It may be concluded, therefore, that to a lesser or greater extent, all levels of rebreather diver from novice to expert are prone to human error, the consequence of which could be exposure to an inappropriate breathing gas and LoC underwater.

Rebreather incident prevention

To help prevent rebreather diving incidents the following key measures are presently implemented or recommended by sport diving training agencies and equipment manufacturers:

- Use of equipment that has been subject to independent third party testing against a recognised international standard;
- Appropriate training standards and their strict application by diving instructors;
- Appropriate dive planning;
- Analysis and clear labelling of all gas cylinders;
- Use of assembly and test checklists;
- Remaining within manufacturers' recommendations/ performance guidelines;
- Remaining within training qualification parameters;
- Pre-breathe and function check prior to entering the water;
- Diving in pairs/teams;
- Frequent oxygen partial pressure display monitoring;
- Remaining within appropriate dive planning parameters;
- Application of appropriate preventive and corrective maintenance.

These incident mitigation measures are also applied within military and occupational diving environments, often to a greater level of detail and enforcement.[8,9] However, despite what is often the rigorous application of equipment maintenance schedules, prescriptive diver supervision and organisational management systems, in the author's experience, human error remains a common characteristic of military and occupational rebreather diving incidents. Therefore, within the sport diving environment it is reasonable to assume that, as a consequence of less formal diving equipment maintenance schedules, supervision and management practices, human error will likely continue to remain a common characteristic of sport rebreather diving incidents with the resulting potential for LoC.

Airway protection

Aspiration of as little as 1–3 $\text{ml}\cdot\text{kg}^{-1}$ body weight of water produces profound alterations in human pulmonary gas exchange.[10] It is also reported that average water aspiration in drowning is relatively small, rarely exceeding approximately 2.2 $\text{ml}\cdot\text{kg}^{-1}$ body weight.[11] Therefore, preventing or limiting fluid aspiration following LoC underwater is critical to surviving such an event. Whilst it is acknowledged that the diver may eventually die as a consequence of exposure to an inappropriate breathing gas, this can take a number of minutes or longer depending upon the breathing gas composition and ambient pressure (depth). If water aspiration is prevented or delayed following LoC, a diving partner may be able to affect a successful rescue. Alternatively it is conceivable that under certain circumstances, the distressed diver may regain consciousness, potentially enabling self-rescue.

To mitigate fluid aspiration following LoC underwater, a 1996 RF2 consensus statement endorsed the use of the full-face mask (FFM). However, a FFM adds to equipment complexity, restricts access to alternative breathing gas supply systems whilst increasing maintenance, training requirements and associated cost. These factors likely account for the sport rebreather diving community having not embraced the widespread use of FFMs despite their potential safety benefits.

One occupational diving equipment manufacturer has developed an innovative hybrid FFM/half mask design.[12] This mask system enables the ready separation of the lower oral section of the mask, which incorporates the rebreather mouthpiece. This design offers FFM airway protection benefits whilst also facilitating ready access to alternative breathing gas delivery systems. However, the sale of this hybrid design has generally been confined to government and occupational diving organisations. This and the relatively high cost appear to have restricted its wider use by sport rebreather divers.

In recognition of the possibility of encountering inappropriate breathing gas and the associated potential for LoC underwater, when a FFM is not used, the mouthpiece retaining strap (MRS) combined with related training has been employed by militaries worldwide for over half a century. It is a common safety design feature of the vast majority of both classic and contemporary military rebreather designs where the manufacturer has endeavoured to provide airway protection in the event of LoC underwater. In its simplest form the MRS is an elasticated adjustable strap secured to the breathing loop/mouthpiece. To optimise its effectiveness, the MRS is worn over the crown of the head and adjusted to positively hold the mouthpiece in position without causing undue discomfort. More sophisticated versions incorporate a padded flange. When retracted around the face by the distended strap, the padded flange enhances the lip seal whilst also helping to secure the mouthpiece in position (Figure 5). The MRS is a relatively low cost, simple and available alternative to the FFM.

Mouthpiece retaining strap efficacy

A literature search has failed to identify any formal evaluation of MRS efficacy. The subject was discussed at Rebreather Forum Three (RF3), Orlando, Florida in May 2012 and a RF3 consensus statement reads: "*The forum identifies as a research question the issue of whether a mouthpiece retaining strap would provide protection of the airway in an unconscious rebreather diver.*"[13] However, it is unlikely

Figure 5
Mouthpiece retaining strap (courtesy Charles Hawks)

that a meaningful prospective experimental evaluation of the MRS could be undertaken in human subjects. In the absence of a specific formal study, the suggestion of MRS efficacy is principally based upon observational (anecdotal) evidence from military diving sources and logic.

As a measure of the perceived potential effectiveness of the oral seal achieved by a correctly worn MRS, when conducting a diver rescue, some closed-circuit oxygen rebreather military user groups are trained to break the MRS oral seal by partially inserting a finger under the unconscious diver's lip at the corner of the mouth. This is believed to help facilitate the venting of expanding gas from the distressed diver's lungs and reduce the risk of pulmonary barotrauma on ascent.[14] Military groups who train this technique believe that an appropriately designed MRS results in an effective seal between mouth and breathing loop mouthpiece. Anecdotal evidence from various experienced military rebreather divers/diving supervisors, including the author, suggest that the use of a MRS has on various occasions been a key contributory factor to surviving LoC underwater. It is also the author's experience as a passenger in a free-flooding combat submersible swimmer delivery vehicle, that whilst in an upright foetal position, the MRS has provided airway protection during periods of sleep lasting up to 10 minutes.

These perceptions are corroborated by one notable study that analysed 153 accidents amongst French military rebreather divers.[15] Fifty-four of these events led to LoC underwater; however, this resulted in drowning in only three cases. The military report states: "*gas toxicities are frequently encountered by French military divers using rebreathers, but the very low incidence of fatalities in over 30 years can be explained by the strict application of safety diving procedures*". These procedures include:

> *"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".*

> *"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".*[15]

The report gives no weighting to either of these factors so it is unclear which, if any played a larger role in preventing drowning in 51 out of the 54 LoC events. However, protecting the airway from water aspiration and effecting rescue at the earliest opportunity are cited as key factors to surviving LoC underwater. The related benefit implied by this military diving study is likely to be translatable to the sport diving setting.

Rebreather solo diving

Of the 80 rebreather fatalities reviewed in the 2007 DAN study, 26 (a third) involved solo diving as a result of either deliberately diving alone or becoming separated from a diving partner. In support of this finding, whilst its accuracy cannot be readily verified, a publically available on-line collation of sport rebreather fatalities suggests that solo diving continues to remain a prominent characteristic of sport rebreather deaths that have occurred since 2007.[16] Due to the increased probability of respiring an inappropriate breathing gas when using a rebreather and the absence of a dive partner to witness early signs of diver distress or performance impairment and to implement rescue, solo rebreather diving appears to present additional risk.

Even a well-designed and correctly fitted MRS is unlikely to provide airway protection over an extended period following LoC. Therefore, to realise any safety benefit accruing from delaying or preventing drowning, the maintenance of close contact with a dive partner is also considered an important component to surviving LoC underwater. This proposition appears to be supported by the French military study, in which divers have survived LoC as a result of MRS use and early rescue by a dive partner.

Sport rebreather design and performance standards

European standard EN14143:2013 sets minimum design and performance parameters for sport rebreathers sold within the European Union, where compliance is a mandatory aspect of consumer law.[17] It is also setting a broader global benchmark for rebreather design standards. However, human error and equipment failure will likely remain a characteristic of sport rebreather use. It follows that the provision of airway protection is a desirable safety design feature regardless of rebreather performance and reliability. Indeed,

Figure 6

Rebreather open circuit bail out valve (courtesy AP Diving)

EN14143:2013 specifies a design requirement regarding a ‘face-piece’, which the standard defines as: “*a mouthpiece assembly, a half mask, a full-face mask or a helmet”*. The standard goes on the state: “*The face-piece shall aid ear clearing by allowing the diver’s nasal passages to be occluded. It shall also minimise the ingress of water during normal use and in the event of a diver falling unconscious or having a convulsion*”.[17] Whilst it is not specified how the minimisation of water ingress is to be implemented, EN14143:2013 states: “*The face-piece harness shall be designed so that the face-piece can be donned and removed easily. It shall be adjustable or self-adjusting and shall hold the face-piece assembly firmly and comfortably in position.*”[17] The standard subsequently defines the design and functional requirements of a retaining strap if fitted. The European rebreather standard, therefore, recognises the potential safety benefit of protecting the airway and breathing loop in the event of LoC and as a consequence incorporated the requirement into its design specification (Anthony G, personal communication, 2014; principle author of ENI4143:2013).

Market trends

To extend the exploration parameters of self-contained sport and scientific diving, to date relatively small groups of ‘technical divers’ have been the most prevalent users of rebreathers. However, a considerably larger sales potential is thought to exist amongst mainstream sport divers. As a consequence, considerable resource is presently being applied by the sport diving industry to introducing rebreathers into this larger market place.[18,19] To help facilitate mainstream rebreather diving, the world’s largest recreational diving training agency has defined a generic recreational closed-circuit rebreather (rCCR) specification and developed what it considers to be appropriate rCCR training standards. As a consequence, manufacturers are either producing dedicated rCCR models or adapting previous rebreather designs to comply with this rCCR specification.[20,21] Rebreather use will likely continue to increase amongst sport divers.

A mandatory rCCR specification safety feature is the bail out valve (BOV) (Figure 6). In an emergency, it enables the diver to manually access a source of open-circuit breathing gas without the need to remove the mouthpiece. However, it is worth noting that the MRS is not a mandatory rCCR safety feature. Despite the EN14143:2013 design requirement previously discussed, the reason for this remains unclear but may result from the fact that the MRS has historically not formed part of sport rebreather design. Therefore, awareness and experience of its application and potential safety benefit is limited amongst the sport rebreather community. Whereas a BOV is increasingly an integral part of sport rebreather design, it continues to remain the norm, contrary to EN14143:2013, for the vast majority of manufacturers to sell sport rebreathers without “*a means to minimise the ingress of water in the event of a diver falling unconscious*” or a means to “*hold the face-piece assembly firmly and comfortably in position.*”[17]

Airway protection spectrum

We may consider the upper end of the airway protection safety ‘spectrum’ to be an occupational diving helmet interfaced with a rebreather. An example is the Secondary Life Support saturation diving emergency bailout rebreather manufactured by Divex.[22] Assuming the watertight integrity of the breathing loop and helmet, water aspiration and, therefore, drowning following LoC, is highly improbable. At the low end of this ‘spectrum’ is the absence of any means of protecting the airway following LoC. Despite acknowledging the increased potential for exposure to an inappropriate breathing gas and LoC when rebreather diving, the sport diving community largely remains positioned at the low end of this ‘spectrum’.

Conclusions

Rebreathers incorporate a high number of inherent failure modes and the potential for human error. Individually or in combination, these can lead to inappropriate breathing gas and spontaneous LoC underwater. If the airway is unprotected, water aspiration and asphyxiation is the likely immediate outcome. Whilst FFMs are considered to offer a high level of airway protection, owing to their cost and complexity they are unlikely to be widely adopted by sport rebreather divers. Military rebreather manufacturers consider the MRS a safety-critical design feature, which is extensively employed throughout the global military rebreather diving community. Observational evidence suggests the correct use of a MRS can be an effective means of preventing or limiting water aspiration immediately following LoC. This potentially extends the window of opportunity for effective rescue or conceivably, self-rescue should consciousness be regained.

Recommendations

In the vast majority of sport rebreather fatalities, drowning is the actual CoD. Therefore, to directly mitigate the immediate consequences of loss of airway protection following LoC underwater, an effective MRS should be a standard component of all rebreathers used by sport divers. In addition, in order to raise awareness of the potential safety benefits, its use should be mandated within sport rebreather training standards.

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Paul Haynes is a military and sport diving mixed-gas closed circuit rebreather Instructor Trainer with a 25-year military, occupational and technical diving background.

Address for correspondence:
Paul Haynes
Director, Haynes Marine Ltd
12 Polbare Close
Stonehaven
Aberdeenshire AB39 3LG
Scotland, UK
phaynes@haynesmarine.com