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Rebreather Fatality Investigation

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Abstract

Sixty-six representatives of rebreather manufacturers, training agencies, government agencies, rebreather users, and DAN met in November 2006 to discuss objectives for rebreather fatality investigations. DAN has collected information on 80 recreational diving rebreather deaths from 1998 through 2006. The annual number of rebreather fatalities appears to have tripled since 1998. The percentage of fatalities involving rebreathers among US and Canadian residents increased from about 1 to 5% of the total number of diving fatalities captured from 1998 through 2004. Rebreather fatality investigations attempt to reduce future occurrences by identifying causative factors, primarily focusing on three areas: medical, equipment, and procedural. Medical investigation dwells on diver health and final cause of death. Equipment investigation addresses potential hardware issues. Procedural problems appear to be more common than equipment problems but are often difficult to identify. Witness reports and 'black box' recordings of rebreather function could help untangle procedural and equipment issues. Enhanced international training and cooperation will facilitate effective incident investigation and, ultimately, the education of the diving community.

Introduction

This paper is a compilation of information from multiple sources: 1) a two-hour meeting before the 2006 Diving Equipment and Marketing Association (DEMA) Show in Orlando with 66 representatives from rebreather manufacturers, training agencies, government agencies, and rebreather users; 2) comments on a draft of the meeting report; and 3) a preliminary review of rebreather fatality data collected by the Divers Alert Network (DAN). The data are from recreational diving with open-circuit fatality data presented for comparison. The term rebreather is used to describe closed-circuit or semi-closed circuit mixed gas scuba. The paper attempts to give the reader a sense of the issues and potential opportunities.

The Problem

Figure 1 summarizes 80 rebreather deaths collected by DAN America for 1998 through 2006. The information was obtained from internet searches or sent to DAN by interested persons. This does not necessarily include all rebreather fatalities in the world, just those about which DAN has been informed. The total number of rebreather fatalities per year appears to have tripled since 1998. In general, annual fatalities among non-US or Canadian residents have been greater than among US and Canadian residents but both are increasing. The most likely explanation for the increase in rebreather fatalities is that rebreathers have become more popular, and manufacturers are selling more. We do not know this for sure, however. Sales data are not currently available.

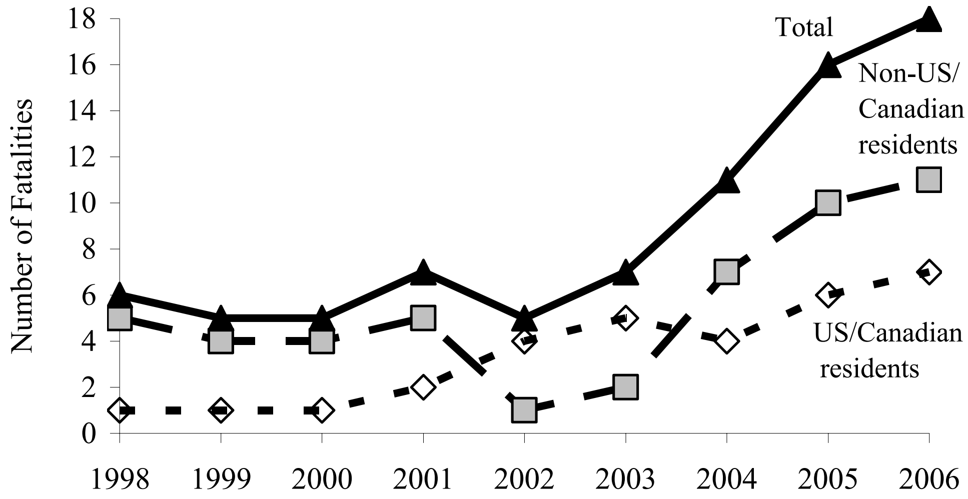

Figure 1: All known worldwide rebreather fatalities.

Figure 2 shows that the percentage of fatalities involving rebreathers among US and Canadian residents has increased from about 1 to 5% of the total US/Canadian fatalities from 1998 to 2004. (This is approximate as the total number of US and Canadian fatalities is not known for certain.) Once again, this probably reflects the growth in rebreather sales, but no sales data are available.

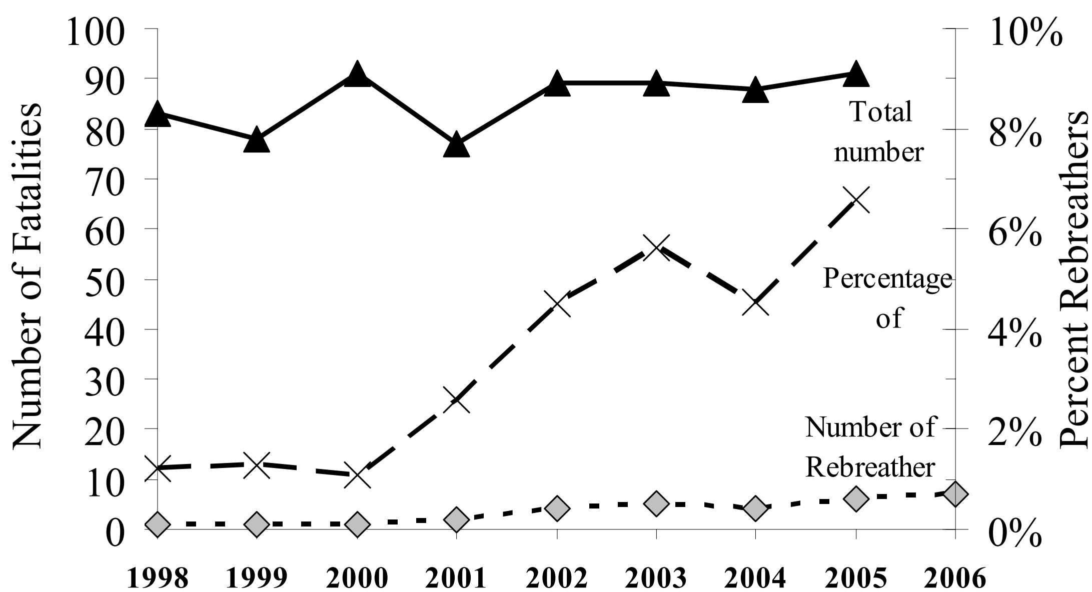

Figure 2: All known fatalities and all known rebreather fatalities among US and Canadian residents.

Risks Other than Death

Does the increase in rebreather deaths suggested by Figures 1 and 2 indicate a rebreather safety problem? Rebreather meetings in 1994 and 1997 were not followed by action to make the root causes of fatalities easier to identify. In the absence of such action, the present rise in deaths might lead to the perception of excessive risk and the imposition of restrictive limitations. Only the rebreather community (*i.e.*, users, trainers, manufacturers, etc.) can change this perception.

The threats may be legislative, legal, or operational. In addition to local ordinances, one opinion at the 2006 DEMA rebreather meeting held that federal terrorism laws passed since 9/11 might be used as pretexts to shut down rebreather diving, not because of terrorist threat, but because of public perception. Another opinion was that private litigation by next of kin is a greater risk. One manufacturer has reported that three dive boats have banned rebreathers in the Los Angeles basin, and some dive shops would not fill pony bottles because they can be used in rebreathers.

There may or may not be a real safety problem, but if private individuals or the public perceive one exists, the consequences will be the same. Multiple voices stated that now is the time to put the house in order before public or private perception becomes reality. Tact, diplomacy, technical development, training, community cooperation, public relations, and cooperation with law enforcement authorities and legislative bodies/agencies will be required. Fatality investigations are unpleasant, and the best outcome is the prevention of similar events. That is why investigations are important.

The community needs to self-regulate. An attorney who is involved in rebreather litigation and is also a rebreather diver stated that local, state, and federal agencies simply do not know what to do. This is a problem for both the industry and the families of rebreather divers who die.

Rebreather vs. Open-Circuit Fatalities: A Preliminary Look

Factual information from fatality investigations is needed to identify the most important points for action and to avoid restrictions on rebreather use. To illustrate how this process might work, we compared 964 open-circuit fatalities from 1992-2003 with 80 rebreather cases from 1998-2006. These are preliminary data and no conclusions are warranted.

We used a simplified form of Root Cause Analysis shown as a four-event sequence in Figure 3 (Rooney and Vanden Heuvel, 2004). Event (a), called the trigger, was the earliest identifiable root cause that transformed an unremarkable dive into an emergency. Event (b), called the disabling agent, was a root cause identified immediately before the disabling injury. Event (c), the disabling injury, caused death or rendered an incapacitated diver susceptible to drowning. Event (d) was the cause of death specified by the medical examiner that might be the same as the disabling injury or might be drowning secondary to the disabling injury. It was not unusual for one or more of the four events to be unidentifiable. This was particularly true for rebreather fatalities that occurred with non-US/Canadian residents which DAN America could not investigate.

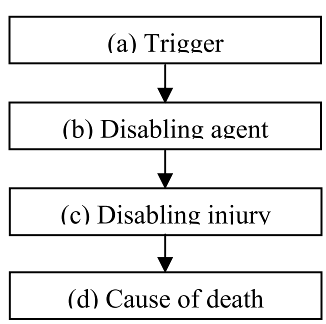

Figure 3: Root cause analysis as modified for diving fatalities.

Figure 4 illustrates triggers that were identified in 338 open-circuit and 30 rebreather cases. Equipment trouble and buoyancy problems appeared more common for rebreathers than for open-circuit. The trigger category equipment trouble included both procedural problems and less common equipment malfunctions that occurred during diving. Only three apparent equipment malfunctions were identified: flooded display; oxygen supply failure; and an unspecified malfunction at 330 fsw (100 msw) in a cave. There were 11 apparent procedural problems that reflected inappropriate preparation (including maintenance) or equipment operation by the diver: oxygen valve not on; electronics not turned on (two cases); gases not checked and displays not on; oxygen sensor incorrectly installed, oxygen valve partly blocked, loose connections; pre-dive malfunction of oxygen system, used emergency semi-closed mode during dive instead; gave display to student and relied on automatic oxygen addition; gas leak in breathing loop and bad oxygen sensor; removed rebreather in wreck to bypass an obstruction; gas supply valve set to an external rather than internal source; and mouthpiece valve sticking but dived anyhow. There were seven buoyancy problems. Four appeared to be rebreather-related and involved mouthpiece removal after ascent with failure to close the mouthpiece followed by sinking. Three were not rebreather related and included: tangled in lift bag, pulled to surface, fatal DCS; drysuit valve failure, blow-up, fatal AGE; and corroded drysuit valve, blow-up from 300 fsw (91 msw), and fatal DCS.

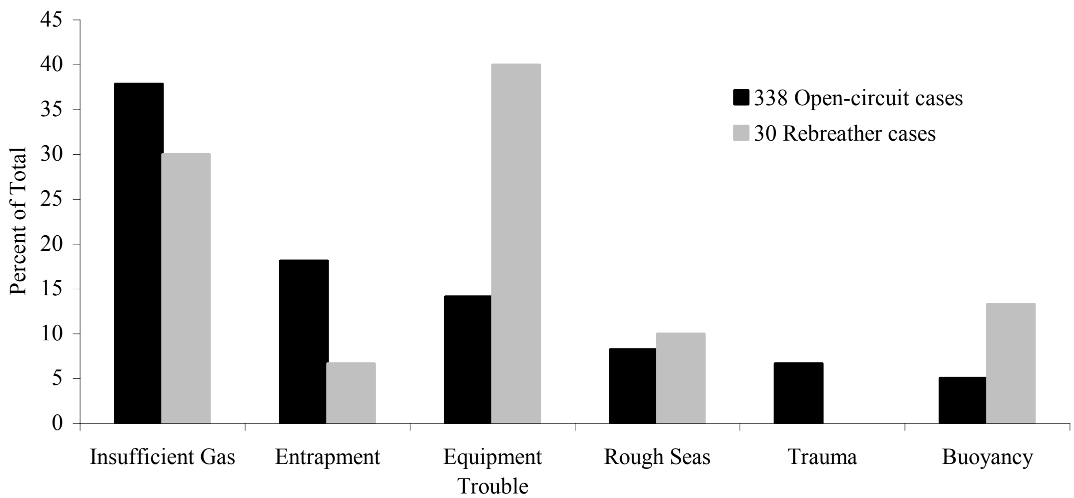

Figure 4: Triggers in open-circuit and rebreather diving fatalities.

Figure 5 shows the disabling agents that were identified. Emergency ascent was important for both open-circuit and rebreathers. Insufficient gas seemed more common with rebreathers which might seem surprising until it is recalled that the diluent supply in a rebreather is small and can be quickly exhausted by a leak or multiple upward and downward excursions. The largest difference between open-circuit and rebreathers was for inappropriate gas which represented apparent hypoxia, oxygen toxicity, or carbon monoxide poisoning. There were four cases of insufficient gas: direct ascent from 250 fsw (76 msw) with DCS and AGE; gas leak in breathing loop with rapid ascent and AGE; loss of consciousness at depth; and open-circuit until 180 fsw (55 msw), buddy-breathed, and drowned. There were five seizures suggesting oxygen toxicity: on switch to open-circuit; at 35-40 min; when caught in a downdraft from 28 to 82 fsw (8.5 to 25 msw); and two with no obvious explanation. Thirteen lost consciousness early in the dive suggesting hypoxia or a cardiac incident. Entrapment with rebreathers was less common than with open-circuit and included: tangled in line while attempting body recovery at 880 fsw (268 msw), drowned; tangled in lift bag at 150 fsw (46 msw) decompression stop, pulled to surface, fatal DCS; tangled in line at 130 fsw (40 msw) in cave, drowned; and tied self to coral during 20 fsw (6 msw) decompression stop, drowned.

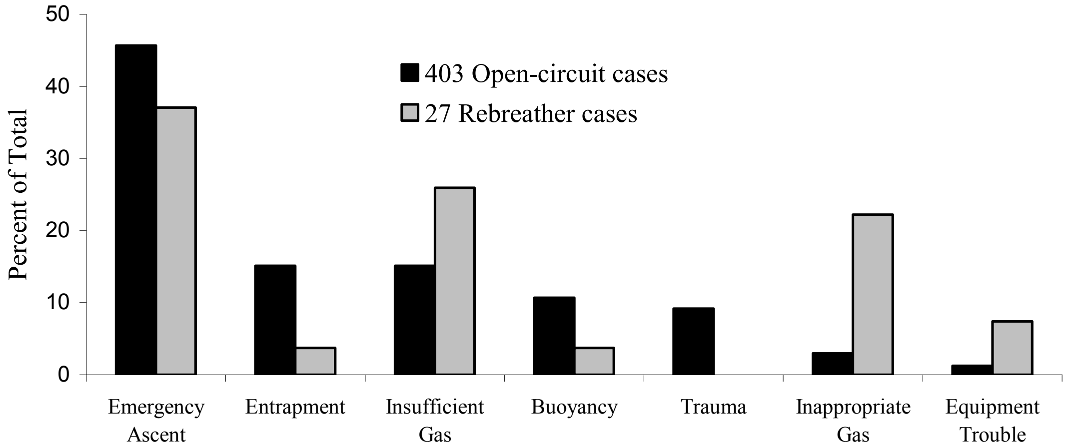

Figure 5: Disabling agents in open- and rebreather diving fatalities.

Figure 6 suggests that drownings and cardiac incidents were less common with rebreathers than with open-circuit while presumed hypoxia and oxygen toxicity appeared to be responsible for over half the disabling injuries with rebreathers.

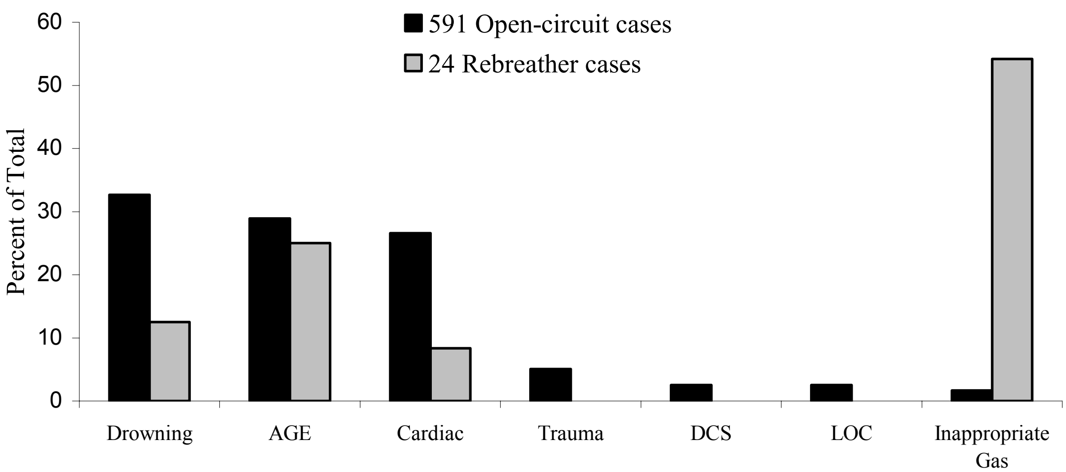

Figure 6: Disabling injuries in open- and rebreather diving fatalities.

In Figure 7, the main cause of death was drowning for both open-circuit and rebreathers. Bear in mind, however, that the disabling injury was more relevant to the prevention of diving fatalities because a disabled or incapacitated diver was incapable of self-rescue and would drown if a buddy or other divers were not present to lend assistance.

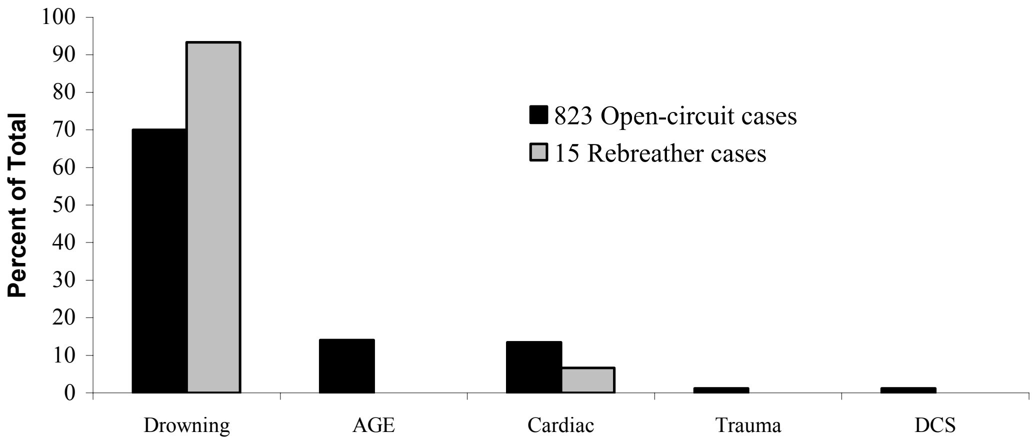

Figure 7: Causes of death in open-circuit and rebreather fatalities.

Other characteristics of the 80 rebreather fatalities included: eight semi-closed; four kits, homemade, or modified; and 26 diving alone, were separated, or lost contact. Practically no information was available on 14 cases. In one case, a diver was dragged by a large speared grouper from 140 to 190 fsw (43 to 58 msw) and lost consciousness on the bottom. A diver who separated from his buddy was found at 268 fsw (82 msw) with a shark bite although it was unknown if this was pre- or post-mortem.

The information presented above was too incomplete on which to base useful conclusions. The purpose of presenting it was to show that it is conceptually possible to identify the main factors associated with different adverse events in diving fatalities. For such an analysis to be successful, however, better and more complete information must be collected. This will require cooperation by the entire rebreather community – divers, operators, and manufacturers – and in addition, law enforcement agencies and medical examiners. There is much work to be done. Some of the issues are addressed below.

Investigation of Diving Fatalities in the UK

In the United Kingdom (UK), when a sudden death of unknown cause occurs or someone dies at work (including death of a student in a diver training course), an investigation or inquest is conducted by a Coroner (Sheriff in Scotland) with the assistance of a jury. (The terms 'coroner' and 'sheriff' have different meanings in the US and UK. A Coroner in the UK, or Sheriff in Scotland, conducts judicial inquiries which are heard in Court.) The coroner's objectives are to establish: (a) the identity of the deceased; (b) when, where, and how death occurred; and (c) whether recommendations to prevent similar accidents are needed. Standard verdicts include: (a) natural causes; (b) accident/misadventure; (c) killed unlawfully; (d) open verdict (insufficient evidence to reach a conclusion); or (e) a narrative verdict in which the jury's factual conclusions are summarized.

Diving fatality investigations attempt to identify causative factors in three areas: medical, equipment, and procedural. Medical investigation focuses on diver health and on the cause of death. All coroners in the US, or post-morticians in the UK, are qualified to assess cardiovascular disease, the most common health problem in diving deaths, but barotrauma, cerebral gas embolism, and decompression sickness require special training.

Drowning is the most frequently assigned cause of death when the real culprit may have been a traceless injury or unwitnessed event. Diving injuries that can result in unconsciousness with no detectable trace other than a drowned diver include: a) deep water blackout; b) hypoxia with semi-closed equipment in shallow water or closed-circuit equipment with the electronics off; c) CNS O_2 toxicity from an oxygen control system malfunction or from breathing the wrong gas at too great a depth; d) CO_2 toxicity from over-breathing (breathing at a higher ventilatory rate than the unit can support with reasonable breathing resistance); and e) CO_2 toxicity from canister channeling or using a canister beyond its functional limit.

In the UK, attendees at an investigation may include the investigating officer (a police office and/or a health and safety inspector), a forensic scientist, a rebreather manufacturer's representative, and a next of kin representative. An opinion was expressed that if the manufacturer attends, the next of kin should be present, or represented, so that all parties have the same information. During an investigation, everything should be photographed and use of a tape recorder with an open microphone should be considered. Video recording is strongly recommended. All evidence and information should be preserved in compliance with the local rules.

A strong opinion held that incident 'investigation' by Internet chat room was to be avoided. Internet forums are useful for communicating knowledge, but people without knowledge who speculate about a fatality under investigation waste time, money and, worse, upset the next of kin. Those who run Internet forums were encouraged to discourage inappropriate speculation or perpetuating miss-information regarding fatalities under investigation. When factual information is available, it should be transmitted to the investigating authority.

Some reviewers were equally strong in support of using the Internet to exchange information about rebreather fatalities as is commonly done. This is clearly an important tool that might be further developed.

Equipment Testing

Equipment testing is important because next of kin tend to focus on equipment error rather than human error as the root cause. In 18 post-incident rebreather tests conducted by the US Navy Experimental Diving Unit (NEDU) since 2002, equipment malfunctions were easy to detect but rare. When they occurred, the most common equipment problems found at NEDU included misadjusted regulators; broken, corroded or poorly maintained components; and contaminated gas. Human error or procedural problems appear to be more likely than equipment problems but can be difficult to identify. NEDU has only focused on equipment testing, not procedural issues. The UK system is more general.

Compared to open-circuit scuba incidents, rebreather testing is time consuming and expensive, and in the UK, investigating authorities are not inclined to request equipment testing unless absolutely essential because a typical cost is ~£3,000-5,000 per day for 5-10 days. The next of kin or manufacturer sometimes offers to contribute, but the UK investigating authority must agree if the evidence is to be used in court.

Rebreather testing is not easy and sometimes not possible, particularly when the equipment is damaged, or there are long shipping delays. Only a fraction of the units are received in suitable condition for testing. For example, a unit that had been stored after flooding may need to have the absorbent chipped out before investigation. Investigation seeks to determine if the diver's hardware (or software) was functioning properly, but equipment can never be tested exactly as it was during the fatal dive. The primary aim of equipment testing is to replicate the dive profile in an unmanned test facility. Complicated cases may require 'reenactment.' A secondary aim pertains to the validation of design standards. Ideally, life support equipment that is sold should be designed to meet accepted standards. The European Union and US Navy have defined the principal standards although they are not in complete agreement. Testing for compliance with standards may require replacement parts from a certified source, usually the manufacturer.

Testing cannot determine if early breakthrough of a CO_2 absorbent canister occurred because a canister cannot be repacked exactly as it had been dived. Another difficulty in investigating CO_2 canisters is flooding which commonly occurs if the diver becomes unconsciousness and drops the mouthpiece. Flooding may corrode and destroy components, particularly if they are aluminum, but even a flooded canister can provide some information. If the canister contents (even a slurry that has migrated to other parts of the breathing loop) are sealed in an airtight container and sent to a test lab such as Qinetiq or Molecular Products, it may be possible to estimate how much of the absorbent had been used by measuring how much calcium hydroxide had been converted into calcium carbonate.

Capabilities desirable for a facility that conducts rebreather tests include: a) knowledge of police investigative procedures to maintain proper chain of custody; b) an unmanned and manned test/dive facility; c) experts in the equipment to be tested; d) ability to conduct and interpret gas analysis, sometimes from minuscule amounts of remaining gas; e) ability to download and interpret dive computer or rebreather black-box data; f) ability to simulate underwater breathing apparatus (UBA)-human interactions; and g) ability to review medical examiner reports for consistency with known or discovered facts.

Two centers in the UK test rebreathers – Qinetiq and HSE. In the US, NEDU has conducted underwater breathing apparatus testing as a public service for at least 30 years, and what the Navy learns helps to make Navy diving safer. Testing can include inspection, unmanned breathing machine evaluations, and manned reenactments in a test pool. Unless litigation is involved, the knowledge is sometimes made public. NEDU tests open-circuit, surface-supplied, and military or civilian rebreathers, but the scope of NEDU ends at equipment evaluation. The Navy does not do complete incident investigations. Investigative agencies that have that responsibility and have requested equipment tests include the US Coast Guard, coroner/medical examiner offices, local fire departments, local police departments, state police, Occupational Safety and Health Administration (OSHA), National Institute of Occupational Safety and Health (NIOSH), and military commands. In the US, the NEDU is probably the best site for equipment testing, and what they learn about civilian equipment is of value to Navy diving, but cost, time, and reluctance to become involved in litigation makes the Navy uncomfortable to serve in that capacity. If the rebreather community could help alleviate these problems, the US might achieve as good a testing system as the UK. There was some discussion after the DEMA meeting about establishing a fund that might help to support equipment testing, but this effort was apparently unsuccessful in gaining traction.

The opinion was expressed that it is in the manufacturers' best interest to make equipment testing as easy as possible. This might include providing an equipment manual, a manufacturer's representative who knows the equipment, replacement parts, and assistance with digital download from equipment instruments. There was disagreement as to whether having a manufacturer's representative would compromise the objectivity of a test, but this is done in the UK with full recording of all proceedings.

Procedural (Human Error) Investigation

Procedural investigations examine a diver's behavior against training and manufacturer standards for equipment use or for environmental stress management (*e.g.*, ascent rate, oxygen and nitrogen exposures, buddy system, decompression procedures, training qualifications, etc.). Witness reports and 'black-box' recordings can help untangle procedural and equipment problems. The importance of black-box data was demonstrated at the DEMA meeting for two rebreather fatalities in which there were recordings of depth, time, O_2 sensor readings, CO_2 scrubber utilization, and O_2 and diluent gas supply pressures. This information made it possible to identify: a) the presence of hypoxia or hyperoxia; b) emergency or rapid ascent; c) buoyancy problems; d) use of the open-circuit emergency mode including gas consumption as a work rate indicator; and e) previous dive history and sensor calibration to show the extent of training on a new unit before a fatal dive. The examples presented were helpful for identifying procedural problems while demonstrating that the rebreathers performed satisfactorily. There appeared to be general agreement at the meeting that black-box data recording should be standard on all rebreathers. However, a black-box can be an expensive add-on for smaller rebreather manufacturers. Perhaps this could be an optional component manufactured by a third-party.

Training

New rebreather divers have a wide range of experience, and ideally, training should reduce the risk of injury or fatality for all. The challenges to training include diver complacency, getting divers to behave as they were trained, and instilling discipline and proper attitude. However, it is so easy to forget even after the best initial training. Forgetting or ignoring training might be less likely if, where possible, the equipment could provide immediate feedback. For example, an alarm that activated if a unit was dived without being turned on might help prevent hypoxic drowning. Another example is a carbon dioxide sensor that would guard against channeling or diving without absorbent.

One opinion held that training by the agencies and the manufacturers' pre- and post-dive checklists were both good. Evidence was available that some instructors had taught incorrect procedures such as how to extend a canister beyond the manufacturers' specifications. A US instructor suggested that boat captains and open-circuit divers might be educated about rebreather divers so they could recognize problems and know how to respond in emergencies. The meeting was informed that British Sub-Aqua Club (BSAC) has done this to make open-circuit divers competent buddies for rebreather divers and to make dive marshals competent supervisors for rebreather divers. It was suggested that BSAC might provide these training courses to US agencies, but some voiced the strong opinion that divers should be responsible for themselves including choice of buddies.

Solo diving was particularly controversial. There was strong discussion about how often rebreather fatalities occurred in divers without buddies. Solo diving was cited as involved in 80-95% of rebreather diving deaths. This estimate was questioned, but an attorney reported that 80% of 40 rebreather fatalities he had investigated involved solo diving. A case was cited that recovery of a hypoxic diver was possible because a buddy was present. However, the points were also made that divers should be trained to look after themselves rather than be buddy-dependent and that "divers are going to do what they want." No one argued these points, but the question remained as to how much emphasis training agencies and diving operators should put on buddy diving.

Actions at a Dive Site after an Incident

In the event of a diving accident, death may not be immediate, and first aid and medical attention take precedence over everything else. But where possible, all equipment should be preserved, no matter how seemingly inconsequential. Everything has to be counted in until it can be positively ruled out. Even a bathing suit proved significant in one investigation. Buoyancy management is particularly important. Weights and the buoyancy compensator or life jacket must be inspected. Many fatality victims were over-weighted or did not ditch their weights. Equipment should not be disassembled. If equipment is to be shipped, it should be packed and protected in hard containers, not shipped in cardboard boxes. Long delays in reaching a test facility may result in the loss of valuable information. Witness names and contact information should be recorded on-site and on-site interviews conducted when possible. (How this might be done remains to be determined.) Finding recreational divers after they have left a dive site can be difficult and time consuming.

Every diving fatality (or potential fatality) should be treated as a homicide and the equipment subjected to a chain of custody with custody cards signed each time it changes hands. If the chain of custody has not been maintained properly, there is no way to be certain that damage may not have occurred during handling after the dive or during shipping rather than during the dive. Equipment should be locked up to prevent tampering.

Each type of rebreather is somewhat different from the others and may require special handling upon recovery to preserve information for investigation. Military divers carry checklists for each breathing apparatus they use. Civilian rebreather manufacturers could develop checklists specifically for their own equipment. The US Navy, Dive Lab, Qinetiq, HSE, and Closed Circuit Research have checklists that might be used as models. DAN volunteered to post links to the manufacturers' websites on the DAN website so that checklists can be accessed for download through a central location.

Constructive interactions with law enforcement are essential. Police dive teams or representatives of an official investigative agency will usually not be on-site. Ideally, dive supervisors and boat captains would be familiar with evidence-preservation procedures and could assist on-site. Should evidence-preservation procedures specifically for diving fatalities be developed in coordination with law enforcement agencies? Should police dive teams be trained in the special requirements for rebreather investigations? Currently, it is not unusual for law enforcement agencies to send equipment to local dive shops that are unfamiliar with rebreathers. Coordination between divers and police dive teams is important to avoid situations in which police divers will not accept assistance from 'non-professionals' who have been involved in a recovery. Written instructions or training courses that are developed might be disseminated to the law enforcement community through umbrella organizations such as the International Association of Dive Rescue Specialists, Inc. It was clear that law enforcement representatives should be involved in future meetings of this nature.

Conclusions

This is a developing discussion that requires significant community cooperation if useful action is to result.

Reference

Rooney J, Vanden Heuvel L. Root cause analysis for beginners. Quality Progress. 2004; July: 45-53.