Common causes of open-circuit recreational diving fatalities.

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Denoble PJ, Caruso JL, deL. Dear G, Pieper CF, Vann RD. Common causes of open-circuit recreational diving fatalities. Undersea Hyperb Med 2008; 35(6):393-406. Diving fatalities causes were investigated in 947 recreational open-circuit scuba diving deaths from 1992-2003. Where possible, cases were classified at each step of a four step sequence: trigger, disabling agent, disabling injury, cause of death (COD). The most frequent adverse events within each step were: (a) triggers – 41% insufficient gas, 20% entrapment, 15% equipment problems; (b) disabling agents – 55% emergency ascent, 27% insufficient gas, 13% buoyancy trouble; (c) disabling injuries – 33% asphyxia, 29% arterial gas embolism (AGE), 26% cardiac incidents; and (d) COD – 70% drowning, 14% AGE, 13% cardiac incidents. We concluded that disabling injuries were more relevant than COD as drowning was often secondary to a disabling injury. Frequencies and/or associations with risk factors were investigated for each disabling injury by logistic regression. (The reference group for each injury was all other injuries.) Frequencies and/or associations included: (a) asphyxia – 40% entrapment (Odds Ratio, OR≥30), 32% insufficient gas (OR=15.9), 17% buoyancy trouble, 15% equipment trouble (OR=4.5), 11% rough water, drysuit (OR=4.1), female gender (OR=2.1); (b) AGE – 96% emergency ascent (OR≥30), 63% insufficient gas, 17% equipment trouble, 9% entrapment; (c) cardiac incidents – cardiovascular disease (OR=10.5), age>40 (OR=5.9). Minimizing the frequent adverse events would have the greatest impact on reducing diving deaths.

INTRODUCTION

Annual reports of diving fatality cases collected by the Divers Alert Network (DAN) indicated that a few apparent causes were common to most cases (1-21). In the study described below, we investigated the frequencies of presumed causes and their associations with disabling injuries. Our objective was to identify the most frequent causes which might be optimal targets for preventive intervention.

METHODS

Data Collection
McAniff began systematic collection of information about U.S. recreational diving deaths in 1970 and published a series of reports from 1970 to 1989 (22, 23). DAN joined this effort in 1989, worked with McAniff until his retirement in 1995, and took on publication responsibility in 1989 (3) with continuation to date (21). These data formed the basis for studies of suspected risk factors (24-34).

DAN is not a primary investigative agency but has evolved an active surveillance system that gathers information about scuba diving fatalities from public, private, and official sources. How many cases the system misses is unknown. Only cases involving U.S. and Canadian residents are described here as
deaths among non-U.S. or Canadian residents were difficult or impossible to investigate. The work was approved by the Duke University Medical Center Institutional Review Board, and information was collected in compliance with the Federal Health Insurance Portability and Accountability Act.

Diving deaths were identified by active search of news reports, the Internet, and a cooperative network of individuals and organizations developed over many years. Following notification of a death, DAN contacted official investigative agencies, medical examiners, hyperbaric chambers, witnesses, and the decedents’ families by telephone, mail, or email. These contacts could be helpful to a greater or lesser degree. Reports might include barest details or a full analysis of equipment, breathing gases, and a description of a complete medicolegal autopsy.

Documents for each case were reviewed by a forensic pathologist trained in diving medicine (JL Caruso (JLC), one of the authors). If present, the cause of death (COD) was as assigned by the medical examiner. If the autopsy report was missing or the COD was inconsistent with the events, JLC assigned a probable COD if he judged sufficient information was available. Discrepancies or inconsistencies that were not reasonably resolvable were assigned as missing values. Information was entered into a standardized Access® database. From notification of a fatality to final review by JLC, the entire process could take 12-18 months to complete.

The present report reviewed 947 open-circuit scuba diving fatalities during open-water diving from 1992-2003. Cases occurring before 1992 did not contain sufficient data and were not reviewed. Cave diving fatalities were common but were not included except when the diver unintentionally ventured into a cavern. (Cave diving is a special overhead environment that warrants separate consideration.) Ice diving fatalities were considered here and were unusual.

Case reports were examined for sequential events defined as triggers, disabling agents, disabling injuries, and causes of death (Fig. 1) and for intrinsic factors such as age, health, experience, or diving activity. If evidence was found for a particular event (e.g., emergency ascent that was witnessed or recorded by a dive computer) or intrinsic factor (e.g., cardiovascular disease in an autopsy report), this was noted. Otherwise, that event or factor was counted as absent.

Diving experience was characterized according to case report estimates of the number of dives in the past year, the total reported lifetime dives, and the annual diving frequency. A “novice” diver was defined as having fewer than 20 lifetime dives; an “occasional” diver as having more than 20 lifetime dives but fewer than 20 in the past year; and a “frequent” diver as having more than 50 lifetime dives and more than 20 in the past year. Emergency ascent was defined as an ascent prompted by a perceived problem or an urgent situation (e.g., insufficient gas).

Sequential Analysis

Accidents on dry land are commonly investigated by ‘root cause analysis’ (RCA) which identifies the sequence of events preceding an untoward outcome (35, 36). In diving fatalities, the events and their significance are often obscure or unknown, so we employed a simpler paradigm that attempted to force each case into the sequence described in Fig. 1. Event (a), the trigger, was the earliest identifiable event that appeared to transform an unremarkable dive into an emergency. Event (b), the disabling agent, was a hazardous behavior or circumstance that was temporally or logically associated with the trigger and perhaps caused Event (c), the disabling injury. The disabling injury was directly responsible
for death or for incapacitation followed by death due to drowning. Event (d) was the cause of death (COD) specified by the medical examiner. COD might be the same as the disabling injury or might be drowning secondary to injury.

It was not unusual for one or more of the four events in Fig. 1 to be unknown, unidentifiable, or apparently not present. Alternatively, some cases had multiple adverse events. This circumstance required judgment concerning the most probable trigger and disabling agent. Extra events not classified as triggers or disabling agents were retained for regression analysis as unclassified adverse events (see Regression Analysis). Despite these difficulties, common patterns were frequent as the following examples illustrate.

(a) A diver ran out of gas, made an emergency ascent, developed an arterial gas embolism (AGE) in the water, and drowned. Insufficient gas was the trigger, emergency ascent was the disabling agent, AGE was the disabling injury, and drowning was the COD.

(b) A diver became tangled in a fish net, ran out of gas, suffered asphyxia, and drowned. Entrapment was the trigger, insufficient gas was the disabling agent, asphyxia was the disabling injury and drowning was the COD.

Note that insufficient gas had different roles in the two examples. In Case (a), insufficient gas was the trigger, and in Case (b), it was the disabling agent. Although drowning was the COD in Case (a), we considered the disabling injury (AGE) to be more relevant to the understanding of diving fatalities. In Case (b), asphyxia was the disabling injury. The discussion below focuses on disabling injuries which were found to have different patterns of triggers, disabling agents, and associations with intrinsic factors.

**Pareto Principle**

The Pareto principle states that most outcomes are associated with a few (the “vital few”) of many possible causes. This empirical concept was first recognized by the 19th century economist, Vilfredo Pareto (37), and adapted for quality assurance in the 20th century by Joseph Juran (38). Undesirable outcomes are reduced by identifying and eliminating the vital few causes. This can be accomplished with the aid of a Pareto chart, a bar graph in which the frequencies of possible causes associated with the undesirable outcome are ordered from greatest to least while accompanying incremental percentages accumulate as a line graph. We used Pareto charts to aid in identifying the most frequent triggers, disabling agents, disabling injuries, and COD associated with diving fatalities.

**Regression Analysis**

The empirical Pareto principle can only identify numerical association – not causality – between events in Fig. 1. Although causality cannot be proven rigorously, associations found in Pareto charts can be tested statistically for supporting evidence. This was accomplished by defining a binary outcome variable for each disabling injury.
preferred over COD as described in Sequential Analysis.) Each outcome variable had a value of one for a given injury and a value of zero for all other injuries. Thus, the reference group for a disabling injury was all other disabling injuries rather than the preferred, but unavailable, reference group of divers who did not die.

Associations of injuries with triggers, disabling agents, and other covariates were evaluated by multivariate logistic regression (SAS/STAT 9.1, Cary, NC) defined by:

\[
\ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \ldots
\]

where \( p \), for example, is the probability of asphyxia as the disabling injury (relative to a reference group of the other injuries), \( X_i \) are covariate indicator variables having values of 0 or 1, and \( \beta_i \) are parameters to be estimated by maximum likelihood from the fatality data.

Covariates included triggers, disabling agents, intrinsic factors (Table 1) not assessed in the Pareto charts, and unclassified adverse events (Sequential Analysis and Table 2). The unclassified adverse events and intrinsic factors recognized that Fig. 1 was oversimplified and diving fatalities are multi-factorial.

A p-value < 0.05 was considered significant while the strength of an association was assessed by the odds ratio (OR) with OR > 2 (or < 0.5) taken as an arbitrary threshold for practical significance. A factor having an OR of 2, for example, would indicate that the odds of death was twice as likely in the presence of that factor when all other factors were held constant.

Questions about how and why accidents occur are frequently difficult to answer because of missing data (36), and missing data are

<table>
<thead>
<tr>
<th>Medical History</th>
<th>Experience</th>
<th>Diving Activity*</th>
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</thead>
<tbody>
<tr>
<td>CVD(^1)</td>
<td>252 (27)</td>
<td>Novice</td>
</tr>
<tr>
<td>Diabetes</td>
<td>37 (4)</td>
<td>Occasional</td>
</tr>
<tr>
<td>Asthma</td>
<td>29 (3)</td>
<td>Frequent</td>
</tr>
<tr>
<td>Respiratory(^2)</td>
<td>28 (3)</td>
<td>Missing</td>
</tr>
<tr>
<td>Seizure history</td>
<td>11 (1)</td>
<td></td>
</tr>
<tr>
<td>Certification</td>
<td></td>
<td>Diver Dress</td>
</tr>
<tr>
<td>Entry level</td>
<td>413 (44)</td>
<td>Wetsuit</td>
</tr>
<tr>
<td>Advanced</td>
<td>275 (29)</td>
<td>Drysuit</td>
</tr>
<tr>
<td>Student</td>
<td>58 (6)</td>
<td>Swim suit</td>
</tr>
<tr>
<td>No certification</td>
<td>57 (6)</td>
<td>Diveskin</td>
</tr>
<tr>
<td>Instructor/Master</td>
<td>54 (6)</td>
<td>Missing</td>
</tr>
<tr>
<td>Missing</td>
<td>90 (10)</td>
<td>Buddy System</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pair</td>
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<td></td>
<td>Missing</td>
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</tbody>
</table>

\(^1\) cardiovascular disease  \(^2\) lung surgery, spontaneous pneumothorax, upper respiratory infection, and congestion  
* includes multiple activities

Table 1. Intrinsic factors related to diver and diving activity in 947 diving deaths. The table shows the number of divers (percentage) with the indicated factor.
particularly common in diving fatalities. Bodies may not have been recovered, critical events may not have been witnessed, and medical examiner reports may have been unavailable. (McAnniff lacked autopsy reports in 32-50% of his cases and could not identify a cause of death in 22% of the events (39).) When we found that a particular factor was missing from a case, we assigned the most common or modal category from cases with data present. If breathing gas was missing, for example, air was assigned as such because this was the most common gas in the other cases. Continuous data were dichotomized. We tested this imputation procedure with an indicator variable and found no apparent bias. These are standard procedures for managing missing data (40, 41).

RESULTS

The median age of the 947 open-circuit diving fatalities was 43 years with an intra-quartile range (IQR, between the 25% and 75%-tiles) of 33-52 and range of 12-79; the median Body Mass Index (BMI) was 27 kg·m\(^2\) (24-31 IQR, 17-54 range); the median dive depth was 60 fsw (30-100 IQR, 3-500 range); and 184 of the decedents (19.4%) were female.

Intrinsic factors were determined by case review and are summarized in Table 1. Medical conditions included those that were previous, current, or indicated by reported medications. Natural diseases, particularly cardiac, were often discovered at autopsy including several instances of pulmonary pathology such as blebs or bullae (gas or fluid-filled sacs). Some decedents had more than one medical condition. Cardiovascular disease (CVD) included coronary artery disease, cardiac surgery, arrhythmias, high blood pressure, and other heart related problems that were reported or indicated by medications. Medical conditions were reported only if positive indications existed. In the absence of an indication, a medical condition was assumed absent although this certainly led to underreporting of the rates.

In Table 2 summarizes identified triggers, disabling agents, and unclassified adverse events for all cases. The sub-categories in Table 2 provide additional detail, but only the major headings were used for regression. Rough
water included high sea states, surf breaking on beaches, rocks, or piers, and strong currents. The inappropriate gas category included carbon monoxide contamination, hypoxia due to corroded gas cylinders or a hypoxic gas mix, and breathing an excessively hyperoxic gas by mistake or default. Excessive hyperoxia was defined as exceeding an oxygen partial pressure of 1.2 atm. While this may appear conservative, recent reports suggest that central nervous system oxygen toxicity may occur at lower partial pressures than previously expected, particularly in association with carbon dioxide retention (42).

**Triggers**

Triggers were identified in 346 of the 947 deaths (37%). Figure 2 shows the resulting Pareto chart for triggers ordered from greatest to least with incremental percentages that accumulated across the trigger categories. According to the Pareto principle, the largest trigger categories were the most important: insufficient gas (41%), entrapment (20%), equipment problems (15%), and rough water (10%), accounting for 86% of all fatalities with identified triggers.

**Disabling Agents**

Figure 3 shows frequencies and cumulative distributions in 332 deaths where a disabling agent could be identified. Emergency ascent (55%), insufficient gas (27%), and buoyancy trouble (13%) were the most common disabling agents and, together, accounted for 95% of the 332 deaths. Rapid ascent was witnessed or recorded by dive computer in over half the cases with emergency ascent, but emergency ascent also included divers who were assisted to the surface, made free ascents, or buddy breathed (Table 2). Panic was reported in about one-fifth of cases with emergency ascent, but the reason for the emergency ascent was unknown in about one-third of the cases. Insufficient gas was often preceded by entrapment or occasionally by breathing apparatus failure as a trigger. Negative buoyancy was more commonly reported than positive buoyancy (Table 2). In 149 cases where buoyancy trouble was identified, 102 were negative, 35 were variable, and 12 were positive. In 64 cases with positive or negative buoyancy, asphyxia was the disabling injury in 71% with negative buoyancy and AGE in 91% with positive buoyancy (p=0.0006).
Disabling Injuries

Of the 947 cases, a COD was assigned by the medical examiner in 814, and drowning was cited as COD in 70% of these. For the majority of those who drowned, however, there was evidence that the prior disabling injury may have incapacitated the decedent. Thus, we elected to focus on the disabling injury as more relevant to diving safety than the subsequent COD, drowning.

Determination of disabling injury was a forensic judgment based on the following criteria.

(a) Asphyxia: asphyxia with or without aspiration of water and with no indication of a prior disabling injury.
(b) Arterial gas embolism (AGE): gas in cerebral arteries, evidence of lung rupture, emergency ascent.
(c) Cardiac incident: acute episode of chest discomfort signaled by the diver, distress without obvious cause, history of cardiac disease, autopsy findings.
(d) Trauma: witnessed trauma, traumatic findings at autopsy.
(e) Decompression sickness (DCS): signs and symptoms, autopsy findings.
(f) Unexplained loss of consciousness (LOC): diver found unconscious without obvious cause.
(g) Inappropriate gas: carbon monoxide contamination, excessively hyperoxic gas mix, hypoxic gas mix.

Figure 4 shows frequencies and cumulative distributions for the 590 disabling injuries that were identified by sequential analysis. The three most common disabling injuries, asphyxia (33%), AGE (29%), and cardiac incidents (26%) contributed to 88% of deaths. Other disabling injuries were ascribed to trauma (5%), DCS (decompression sickness; 2.5%), unexplained loss of consciousness (LOC; 2.5%), and inappropriate gas (2%).

Disparity will have been noted among the number of triggers (346), disabling agents (332), disabling injuries (590), and COD (814). This reflects the incomplete nature of fatality case data and illustrates why alternative methods such as regression analysis are useful for checking empirical conclusions derived from Pareto charts.

We now describe characteristics associated with the three most common disabling injuries (asphyxia, AGE, and cardiac incidents) and the four that were less common (trauma, DCS, unexplained LOC, and inappropriate gas). To facilitate comparisons among the three common disabling injuries, Table 3 (see page xxx for Table 3 a, b, c) shows corresponding percentages of triggers and disabling agents and odds ratios determined by regression. The four less frequent injuries are also described as understanding their characteristics may help reduce future occurrences.

Asphyxia as Disabling Injury

Asphyxia was assigned as the disabling injury in 193 of the 590 cases in which a disabling injury could be identified, and triggers were identified in 148 of the 193 asphyxia cases. Triggers for asphyxia included entrapment, insufficient gas, equipment trouble, and rough water (Table 3a). When entrapment (40%) was assigned as a trigger, case reports
indicated the causes were kelp, wrecks, mooring lines, under ice, fishing line or nets, and floodgates or drains. When insufficient gas was assigned as a trigger (32%), it was the first identifiable adverse event in the sequence Fig. 1, but why the gas supply was exhausted was unknown. Equipment trouble as a trigger (15%) included regulator free-flow, unanticipated gas consumption, diver error in using the breathing apparatus, buoyancy compensator (BC), weight belt, or drysuit. Rough water as a trigger (11%) included high sea states, strong currents, or surf on beach, rocks, and piers.

A disabling agent (the event after the trigger in Fig. 1) was identified in 120 of the 193 asphyxia cases. Disabling agents included insufficient gas (62% of disabling agents) triggered by entrapment, equipment trouble, or excessive gas consumption such as from heavy exercise in rough water. When buoyancy trouble (17%) was a disabling agent, it was triggered by over- or under-weighting, insufficient gas to inflate the BC, or an over-inflated BC or drysuit. Emergency ascent (13%) as a disabling agent was typically triggered by entrapment or insufficient gas and was sometimes associated with asphyxia rather than AGE.

Regression analysis for asphyxia as the disabling injury indicated an OR of ≥30 for entrapment (95% lower and upper confidence limits 16.4, ≥30), 15.9 for insufficient gas (8, ≥30), 4.5 for equipment trouble (2, 9.9), 4.1 for wearing a drysuit (1.6, 10.7), and 2.1 for being female (1.1, 3.9). An OR of 2.1 for females indicated that females were more likely to have asphyxiated while males were more likely to have had another disabling injury (e.g., AGE, cardiac incident, trauma, etc.). In general, the odds ratios shown in Table 3 reflected the magnitude of corresponding triggers. Disabling agents for asphyxia were less specific as they often occurred in the reference group which included the other disabling injuries. The ideal reference group, of course, would be divers who did not die.

Some known important additional contributing factors were difficult to assess including distress or panic which was reported in about a fifth of the cases and sometimes caused aspiration or increased gas consumption. Decedents were also diving alone or became separated from their buddies in about 40% of cases with asphyxia as the disabling injury, but diving alone was not specific to asphyxia and, therefore, did not stand out.

**AGE as Disabling Injury**

AGE was assigned as the disabling injury in 171 of 590 cases for which a disabling injury could be identified. Triggers were identified in 82 of the 171 AGE cases (Table 3b) and included insufficient gas (63%), equipment trouble (17%), and entrapment or entanglement (9%). Case review indicated that approximately three-quarters of AGE deaths were triggered when divers exhausted their breathing gas, panicked, or developed equipment problems.

Disabling agents were identified in 139 of the 171 AGE cases with emergency ascent (96%) most common. Loss of consciousness during ascent, at the surface, or just after leaving the water was typical with AGE, and drowning as COD was secondary for many divers who remained in the water. For 55 of the 171 AGE cases, for example, the COD was reported as drowning suggesting that divers disabled by AGE were at risk of drowning.

Table 3b indicates that regression found a strong association of AGE with emergency ascent as the disabling agent (OR≥30; 24.4, ≥30) but no associations with events such as insufficient gas since these were common in many disabling injuries (e.g., insufficient gas was present in 78 (40%) asphyxia cases and 56 (33%) AGE cases).
Cardiac Incidents as Disabling Injury

A cardiac incident was assigned as the disabling injury in 156 of 590 cases in which a disabling injury could be identified. Overt triggers and disabling agents were rarely associated with cardiac incidents (Table 3c), but cardiac incident reports indicated that about 60% of decedents noted dyspnea, fatigue, distress, chest pain, or an ill-feeling, and 10% of these occurred before the last dive. Problems began upon entering the water in 24% of the cardiac incidents, on the bottom in 46%, and after leaving the bottom in 20%. Loss of consciousness could occur before, during, or after diving. Autopsy reports were available for 56% of cases from 1997-2003, and there was usually evidence of significant cardiovascular disease but rarely of myocardial damage. Absence of myocardial damage suggested that these incidents may have resulted from either fatal dysrhythmias or drowning subsequent to unconsciousness before heart muscle injury could occur (which may take up to several hours). Regression found that disabling injuries classified as cardiac incidents were associated with CVD (OR=10.5; 6.1 and 18.1) and age greater than 40 years (OR=5.9; 3 and 11.6) but not with BMI although BMI was greater in the cardiac incident group (30.5 kg·m\(^{-2}\) mean, 5.8 sd, 21-48 range) than in the asphyxia (27.8 kg·m\(^{-2}\) mean, 6.3 sd, 18-54 range) or AGE (28.7 kg·m\(^{-2}\) mean, 5.8 sd, 17-50 range) groups.

### Table 3a. Asphyxia (193)

<table>
<thead>
<tr>
<th>Event or Factor*</th>
<th>Trigger</th>
<th>Disabling Agent</th>
<th>Odds Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrapment</td>
<td>40%</td>
<td></td>
<td>&gt;30</td>
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<tr>
<td>Insufficient Gas</td>
<td>32%</td>
<td>62%</td>
<td>15.9</td>
</tr>
<tr>
<td>Buoyancy Trouble</td>
<td>15%</td>
<td>17%</td>
<td>4.5</td>
</tr>
<tr>
<td>Equipment Trouble</td>
<td>15%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergency Ascent</td>
<td></td>
<td>13%</td>
<td></td>
</tr>
<tr>
<td>Rough Water</td>
<td>11%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Drysuit 4.1
Female 2.1

### Table 3b. AGE (171)

<table>
<thead>
<tr>
<th>Event or Factor*</th>
<th>Trigger</th>
<th>Disabling Agent</th>
<th>Odds Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrapment</td>
<td>9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insufficient Gas</td>
<td>63%</td>
<td></td>
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</tr>
<tr>
<td>Equipment Trouble</td>
<td>17%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emergency Ascent</td>
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<td>96%</td>
<td>&gt;30</td>
</tr>
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### Table 3c. Cardiac incidents (156)

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<th>Event or Factor*</th>
<th>Disabling Agent</th>
<th>Odds Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>*CVD</td>
<td></td>
<td>&gt;10.5</td>
</tr>
<tr>
<td>*Age&gt;40 years</td>
<td></td>
<td>5.9</td>
</tr>
</tbody>
</table>

Table 3. Triggers, disabling agents, and odds ratios determined by regression that were associated with the disabling injuries: asphyxia, AGE, and cardiac incidents in 590 cases where disabling injury was identified. The 95% confidence intervals for the odds ratios are given in the text.

Trauma as Disabling Injury

Thirty cases were assigned trauma as the disabling injury. There is little mystery concerning such cases, and while rare, periodic reminders concerning trauma hazards are needed to reduce their occurrence (43). Nine cases occurred on rocks in the surf zone during shore entry or exit, nine when the diver was struck by a boat propeller, four when struck by a jet-ski or powerboat, two due to shark attack, two due to electric shock, one due to alligator attack, one when struck by a large fish that was just speared, one when struck by a large marine mammal going after a stringer of speared fish, and one as a result of pre-dive trauma to the spleen. Regression disclosed that traumatic injuries were associated with rough water (OR=2.6; 1.2 and 5.6) and being a frequent diver (OR=2.4; 1 and 5.4).

DCS as Disabling Injury

Disabling injuries attributed to DCS were reported in 15 cases of dives with a median depth of 226 fsw (130–250 fsw IQR). Eight decedents had insufficient gas and made emergency ascents with omitted decompression.
Six were wreck diving, four were spear-fishing or collecting game, and four made multiple repetitive dives with short surface intervals. One ran out of gas due to regulator free-flow, one became positively buoyant when his drysuit inflation valve malfunctioned, and one was dragged deep by a speared fish. Regression found that DCS was associated with diving deeper than 180 fsw (OR≥30; 24.1 and ≥30), diving alone (OR=17.2; 3.1 and ≥30), and emergency ascent with omitted decompression (OR=16; 3.1 and ≥30).

Unexplained Loss of Consciousness (LOC) as Disabling Injury
Disabling injuries classified as unexplained loss of consciousness were reported in 15 cases. Five occurred on deep dives (170, 190, 232, 340, and 400 fsw). Four involved divers with diabetes, and two involved nitrogen-oxygen diving. In one of these, the decedent had a witnessed seizure at 70 fsw while breathing a reported 32% nitrox mix with an oxygen partial pressure of 1 atm, a level too low to be expected to cause oxygen toxicity. In the other nitrox case, a diver breathing a mix of unspecified oxygen content became incapacitated on a wreck at 120 fsw. One student diver lost consciousness on the surface during a resort course while waiting for an instructor who was supervising other students. In four cases, no trigger or disabling agent was identified although an autopsy demonstrated significant coronary artery disease in one. Regression found that LOC was associated with diabetes (OR=12; 3.1, ≥30), frequent divers (OR=8.2; 2.4, 28.4), and student divers (OR=4.6; 1.3, 16.3).

Inappropriate Gas as Disabling Injury
The disabling injury was identified as breathing an inappropriate gas mixture for 10 decedents. Four appear to have developed CNS oxygen toxicity. One was found vomiting at 224 fsw where he reportedly breathed 100% oxygen. A second had a witnessed seizure at 253 fsw after exhausting his bottom gas and breathing a high oxygen content travel gas. A third was reported to have used a nitrogen-oxygen mix with 38% oxygen at 135 fsw (1.88 atm oxygen partial pressure) where he was found unconscious. After a 180 fsw dive, a fourth had a witnessed seizure during a 20 fsw decompression stop while breathing 100% oxygen at a partial pressure of 1.61 atm. (This diver was reported to have been taking many medications.) Three decedents succumbed from carbon monoxide contamination. Carbon monoxide contamination was documented in two cases (32% carboxyhemoglobin and 537 parts per million carbon monoxide in the breathing gas) and reported in one case without documentation. Two decedents developed hypoxia: one from corrosion in his tank that depleted the oxygen content to less than 1% and a second from a low oxygen content mix for use during a deep dive but breathed at shallow depth. Regression disclosed that LOC was associated with insufficient gas (OR=29.5; 4, ≥30), diving deeper than 150 fsw (OR=27.6; 3.9, ≥30), and diving with a helium mixture (OR=13.9; 1.5, ≥30).

DISCUSSION

Association and Causality
Diving safety guidelines are traditionally based on fatality case reviews in which apparent associations are tacitly assumed to be causes (44-46). The leap from association to causality is not unreasonable in a situation such as an entanglement that precedes asphyxia where there was an immediate, obvious, and direct connection. Indirect associations such as between wearing a drysuit and asphyxia are less certain and demand further verification.
We conducted both sequential and regression analysis because if agreement occurred, the case for causality was stronger. Requirements for confident causal inference include strong, consistent, and specific associations that do not conflict with operational or medical understanding (47, 48).

**Limitations**

Assessing associations and making causal inferences based on surveillance system data, such as that from diving fatalities, is uncertain because of inherent defects in data quality and completeness (47, 49, 50). Surveillance system data are more appropriate for hypothesis generation than for hypothesis testing although multiple studies based on independent data increase confidence. International data sources such as that collected by the British Sub-Aqua Club (BSAC; (51)) and Project Stickybeak in Australia (52, 53) might be useful in this regard. Statistical adjustment by regression can reduce confounding among multiple variables, but uncertainty from chance is less likely than from bias. This applies to the work reported here for which the following limitations were identified.

(a) The four-event sequential paradigm of Fig. 1 was oversimplified. Including all apparent events in a complete RCA might provide additional useful information (47, 49, 50).

(b) A single reviewer (author PJD) evaluated the triggers, disabling agents, and disabling injuries, and a single reviewer evaluated the COD (author JLC). The reviewers were well-credentialed for their tasks, but post-hoc and single reviewer bias were possible. Greater certainty would be achieved with multiple reviewers.

(c) Disabling injuries were identified for only 590 of the 947 decedents. Triggers and disabling agents were even more difficult to identify.

(d) Post-mortem examination of divers has requirements beyond standard autopsy practice that was not always implemented by medical examiners (54).

(e) Ascertainment bias existed because a factor not mentioned in a case report was assumed not to be present (e.g., cardiovascular disease).

(f) The reference group for each disabling injury was all other disabling injuries. In consequence, triggers and disabling agents associated with specific disabling injuries were not always identified completely, and their relative importance was necessarily conditional on death. Surviving divers would be a better reference population.

(g) A rule-of-thumb in regression analysis requires at least 10 cases for every parameter that is estimated to avoid overfitting (55). This was satisfied for asphyxia, AGE, and cardiac incidents but not for trauma, DCS, loss of consciousness, and inappropriate gas. We reported these results for completeness.

**Implications for Diving Safety**

Not surprisingly, analysis of diving fatality case data identified many triggers and disabling agents that are the focus of existing diving safety guidelines (44-46). What is new is recognition that a majority of fatalities were associated with a minority of triggers and disabling agents. This suggests that diving fatalities might be reduced by additional emphasis on the prevention of key triggers, disabling agents, and intrinsic medical factors in accordance with the Pareto principle. The design and implementation of practical solutions for avoiding triggers and disabling agents is the province of training specialists. We confine ourselves to a few summary conclusions and a comment on medical factors. Some diving fatalities are unavoidable, but the practically irreducible level appears yet to be achieved.
At 41%, insufficient gas was the most prominent trigger associated with diving deaths (Fig. 2). More attention to gas management and emergency gas sources would seem to be the obvious solution. Entrapment (20%), the next most common trigger, suggested avoidance and extrication skills need emphasis. Equipment problems were the third largest trigger (15%), but no one equipment component seemed to dominate (Table 2).

Emergency ascent (55%) was the most prominent disabling agent in response to an initiating trigger (Fig. 3). While preventing triggers is a top priority, coping with unavoidable emergency ascent would break the sequence of Fig. 1 and perhaps avoid a fatal outcome. Alternate air sources and reliable buddies may be useful as 57% of decedents who began with an assigned buddy were separated prior to death.

Buoyancy trouble was infrequently identified by sequential analysis (Fig. 1) and Pareto charts (Table 3, Figs. 2 and 3), but it was the most common adverse event, and negative buoyancy was far more frequent than positive buoyancy (Table 2). Buoyancy trouble was an obvious trigger when a BC or drysuit was overinflated or failed to inflate, but when buoyancy trouble was present throughout an exposure, as was not unusual, the effects could be less direct such as increased exertion or making a diver less capable of coping with stress. Thus, buoyancy trouble may be an important contributing factor that was overlooked in the simple paradigm of Fig. 1.

Deaths associated with the disabling injuries asphyxia and AGE were qualitatively different from those associated with cardiac incidents where cardiovascular disease (OR=10.5) and age over 40 years (OR=5.9) were the only identified factors (Table 3). The likelihood of underlying disease was indicated by the observation that 60% of decedents designated as cardiac incidents had complained of dyspnea, chest pain, or feeling unwell before or during diving. Similar reports were rare for other disabling injuries. The physical activity of diving might have triggered a cardiac incident that would not necessarily have been fatal on dry land but led an incapacitated diver to drown. An individual who feels unwell should not begin a dive or should end a dive immediately. Divers who meet the American Heart Association criteria for increased cardiac risk (56) are advised to undergo evaluation of cardiac health and fitness for physical activity before taking up or resuming diving.

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