Thirty years of American cave diving fatalities

Leah Potts, Peter Buzzacott and Petar Denoble

Abstract

(Potts L, Buzzacott P, Denoble P. Thirty years of American cave diving fatalities. *Diving and Hyperbaric Medicine*. 2016 September;46(3):150-154.)

Introduction: Cave divers enter an inherently dangerous environment that often includes little visibility, maze-like passageways and a ceiling of rock that prevents a direct ascent to the surface in the event of a problem.

Methods: Reports of cave diving fatality cases occurring between 01 July 1985 and 30 June 2015 collected by Divers Alert Network were reviewed. Training status, safety rules violated, relevancy of the violations, and root causes leading to death were determined.

Results: A total of 161 divers who died were identified, 67 trained cave divers and 87 untrained. While the annual number of cave diving fatalities has steadily fallen over the last three decades, from eight to less than three, the proportion of trained divers among those fatalities has doubled. Data regarding trained cave divers were divided into two equal 15-year time periods. Trained cave divers who died in the most recent time period were older but little else differed. The most common cause of death was asphyxia due to drowning, preceded by running out of breathing gas, usually after getting lost owing to a loss of visibility caused by suspended silt. An overwhelming majority of the fatalities occurred in the state of Florida where many flooded caves are located.

Conclusion: Even with improvements in technology, the greatest hazards faced by cave divers remain unchanged. Efforts to develop preventative interventions to address these hazards should continue.

Key words

Deaths; recreational diving; technical diving; root cause analysis; epidemiology; DAN – Divers Alert Network

Introduction

Cave divers enter an inherently dangerous environment that includes little visibility, maze-like passageways and a ceiling of rock that prevents a direct ascent to the surface in the event of a problem. In 1966, an American report contained 11 cave and spring diving fatalities out of 86 documented skin and scuba diving fatalities.[1] Since then, hundreds of recreational divers have died in US caves.[2] In 1979, Sheck Exley published the first cave diving instructional text, called *Basic cave diving: blueprint for survival,* that provided safe cave diving guidelines and used accident analysis to illustrate the effectiveness of these practices.[3] At that time, training agencies reached a consensus that most cave diving deaths were caused by breaking one or more of the following guidelines:[4]

- always limit penetration into the cave to one-third of the starting amount of gas;
- always have a continuous guideline to the surface;
- always dive at, or shallower than, a safe depth for the gas being used.

To round out the five safe cave diving rules that make up most of today's training courses, two more rules were added five years later:[5]

- all divers entering a cave must have cave diver training;
- every diver should have three light sources, each having the ability to burn for the entire scheduled dive time.[5]

The five are known as the 'Golden Rules' of cave diving.

Previous cave diving fatality research compared trained with untrained divers but the continued relevance of the five rules has not been examined since they were finalised in 1984.[2] Technology has advanced remarkably in recent decades in all fields of engineering and scuba diving equipment is no exception. In 1997, AP Valves released the first production closed circuit rebreather (CCR) marketed for recreational diving, which soon gained popularity in the technical diving community including among cave divers. A rebreather essentially recycles exhaled gas by removing carbon dioxide and topping up metabolised oxygen. This enables a diver to stay longer underwater without carrying additional tanks of breathing gas. There are various types of CCR available today and hazards associated with them have been described previously.[6] In this paper 'rebreather' refers to any form of scuba that recycles exhaled gas, including semi-closed rebreathers, CCRs, electronic and manual rebreathers.

Once the exclusive preserve of military divers, long-range diver propulsion vehicles (DPV) are now commercially available, enabling greater distance penetrations into caves, as are dive lights with greatly improved times before failure, heated dry suit undergarments enabling longer dives in cold water and other technological advances. If and how these advances may have affected the hazards modern cave divers face has not been previously explored. The aim of this study was to review characteristics of recent mortality among trained cave divers in the USA, and to provide a foundation upon which to build new preventative interventions if needed, or to reinforce existing efforts.

Methods

Divers Alert Network (DAN) collects information about recreational scuba diving fatalities and maintains a database. An individual case file is created for each fatality and these case files may include medical examiner or coroner's reports, autopsies, witness statements, recovery divers' reports, news clippings, information from the next of kin and/or the dive buddy, dive profiles downloaded from dive computers, court transcripts, sheriff's reports or any other relevant information. From this database, cave diving fatality cases occurring between 01 July 1985 and 30 June 2015 were extracted and reviewed. Cave diver training status was determined, (trained, untrained or unknown) and, after describing the trend in proportions trained or untrained, the unknown and untrained divers were removed and only trained cave divers were further considered. The study protocol was approved by the Institutional Review Board of the Divers Alert Network (approval number 011−14).

ROOT CAUSE ANALYSIS – ALL YEARS

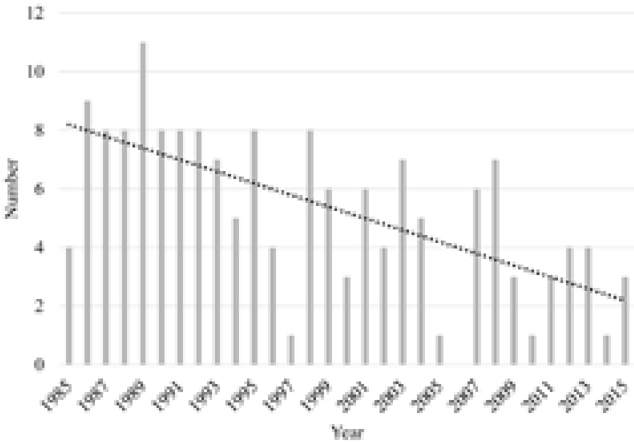
The causes of each fatality were classified into four consecutive steps, as described previously in diving fatality root cause analyses.[2,7,8] The 'medical cause of death' was accepted as established by a medical examiner. Based on available evidence, root causes were classified as: 'second tier', a mutually exclusive binary classification based on common circumstances associated with each cause of death (e.g., ran out of gas: yes/no); the 'harmful action' that was thought to have led to the second tier status, and finally the 'trigger', the reason the harmful action happened (the most significant contributing factor). While each causal path usually involves many possible contributing factors, this analysis considered the most common and relevant factors in each cause of death (e.g., running out of gas is the most common event that precedes drowning). The available evidence was queried following a causal taxonomy instrument developed in 2007.[2] This method has been shown to have high inter-rater agreement. Reviewers for this study were both trained and active cave divers. The classification instrument was then reduced to include root causes in only trained cave diver fatalities in the USA and divided into two 15-year groups. The early group included fatalities that occurred between 01 July 1985 and 30 June 2000, the late group between 01 July 2000 and 30 June 2015.

As all divers in this sub-analysis were trained, the training rule was met for each case. As well as classifying the root causes, violations of any of the other four safe-cave-diving rules were noted. Each rule broken was then deemed relevant or irrelevant to the fatality based on whether or not the violation directly affected the outcome.

CHARACTERISTICS – EARLY AND LATE GROUPS

Data were stored in an Excel® spreadsheet and analysed using SAS version 9.4 (Cary, NC). The trend for cave diving fatalities to increasingly involve trained cave divers was tested for significance with a Cochran-Armitage test. The linear variables age and distance into the cave were tested for normality (Proc Univariate). Age was normally distributed (skewness 0.55, kurtosis -0.21). Distance was not and so a fitted lognormal distribution was tested using Anderson-Darling, Cramér-von Mises and Kolmogorov-Smirnov tests. At $\alpha > 0.10$ significance level, all tests supported that the lognormal distribution provided a good model for the distribution of distance into the cave. Student's *t*-tests were then used to assess differences in age and log-distance between early and late groups. Logistic regression was used to test for differences in binary outcomes between these groups, (sex, DPV use, use of closed circuit). Significance in all cases was accepted at $P < 0.05$.

Figure 1
Annual USA cave diving fatalities 1985−2015 with trend line



Results

A total of 161 divers were initially identified, 67 trained and 89 untrained in cave diving, with five divers having an undetermined training status. While the number of cave diving fatalities has steadily fallen over the last three decades (Figure 1), the proportion of trained divers among those fatalities has steadily increased. Table 1 presents the training status of the fatalities in each group. There was an almost complete reversal of trained and untrained proportions between the two time periods (two-sided Cochran-Armitage trend test $P < 0.0001$).

Sixty-one of the 67 cave-trained fatalities occurred in the state of Florida. The Devil's system led with 14 deaths. Jackson Blue Spring, Little River Spring, and Peacock Springs followed, accounting for five deaths each. Four deaths took place in the Eagle's Nest system and three deaths occurred at Madison Blue Springs.

Table 2 summarises the demographics of the divers, details of the dives and the equipment used. Trained cave diver fatalities in the most recent time period were older ($P = 0.002$). While the latter group included double the

Table 1
Cave diving fatalities 1985–2015 by training status; *n* (%); * $P < 0.0001$

	Untrained	Trained	Total
July 1985–June 2000	66 (69)	30 (31)*	96 (62)
July 2000–June 2015	23 (38)	37 (62)*	60 (38)

Table 2
Characteristics of trained cave divers, dive data and equipment used by time period; † data sources used feet; DPV – diver propulsion vehicle; * $P = 0.002$

	Early group (n = 30)	Later group (n = 37)	Overall (n = 67)
Age (years) mean (SD; *n*)	36 (11; 30)	45 (12; 36)*	40 (12; 66)
Male/female ratio	28/2	32/5	60/7
Depth (feet†) mean (SD; *n*)	122 (78; 29)	102 (71; 27)	112 (74; 56)
Distance (feet†) mean (SD; *n*)	698 (850; 24)	1,029 (1,043; 27)	873 (962; 51)
Breathing circuit (*n*)			
Open	28	29	57
Closed	1	6	8
Single or double (*n*)			
Single fatality	28	32	60
Double fatality	2	5	7
DPV used (*n*)	6	11	17

percentage of females of the earlier group, this was not significantly different ($P = 0.37$). Recent deaths occurred further into the cave ($P = 0.06$). DPV use increased non-significantly from six of 30 divers in the early group to 11 of 37 in the latter group ($P = 0.50$). The majority of fatalities from both periods occurred wearing open-circuit cylinders on the back and four in each period were diving with the cylinders in side-mount configuration. The number of fatalities using CCRs increased non-significantly from one to seven ($P = 0.11$).

Rules broken and those which were considered by the two reviewers to have been relevant to the outcome are presented in Table 3. At least one rule was broken by 13 of the 30 divers in the early group and 14 of the 37 in the later group. The rule of thirds was most commonly broken (n = 20) and most commonly relevant to the outcome (n = 11), followed by the line rule and gas rule (Table 3). The light rule was not considered relevant to any fatalities.

The causal chain of each trained cave diver fatality is shown in the taxonomy of cave diving fatalities flowchart in Figure 2. The most common cause of death was asphyxia due to drowning (n = 41). In 28 of those, the second tier was running out of gas, and the most common harmful action preceding this was getting lost (n = 12). Triggers for getting

Table 3
Summary of broken rules and relevancy by time period; *n* (%)

	Early group (n = 30)	Later group (n = 37)	Overall (n = 67)
Rules broken			
Thirds rule	6	8	14
Gas rule	4	5	9
Line rule	6	2	8
Light rule	1	2	3
Broken and relevant			
Thirds rule	3	8	11
Line rule	5	2	7
Gas rule	2	2	4
Light rule	0	0	0

lost included loss of visibility due to suspended silt (LVSS) (n = 6), taking a wrong turn in a complex cave system (n = 3) and entering a cave without a continuous guideline back to safety (n = 2).

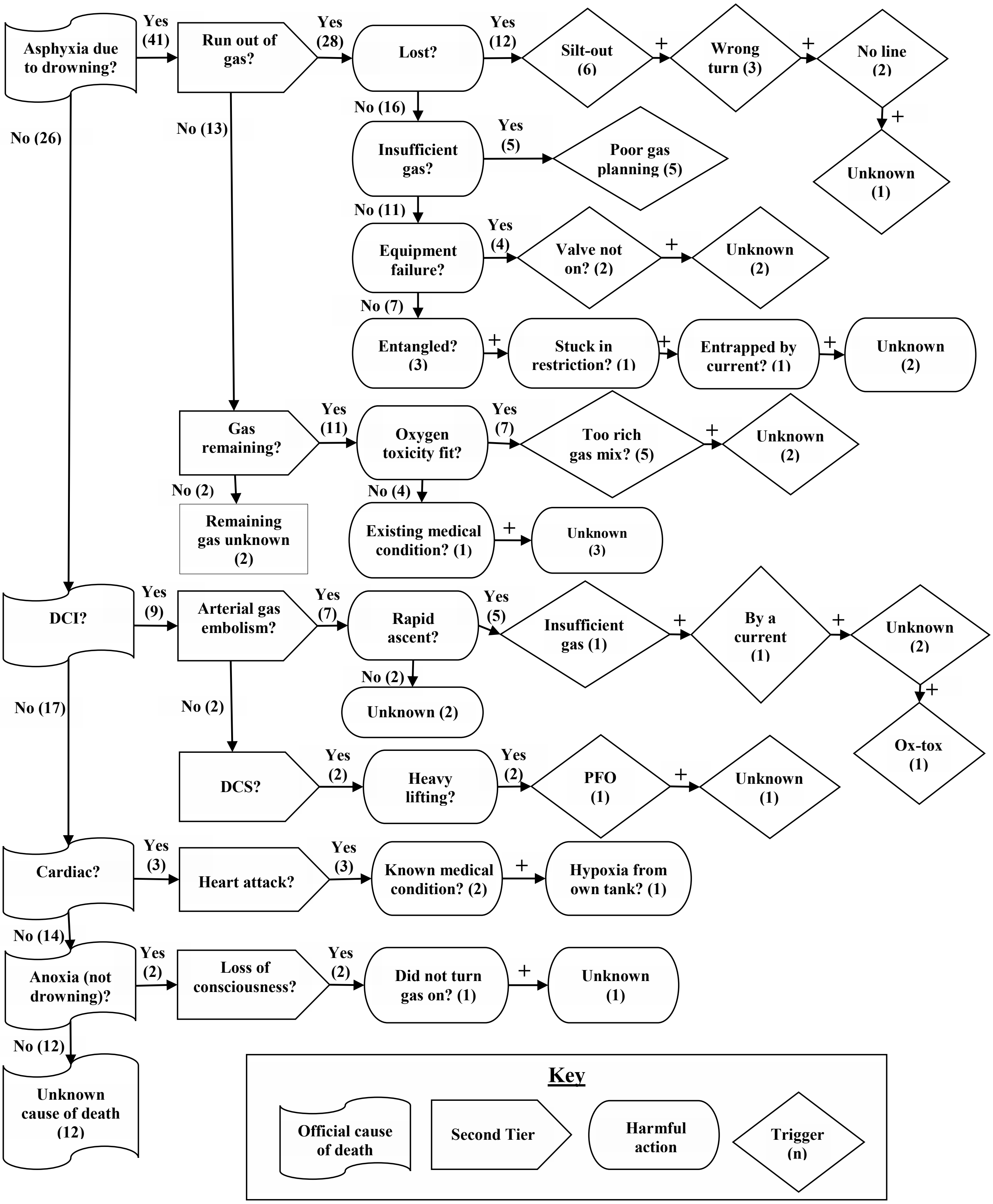
Eleven drownings occurred due to other harmful actions: seven had witnessed convulsions (seizures) at depth; in at least four of those, the harmful action was using the wrong tank with a breathing gas mix which was toxic at the dive depth and a fifth diver had old oxygen sensors in his rebreather. For two divers, the remaining gas was not known (Figure 2) and there were two more divers who appeared to have suffered CNS seizures; one in which there was no medical examiner's report or death certificate, so the case was classed as 'unknown', and one where the cause of death was determined to be arterial gas embolism, following the harmful action of a rapid ascent caused by oxygen toxicity.

Also notable are two divers who apparently did not trust the direction of line arrows indicating the direction towards the nearest exit and swam further into the cave, while the surviving buddies followed the direction of the arrows to a safe exit. The cause of death in two further divers was reported as 'anoxia' (not drowning); one in which the diver did not open the valve of his rebreather oxygen cylinder and the other where the diver remained in a coma for two weeks before dying.

Discussion

The apparent annual decrease in cave diving fatalities in the US and that fewer were untrained may be because of the increased availability of cave diver training and restricted access to caves for untrained divers. However, this is somewhat speculative in the absence of known denominators. The average age of fatalities among trained cave divers has increased at a comparable rate to that among recreational diving fatalities generally, by approximately two years in every four.[9] Concurrently, the proportion of females among the fatalities has doubled but remains

Figure 2
Taxonomy of USA cave diving fatalities in divers trained in cave diving techniques; Ox-tox – oxygen toxicity



relatively small and statistically insignificant. Whether or not the proportion of women fatalities observed in this study is commensurate with the proportion of women who cave dive, or the proportion of cave dives made by women, cannot be determined from this study alone. Aside from increasing age, there is little difference in anthropometrics between the early and late groups of cave diving fatalities.

When it comes to the five golden rules, two, in particular, have emerged as crucial to survival: the line rule and the thirds rule. Maintaining a continuous guideline to the surface remains as essential as ever. The logic behind turning the dive when no more than a third of the total gas reserve has been spent is that any solo diver or pair of divers would have the minimum gas required to exit even if they were to lose half their total gas at the point of maximum penetration. Among the cave-diving-trained fatalities in this study for whom breaking the thirds rule was thought relevant, all but one ran out of gas, whereas among those for whom breaking the thirds rule was not considered relevant ($n = 56$), 19 died owing to other circumstances (e.g., entangled in line or stuck in a restriction) and nonetheless ran out of gas. Solo cave divers and buddy pairs especially may want to consider if the rule of thirds is adequately conservative for their intended dive. While the thirds rule aims to mitigate a catastrophic loss of gas, it may not adequately account for unintended delays such as loss of visibility from suspended silt, entanglement or entrapment in a restriction.

As in a larger study that included untrained cave divers, drowning was the most common cause of death.[2] In both studies, the commonest cause of drowning was running out of air due to loss of visibility. Since most oxygen toxicity seizures are preventable, cave diver training agencies should also continue to reinforce the rule "*always dive at, or shallower than, a safe depth for the gas being used*". Promoting the analysis of all breathing gases before every dive and clear marking of the cylinders is also important for diving safety. Four divers breathed an oxygen-rich gas at depth that was intended for decompression and a fifth diver is thought to have been using a rebreather with out-of-date oxygen sensors and a malfunctioning solenoid. This combination may have raised the inspired partial pressure of oxygen without alerting the electronic alarm system. Individual variation in susceptibility to oxygen toxicity may also be a key factor, possibly contributing to four more cases, when coupled with additional factors such as exercise.

Conclusions

The proportion of divers dying in caves in the US who were not trained for cave diving has steadily fallen over the last three decades. The average age of trained cave divers who died, as with recreational divers in general, has increased. Fatalities involving DPVs, rebreathers and greater distance penetrations are also on the rise, though none statistically significantly, given the relatively small numbers. Use of these new types of equipment and styles of diving are not specifically covered by the five historic safe cave diving rules and should only be adopted after careful personal consideration, for example, with regards to DPV redundancy. The line rule and thirds rule are as relevant as ever and we recommend that cave divers pay particular attention to gas planning and use of a continuous guideline. We recommend that divers do not get off the guideline, particularly during loss of visibility, as well as doing double and triple checks that the gases they are breathing are appropriate for their intended dive depths.

References

1 Webster DP. Skin and scuba diving fatalities in the United States. *Public Health Rep*. 1966;81:703-11.
2 Buzzacott P, Zeigler E, Denoble P, Vann R. American cave diving fatalities 1969-2007. *International Journal of Aquatic Research and Education*. 2009;3:162-77.
3 Exley S. *Basic cave diving: a blueprint for survival*. Brandford, FL: National Speleological Society Cave Diving Section; 1979.
4 Zumrick JL, Prosser JJ, Grey HV, editors. *NSS Cavern Diving Manual*. 1st ed. Branford, FL: National Speleological Society Cave Diving Section; 1988.
5 Jablonski J. *Beyond the daylight zone: The fundamentals of cave diving*. High Springs, FL: Global Underwater Explorers; 2001.
6 Fock AW. Analysis of recreational closed-circuit rebreather deaths 1998-2010. *Diving Hyperb Med*. 2013;43:78-85.
7 Denoble PJ, Caruso JL, Dear GL, Pieper CF, Vann RD. Common causes of open-circuit recreational diving fatalities. *Undersea Hyperb Med*. 2008;35:393-406.
8 Lippmann J, Lawrence CL, Wodak T, Fock A, Jamieson S, Walker D, Harris R. Provisional report on diving-related fatalities in Australian waters 2010. *Diving Hyperb Med*. 2015;45:154-75.
9 Denoble PJ, Pollock NW, Vaithiyanathan P, Caruso JL, Dovenbarger JA, Vann RD. Scuba injury death rate among insured DAN members. *Diving Hyperb Med*. 2008;38:182-8.

Acknowledgements

The authors wish to thank the many agencies that assist DAN in diving fatality research, and DAN fatality researchers Jeanette Moore and Brittany Trout.

Conflicts of interest: nil

Submitted: 04 December 2015; revised 14 March, 05 May and 24 July 2016
Accepted: 25 July 2016

Leah Potts[1,2], Peter Buzzacott[1,3], Petar Denoble[1]

[1] Divers Alert Network, Durham, North Carolina, USA
[2] Department of Agricultural and Biological Engineering, University of Florida, Gainesville, Florida, USA
[3] School of Sports Science, Exercise and Health, University of Western Australia, Crawley, Australia

Address for correspondence:
Peter Buzzacott
Divers Alert Network
6 West Colony Place
Durham, 27705, USA
pbuzzacott@dan.org