

Original articles

The incidence of decompression illness in 10 years of scientific diving

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Abstract

(The incidence of decompression illness in 10 years of scientific diving. Dardeau MR, Pollock NW, McDonald CM and Lang MA. *Diving and Hyperbaric Medicine*. 2012;42(4):195-200.)

Background: The American Academy of Underwater Science (AAUS) constitutes the single largest pool of organizations with scientific diving programmes in North America. Members submit annual summaries of diving activity and any related incidents.

Methods: All diving records for a 10-year period between January 1998 and December 2007 were reviewed. Incidents were independently classified or reclassified by a four-person panel with expertise in scientific diving and diving safety using a previously published protocol. Subsequent panel discussion produced a single consensus classification of each case.

Results: A total of 95 confirmed incidents were reported in conjunction with 1,019,159 scientific dives, yielding an overall incidence of 0.93/10,000 person-dives. A total of 33 cases were determined to involve decompression illness (DCI), encompassing both decompression sickness and air embolism. The incidence of DCI was 0.324/10,000 person-dives, substantially lower than the rates of 0.9-35.3/10,000 published for recreational, instructional/guided, commercial and/or military diving.

Conclusions: Scientific diving safety may be facilitated by a combination of relatively high levels of training and oversight, the predominance of shallow, no-decompression diving and, possibly, low pressure to complete dives under less than optimal circumstances.

Key words

Decompression illness, decompression sickness, occupational health, safety, scientific diving, epidemiology

Introduction

Scientific diving is diving performed by individuals that is necessary to and part of a scientific research or educational activity, in conjunction with a project or study under the jurisdiction of any public or private research or educational institution or similar organization. Divers can join programmes with or without prior diver training or experience. Once in the programme they undergo medical evaluation, skill evaluation and diver training. Diving operations are required to adhere to formal programme rules, including depth and, often, task restrictions. Scientific diver currency requires meeting standards of minimum diving activity, refresher training and periodic medical review. A diving officer, acting on behalf of an institutional diving control board, is typically responsible for the training and monitoring of all scientific diving activity, ensuring compliance with rules and safe and effective dive team operations. While much of the diving is conducted as shallow, multi-level, no-decompression exposures, operations are conducted under a range of conditions, from tropical to polar, fresh and saltwater, sea level and high altitude, demanding both skill and appropriate real-time decision-making to prioritize safety. The safety record of scientific diving programmes is generally recognized as very good, but the published documentation is limited.

A review of adverse events reported within the scientific diving community concluded that total pressure-related injury rates from 1998 to 2005 were similar to those calculated by the US Occupational Safety and Health Administration (OSHA) for scientific divers during the late 1970s.¹ The computation of injury rate per 100 workers per year was matched to the earlier OSHA method. Both studies included minor barotrauma as well as decompression illness (DCI – the collective term for decompression sickness [DCS] and arterial gas embolism [AGE]) but did not address the incidence of only DCI. The limited reports on the incidence of DCS for scientific diving range from 0/10,000 person-dives in Australia to 2.8/10,000 person-dives in the Antarctic.^{2,3} These rates are relatively low when compared to the 1.4–35.3/10,000 person-dive estimates for commercial and military diving communities, but additional documentation is required.³

The American Academy of Underwater Sciences (AAUS) was formed in 1977 as a collection of organizational member programmes representing a range of public and private academic institutions, educational entities and research units with active involvement in scientific diving. AAUS membership requires programmes to submit annual summaries of dives, mode of diving and any incidents associated with scientific diving. These diving records make

AAUS a major source of data on scientific diving in North America. Our goal was to determine the incidence rate of DCI in a large and diverse record of scientific diving.

Methods

We reviewed 10 years of diving records reported by AAUS organizational members, from January 1998 through December 2007. Human subjects research approval for the study was provided by the Divers Alert Network's institutional review board.

A four-person review panel, experienced in scientific diving, the administration of scientific diving programmes, and diving safety, reviewed all submitted incident reports. While incident types (hyperbaric, near drowning, etc) were defined for reporting purposes, there was some latitude for diving safety officers to determine what was reportable.¹ A four-step filtration process was employed to remove cases representing other-than-DCI. The first step excluded records that were 'non-events' (submission error) or 'no injury' cases. The second excluded cases that were not pressure-related. The third excluded cases of minor barotrauma (e.g., ear squeeze). The remaining cases (possible DCI) were then classified or reclassified as 'DCI', 'ambiguous' or

'not DCI' using a modified version of previously described standardized criteria designed for objective post hoc, non-clinical assessment (Table 1).⁴ The panel reviewed all possible DCI cases independently and then came together to assign final classification based on consensus decision. Contentious or incompletely documented cases were further investigated through interviews with involved persons. Ambiguous cases were considered to be cases of DCI for the computation of incident rates.

All data in the present study reflect person-dives, that is, even when a team of two or more dives together, each diver reports the dive as an individual event. Incident rates and 95% binomial confidence intervals (CI) are presented as cases per 10,000 person-exposures. A Chi-square contingency table was used to compare annual differences in DCI across reporting years. Significance was accepted at $P < 0.05$.

Results

Annual scientific diving activity reported by AAUS members appears in Figure 1. The number of members reporting increased substantially during the study period (ranging from 54 to 94), in turn increasing the number of divers (ranging from 2,716 to 4,101) and person-dives tallied

Table 1

Case (diagnosis) classification/reclassification (adapted from⁴); AGE –arterial gas embolism, DCI – decompression illness

Cases classified as 'not DCI'

- a) Cases with single dives to less than 9 metres' sea water (msw) and symptoms that could not be attributed to AGE;
- b) Cases with symptom onset times more than 48 hours after the last dive or altitude exposure;
- c) Cases with signs and symptoms likely due to a non-diving cause of injury upon review of medical history;
- d) Isolated headache, dizziness, anxiety, general weakness, fatigue, or subjective numbness and tingling of both hands and feet, in the absence of other symptoms or without objective findings.

Note: Cases with no response to recompression were reviewed extensively before being classified as 'not DCI'.

Cases classified as 'ambiguous'

- a) Cases with sufficient exposure but minimal or atypical symptoms;
- b) Cases in which symptoms resolved spontaneously without recompression in less than 20 minutes with surface oxygen or less than 60 minutes without oxygen;
- c) Cases with confounding medical conditions that could explain the symptoms;
- d) Combinations of headache, dizziness, anxiety, general weakness, fatigue, and subjective numbness and tingling of both hands and feet, in the absence of other symptoms or without objective findings.

Cases classified as 'DCI'

Decompression sickness:

- a) Cases with a dive depth of at least 9 msw;
- c) Joint/limb pain, skin/lymphatic symptoms, constitutional/non-specific symptoms;
- d) Serious neurological, cardiopulmonary, mild neurological and simultaneous presence of pain and constitutional symptoms.

AGE:

- a) Cases with symptom onset in less than 15 minutes post-dive;
- b) Cases with cerebral neurological symptoms, signs or findings;
- c) Cases with symptom duration greater than 15 minutes.

Note: Rapid ascent, out-of-air incident, or the presence of cardiopulmonary symptoms increased the confidence of an AGE diagnosis.

Figure 1

Number of divers and reported scientific dives by year

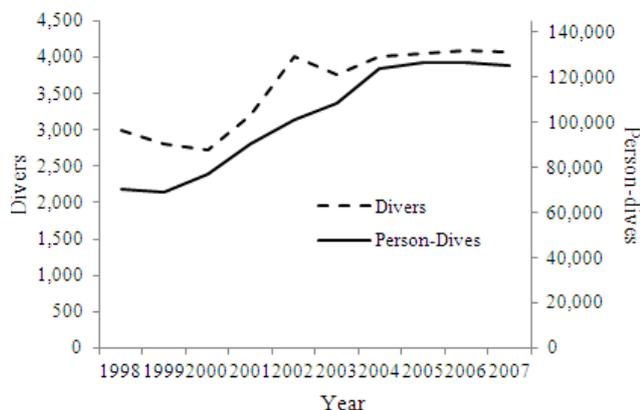
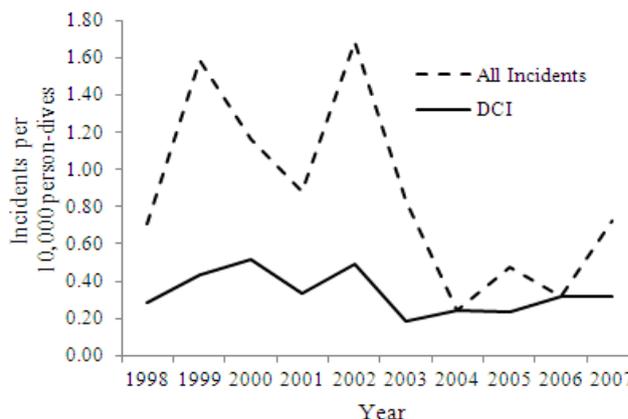


Figure 2

All incidents and DCI cases reported



annually (ranging from 68,598 to 126,831; Figure 1). The number of dives completed by individual organizational members varied tremendously, based on the size of the diving programme and active scientific diving projects. Most organizational members were American institutions, with only three to five based outside the United States for any given year.

The 10-year study period captured 1,019,159 person-dives and 102 incidents occurring in conjunction with these exposures. No case involved multiple victims of a single event. A summary of the case count by year before and after filtration and/or reclassification to include only DCI cases appears in Figure 2. Steps to improve the reporting of organizational member diving activity began with the 2004 reporting cycle and culminated in the implementation of a formal training programme for new diving safety officers in 2006. It is possible that the apparent decline in reporting non-DCI events was associated with heightened awareness gained through these efforts.

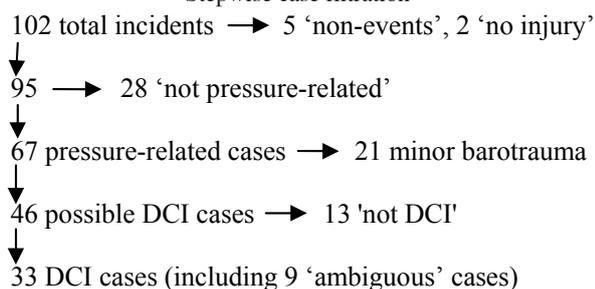
The stepwise filtration of incident reports is summarised in Table 2. The first step excluded seven cases; five as ‘non-events’ and two as ‘no injury’. The second step excluded 28 cases as ‘not pressure-related’ (including two fatalities resulting from medical emergencies – one a myocardial

infarction following an unremarkable checkout dive and the other a case of unexplained sudden death following a very short, shallow exposure). The third step excluded 21 cases of mostly minor barotrauma, yielding 46 cases of possible DCI.

The 46 cases of possible DCI we identified included 13 that were treated with recompression but then classified as ‘not DCI’. Of these, five involved a history of back or shoulder injury that did not respond to hyperbaric treatment, five involved unrelated medical conditions that were initially submitted as DCS, and three cases involved symptoms more likely related to environmental conditions (thermal stress and anxiety). In only one case did we ‘overturn’ a physician diagnosis of DCS (in agreement with a follow up by another physician who ruled out DCS). In one other case, we retained a classification of DCS when a physician changed his diagnosis to rule out DCS following recompression therapy. This incident involved a diver who reported having shoulder pain pre-dive that felt better at depth and returned post-dive (he had dived two days earlier). The pain was fully resolved upon completion of a US Navy Treatment Table 6. Ultimately, 33 cases were classified as DCI, 25 with fully evolved symptomology and eight with ambiguous symptoms. Recompression therapy was reported to be successful in 28 of the 33 DCI cases; 19 with a single treatment and nine with multiple treatments.

Table 2

Stepwise case filtration

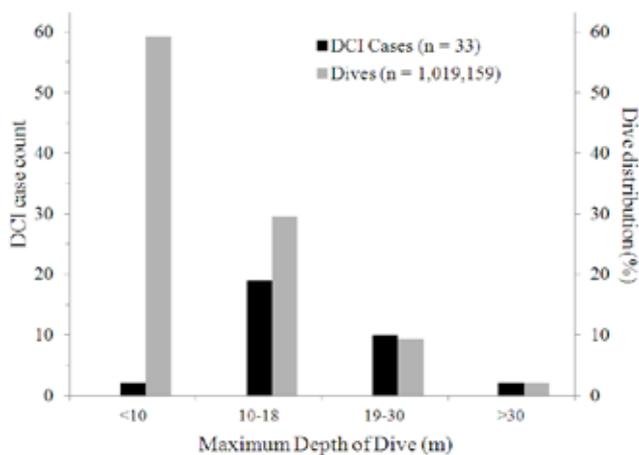


The 95 valid incident reports yielded an all-events incidence rate of 0.93/10,000 person-dives. The 33 DCI cases yielded a rate of DCI of 0.324 per 10,000 person-dives (95% CI 0.234 to 0.424). The annual rates of DCI were not significantly different (X^2 [df 9; crit 16.92] = 3.32), ranging from a low of 0.18/10,000 persons-dives in 2003 to a high of 0.52/10,000 person-dives in 2000 (Figure 2).

The distribution of maximum depth for all captured dives was 59% < 10 metres’ sea water (msw), 30% 10–18 msw, 9% 19–30 msw and 2% > 30 m (Figure 3). Exposures with a maximum depth < 10 msw included only one case diagnosed

Figure 3

Depth distribution of DCI cases (count) & dive distribution (%)



as an arterial gas embolism and one ambiguous DCI case. All but four DCI incidents occurred on dives with maximum depths between 9 and 30 msw. Two DCS cases occurred on dives to depths in excess of 40 msw.

Discussion

DCI is a relatively rare event, requiring monitoring of exposures over a broad geographic area and a long time period to yield meaningful rates.⁵ A number of incidence measures have been published, but all with much smaller exposure numbers than the current study (ranging from 14,944 to 700,000 exposures). DAN's Project Dive Exploration estimates of the incidence of DCI in the recreational community to be 2.0–4.0/10,000 person-dives.^{4,6,7} This is higher than previously reported rates of 0.90/10,000 person-dives (DCS) and 0.96/10,000 person-dives (DCI).^{8,9} DCS rates among divemasters and instructors have been estimated at 12.7–15.2/10,000 person-dives.¹⁰ The rate of DCI among military sport divers has been estimated at 1.34/10,000 person-dives.¹¹ Shallow, no-decompression dives among navy divers produced incidence of DCS of 2.9/10,000 person-dives.¹² The US National Oceanic and Atmospheric Administration (NOAA), which conducts both working dives as well as scientific dives, reported a DCS incidence of 1.8/10,000 person-dives.¹³ The incidence of DCS in commercial decompression diving has been reported to be as high as 35.3/10,000 person-dives.¹⁴ A more recent study reported commercial diving DCS incidence rates ranging from 1.4 to 10.3/10,000 person-dives depending on the depth of dive operations.¹⁵

Long-standing Antarctic scientific diving programmes are managed by several nations.^{16,17} The incidence rate of DCS for Antarctic scientific diving is reported as 2.8/10,000 person-dives (there were no cases of AGE).³ Outside of Antarctic scientific diving, DCS/DCI incidence rate estimates in the scientific diving community are lower than in other diving populations.³ Estimates range from 0/10,000

dives to 0.6/10,000 person-dives.^{2,18} The zero estimate was based on 14,944 person-dives and the 0.6/10,000 estimate included only one case of DCS in 15,711 exposures. The rate of 0.32 incidents per 10,000 person-dives reported in the current study falls within this range. The requirements for routine diving medical surveillance, equipment maintenance requirements, and additional training and oversight combined with the predominance of shallow, no-decompression diving, may result in lower incident rates in the scientific community than in other diving populations.^{5,19}

Risk estimate efforts have several limitations. A frequent challenge of epidemiological studies is the accurate quantification of all relevant activity, effectively the denominator needed to compute incident rates. Exposure to DCI among recreational divers has been determined using prospective studies, or more roughly estimated by surveys or by surrogate counts such as cylinder fills.^{4,6,9,11,20} Less available are the data generated by occupational diving programmes that require routine logging of both dives and incidents. An additional complication of studying DCI is the potential confounding of clustering as injury may be likely to affect multiple individuals on a shared dive. It is not always clear whether the reported denominator is the number of dives or the number of person-dives.¹⁸

A major challenge is the sometimes idiosyncratic and often difficult-to-define nature of DCI. Given the difficulty of diagnosis, combined with a tendency to treat conservatively, it is not surprising that many cases treated as DCI may in retrospect be classified or reclassified as 'not DCI' or 'ambiguous'. Of 435 cases of DCI reported in the recreational diving community treated with recompression, 85 (20%) were objectively reclassified as not DCI, making it clear that appropriate incident rate computation is dependent upon careful evaluation of individual cases.⁶ In another study 10 of 104 recompressed cases were reclassified as 'not DCI'.¹¹ The current study resulted in the reclassification of 13 of 46 cases from possible DCI to 'not DCI'. It is important to note that the classification/reclassification criteria used in this study were intended to enable objective post hoc assessment for scientific, not clinical purposes. While the reviewers in the current study all had extensive experience with professional diving, none were medical clinicians. The lack of clinical expertise could lead to errors in case classification and our findings are not intended to challenge clinical skill or decision-making.

Notwithstanding evidence that DCS may be over-reported and often treated conservatively, there are also an unknown number of unreported cases. Prior to the 1980s, when minor symptoms of pain were more accepted as a routine part of diving, divers may have been reluctant to report symptoms. Even with the current emphasis on early reporting and the greater accessibility to treatment, some divers may still be hesitant to report minor symptoms. This situation produces some uncertainty with the estimated numerator as well.

There may also be some variability in incidents deemed reportable by individual institutions. Some might choose to report only cases in which time loss or injury occurs. Others might choose to report all events, regardless of cost or outcome. Data collection could be improved by comprehensive definition of reportable events, changing from annual reporting to near-real-time reporting of incidents, and adding further structure to case-review procedures.

Documenting the degree of risk associated with a given dive or dives is also problematic. We have presented the maximum depth of the dive in which the incident occurred or followed, but this may miss information of potentially substantial value. Decompression stress can be influenced by the specific profile of a given dive and also by previous dives in a series. AAUS diving records do not currently include depth-time profiles for dives and information regarding dives preceding an incident dive is frequently incomplete, effectively making it impossible to quantify decompression stress independent of outcomes. Our data do confirm a high level of safety for dives conducted in less than 10 msw depth. This is certainly expected in terms of decompression safety and a welcome observation regarding severe barotrauma. The total number of cases of DCI is too small to make strong statements regarding the distribution of DCI in the depth categories greater than 9 msw. The progressive nature of scientific diver depth authorization does help to ensure that divers have greater experience for increased working depths, which may promote safety.

AAUS represents a substantial number of programmes involved with scientific diving, but many agencies and organizations conducting scientific diving do not report to AAUS. For example, NOAA conducted 208,459 person-dives between 1981 and 2004, of which some would certainly meet the definition of scientific diving.¹³ Similarly, the Alaska Department of Fish and Game made over 10,933 person-dives between 1990 and 2000.²¹ Ultimately, while capturing an impressive amount of activity, AAUS dives are not the only scientific dives performed by US organizations.

Despite the limitations of this study and many others evaluating diving risk, it does appear that scientific diving represents one of the safer forms of diving. This safety may be facilitated by a combination of relatively high levels of training and oversight, the predominance of shallow, no-decompression diving and, possibly, low peer or institutional pressure to complete dives under less than optimal circumstances. Additional research to compare the decompression stress of actual exposures, the pressure to conduct dives, reporting practices, and other variables that exist between the diving sub-fields could provide useful insights to understand the real risks.

Conclusions

We reviewed incidents reported in conjunction with 1,019,159 scientific dives documented by AAUS organizational members from January 1998 through December 2007. A total of 95 valid incidents were reported, yielding an all-incidents rate of 0.931/10,000 person-dives. Case-by-case review indicated that 33 of the cases involved DCI. The incidence of DCI was 0.324/10,000 person-dives (including ambiguous cases). This rate is substantially lower than the previously published rates for recreational diving, instructional/guide diving, commercial and military diving. Data collection efforts may be improved by developing real-time incident reporting guidelines instead of relying primarily on annual reporting, and developing additional protocols for immediate follow up of defined cases.

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Conflict of interest

All four authors are current or past members of the AAUS Board of Directors.

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