DIVERS ALERT NETWORK

DAN ANNUAL DIVING REPORT

2021 EDITION

A report on 2019 diving fatalities, injuries, and incidents

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FRAUKE TILLMANS, PHD
EDITORS

DIVERS ALERT NETWORK
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FOREWORD

William Ziefle, DAN President and CEO

The 2021 DAN Annual Diving Report presents detailed analyses of dive incidents as well as trends we observed in 2019. Our Annual Diving Report is one example among many of DAN's commitment to promoting diver safety through data collection, analysis, and dissemination of findings. This report is intended to be a resource for divers, dive instructors, medical professionals, and researchers alike.

The report begins with an overview of the data collection process, highlighting the methods used to gather and verify information about dive injuries and fatalities. These include notifications from affiliated organizations, internet searches, and direct reports from individuals. The DAN Medical Services Call Center (MSCC) plays a pivotal role in managing and documenting these incidents, ensuring that relevant data is captured.

Various members of DAN staff, partners at international DAN offices, and outside contributors delve into dive injury and fatality statistics to provide a detailed breakdown of incidents by geographic location, diver classification, and type of dive. This analysis includes a comparison to previous years, offering insights into trends and potential areas of concern.

This year's report highlights accidents in which the diver was practicing breath-hold diving (freediving and/or snorkeling) or technical diving and features a special review of the diving activities of and incidents involving minor children.

Breath-hold diving has deep historical roots and modern recreational appeal. This report examines the risks associated with breath-hold diving, including shallow water blackout, and the physiological challenges posed by prolonged apnea. The data underscore the importance of proper training and vigilance to mitigate these risks.

Technical diving continues to grow in popularity. As a discipline that involves greater depths, extended bottom times, and the use of specialized equipment, it involves unique risks, which this report highlights. Among these risks are equipment failures and the physiological stresses of deep diving. Detailed case studies provide valuable lessons for tech divers and instructors.

This report also includes an in-depth analysis of breathing gas contaminants. We cover sources, detection methods, and health implications of various contaminants, including carbon dioxide, carbon monoxide, and oil particulates.

2019 presented an opportunity to publish a study about diving incidents involving minors, highlighting the unique physiological and psychological challenges young divers face. Analysis of these incidents reveals that minors are particularly susceptible to ear, nose, and throat injuries. The report calls for specialized training and supervision to better ensure the safety of young divers.

By analyzing incidents and trends, DAN provides the diving community with knowledge that can help prevent accidents and improve safety. This report is a testament to the dedication of DAN and its partners in promoting safe diving practices worldwide. We hope that it will inspire continued vigilance and innovation in diving safety, helping to ensure that divers of all ages and skill levels can confidently explore the underwater world.

Bill Zeifle,
President & CEO,
Divers Alert Network

SECTION 1. **DIVING FATALITIES**

S. Lesley Blogg PhD, Catherine Harris, James Chimiak MD, Frauke Tillmans PhD

INTRODUCTION

The 2021 DAN Annual Diving Report presents descriptive statistics and selected case summaries of recreational diving fatality data collected in 2019.

The annual number of deaths, and the age of the victims are known major trend indicators, and where possible all data are compared to that from the previous 10 years. This helps to produce more accurate reports, as there is often significant variation in reporting of fatalities from year to year.

THE DATA COLLECTION PROCESS

INITIAL NOTIFICATION AND CASE QUALIFICATION

The data collection process has not changed since 2016, and begins with an initial notification that may come as voluntary reports from affiliated organizations and individuals, active internet searches, and automated internet alerts. News alerts are used to monitor online news media outlets for keywords that involve scuba and breath-hold related deaths. Sorting through these results is difficult, as regardless of how refined the criteria are there is a pool of redundant and useless reports that far exceed the number of accident cases.

Other sources of notifications regarding fatalities come from individual reports made by families of DAN members, and friends and acquaintances of decedents who are aware of DAN's fatality data collection efforts. The DAN Medical Services Call Center (MSCC) is the most valuable single resource, as the DAN Medical Services Department assists with the management of any diving incident that is called in, whether the victim is a DAN member or not.

All recreational compressed gas diving fatalities that occur in the U.S. or Canada and all deaths of U.S. or Canadian citizens, no matter where they occur, are marked for follow-up by a DAN member of staff. In the present report, recreational compressed gas diving includes students, certified divers, and diving professionals (instructors and dive guides) involved in non-commercial diving.

Rebreather diving fatalities are also reported within this classification. A more in depth analysis of rebreather accidents can be found in Section 5 of this report. Any fatalities that occur outside the U.S. or Canada and involve citizens of other countries are classified as foreign and are not followed-up due to logistic issues.

Cases that occur during non-recreational dives (e.g., military, commercial, fishing, and public safety dives) are classed as non-recreational and are also not followed up. Breath-hold fatalities, including freediving and snorkeling, are classified as a separate group. These data can be found in Section 4 of this report. DAN aims to collect all breath-hold data available, regardless of the geographical location of the accident or citizenship of the decedent.

INVESTIGATOR AND MEDICAL EXAMINER REPORTS

Local law enforcement agencies, medical examiners, the coroner's office, the U.S. Coast Guard (USCG) and Canadian Coast Guard frequently investigate diving-related deaths in their relevant territories. A proportion of victims are subject to autopsies, though not all, and it can take over a year to complete the investigation and produce reports. DAN tries to obtain all available reports, but there are often administrative hurdles to overcome, including privacy regulations of the relevant agencies. Thus, in many cases, these reports cannot be collected, which impedes DAN's ability to conduct analysis.

REPORTS FROM WITNESSES AND NEXT OF KIN

DAN uses the Fatality Reporting Form as a guide in order to collect data from witnesses and family members. The form may be requested from the DAN Research or Medical Services departments. When necessary, a family member of the decedent may be contacted to assist in the data-collection process. Family members may complete the Fatality Reporting Form and/or provide authorization for the release of the decedent's autopsy report.

The incident reporting form on the DAN website (https://redcap.link/DAN-report-an-incident) can also be used by family members and witnesses to report diving fatalities or to provide additional details regarding already reported fatalities.

There were 22 fatalities reported directly to DAN's Medical Services Call Center, which is low when compared to the previous years 2014–2017, as in 2018 (Table 1-1).

Table 1-1. Total number of fatality notifications received through the DAN Medical Services Call Center (MSCC).

Year	Total Count
2014	30
2015	28
2016	48
2017	58
2018	18
2019	22

DAN uses the Fatality Reporting Form to collect data from witnesses and family members. The form may be downloaded from the DAN website: https://dan.org/wp-content/uploads/2020/08/Diving-Fatality-Reporting-Form.pdf or requested from the DAN Research or Medical Services departments.

DATA ENTRY AND ANALYSIS

DAN Research maintains the diving fatality data on a secure server. Once all pertinent information has been gathered and added to the database the results are analyzed and published in the DAN Annual Diving Report.

NUMBER OF FATALITIES COLLECTED BY DAN

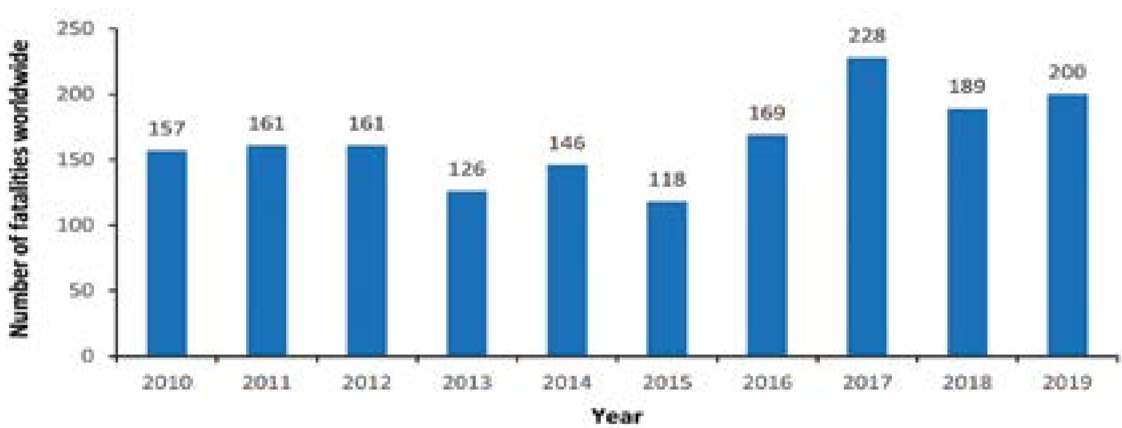
In 2019 DAN received notification of 200 deaths involving diving activities worldwide, a similar number to that reported for 2018 (n=189; Figure 1-1). The total number of recreational diving fatalities (n=104) is also similar to that reported in 2018 (n=100); a breakdown of cases by DAN diver classification is given in Table 1-2. In total there were 72 reported deaths in the U.S. and Canada, which is high compared to a 10 year mean of 45 deaths.

Table 1-2. Total number of fatalities collected worldwide in 2019 by diver classification (n=200) *This category might include boat work, dock repair, laying line, staging tanks etc.

Diver Classifications	United States and Canadian Citizens	Other	Total
Recreational	36	55	91
Breath-hold	15	36	51
Technical	8	30	38
Task*	3	2	5
Commercial	1	4	5
Public Safety	0	1	1
Military	0	0	0
Not known/ Unreported	4	5	9
Total	**67**	**133**	**200**

Once all pertinent information has been gathered and added the database, the results are analyzed and published in the DAN Annual Diving Report.

Figure 1-1. Total number of fatalities worldwide collected by DAN 2010–2019.



The number of follow-up cases for the United States, Canada, and other countries in 2019 is shown in Table 1-3. The worldwide follow-up cases (n=57 vs. 10-year mean n=79) and those for the U.S. and Canada combined (n=44 vs. n=58) was seen to be low when compared to the previous ten years. A comparison of worldwide cases by year from 2009 is show in Figure 1-2. These data further reflect the trend in a reduction of follow-up cases seen in 2018/2019, from a zenith of 154 follow-up cases in 2016. Non follow-up cases remained at a similar level as in recent years.

Table 1-3. Number of follow-up cases in the United States, Canada, and other countries for 2019 (n=57).

Country	Total count (2009–2018)	10-Year mean	Total count (2019)
United States	519	52	40
Canada	57	6	4
Other	207	21	13
Total	**783**	**79**	**57**

GEOGRAPHICAL AND SEASONAL DISTRIBUTION OF FATALITIES

The number of fatalities by country of death for 2019 is shown in Table 1-4 by International Organization for Standardization (ISO) region, and highlighted in Map 1-1. These data reflect the number of reports obtained by DAN through data collection efforts. It is unsurprising given DAN's proximity that the majority of fatalities captured occurred in the North America, however a large number of accidents were captured in Asia and Europe as well.

The country with the largest number of fatalities was the U.S. (n=67), followed by Australia (n=14), France (n=9), the United Kingdom (n=9), New Zealand (n=8), Indonesia (n=7), and the Maldives (n=6). Given the skew in the data towards North America, it is perhaps not surprising that over half (n=115) of the 200 diving related deaths recorded by DAN in 2019 occurred in the five months May to September, across summer in the northern hemisphere (Figure 1-3).

The number of fatalities reported in the U.S. and Canada for 2019 by state or province are reported in Table 1-5, where they are compared to the previous 10-year mean. These regions are also highlighted in Map 1-2.

Numbers of fatalities were increased slightly for Florida compared to previous years, while figures for California were lower than usual, at just four fatalities compared to a 10-year mean of 10. Figures increased dramatically for Hawaii, from eight in 2018 (the highest value per state in that year) to 22 fatalities in 2019; this is a large rise when

Table 1-4. Number of fatalities by country of accident in 2019.

Country by ISO region	n	Country by ISO region	n
North America	**72**	**Oceania**	**25**
United States	67	Australia	14
Canada	5	New Zealand	8
Europe	**41**	Fiji	2
France	9	Solomon Islands	1
United Kingdom	9	**The Caribbean**	**15**
Ireland	5	Antigua and Barbuda	4
Belgium	2	Cayman Islands	3
Greece	4	Bahamas	2
Italy	2	Barbados	2
Malta	2	St Kitts and Nevis	2
Spain	2	Dominican Republic	1
Croatia	1	Jamaica	1
Germany	1	**Central America**	**9**
Iceland	1	Mexico	5
Latvia	1	Belize	4
Switzerland	1	**Southern Africa**	**4**
Ukraine	1	South Africa	3
Asia	**28**	Madagascar	1
Indonesia	7	**Middle East**	**2**
Maldives	6	Saudi Arabia	2
Thailand	4	**Central Africa**	**1**
Malaysia	3	São Tomé and Príncipe	1
China	2	**Northern Africa**	**1**
India	2	Cabo Verde	1
Taiwan	2	**South America**	**1**
Japan	1	Colombia	1
Mauritius	1	**Total**	**200**

compared to a Hawaiian 10-year mean of four fatalities per year.

Table 1-6 breaks down the activity or accident type of the 22 decedents recorded in Hawaii. Half (n=11) of the victims had been snorkeling at the time of their accidents, while only four were scuba diving, and four breath-hold diving. The high number of snorkel accidents continues the trend that has been seen in Hawaii in recent years, where the activity has been the leading cause of tourist deaths.

While DAN aims to follow-up with all accidents, there are challenges in obtaining information as means of access and processes vary across states and other countries. Though Hawaii is a U.S. state, their process for obtaining investigative records involves more time and consideration than other states. As a state with

Figure 1-2. Number of dive fatalities and follow-up cases collected by DAN by year worldwide.

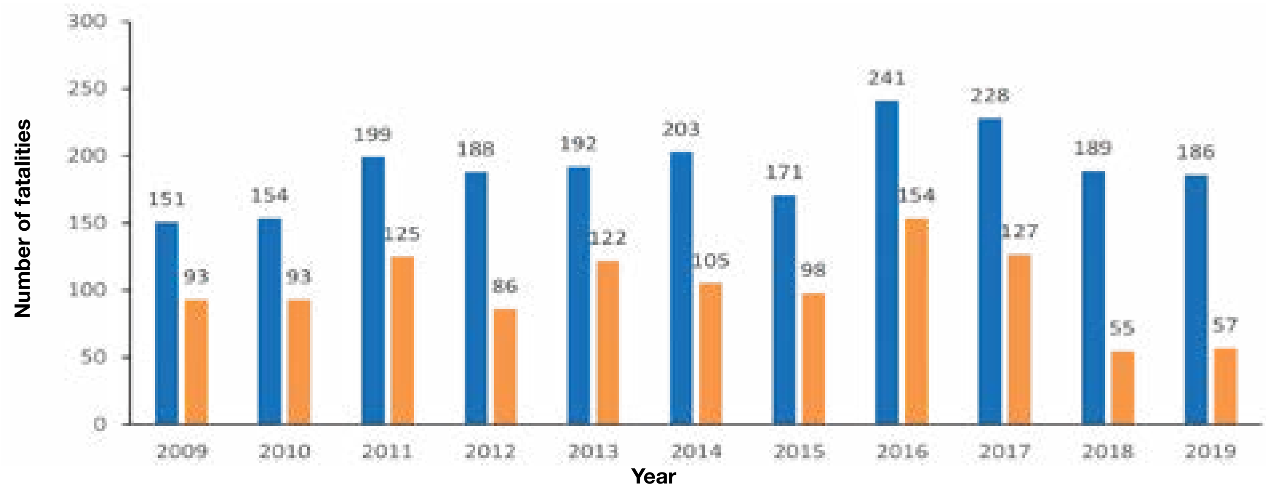
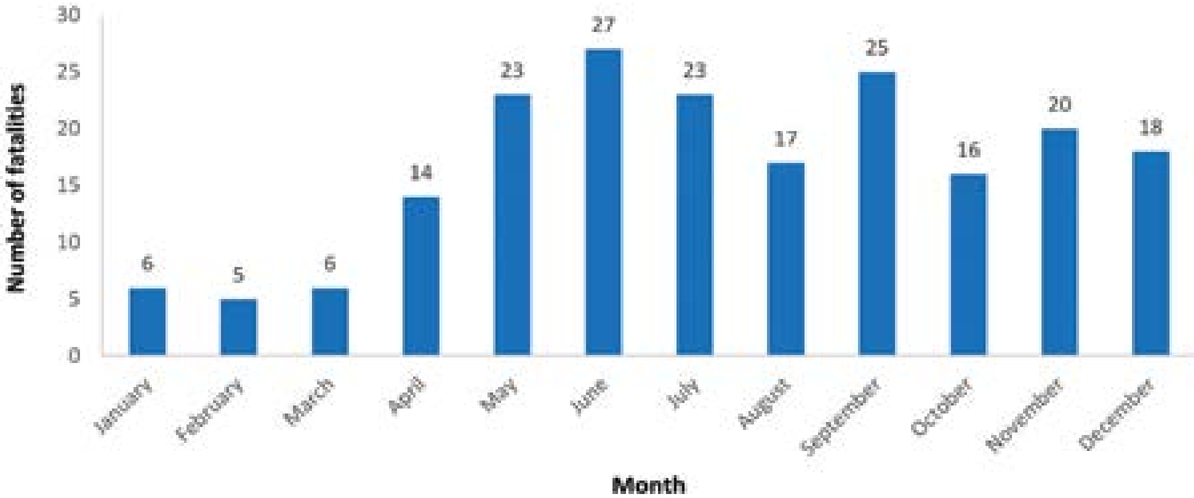


Table 1-5. Number of cases reported in the United States and Canada by state/province for 2019, compared to previous 10-year mean. Mean values were rounded to reflect whole numbers as the data pertains to individuals.

State/Province	2009–2018	10-year mean	Total count 2019
United States			
Florida	163	16	19
California	97	10	4
Hawaii	44	4	22
Washington	30	3	1
Massachusetts	22	2	1
Michigan	16	2	0
North Carolina	14	1	2
Pennsylvania	14	1	0
New York	13	1	1
New Jersey	12	1	0
Wisconsin	11	1	0
Nevada	6	1	0
Ohio	6	1	0
South Carolina	6	1	2
Alabama	4	0	1
Illinois	4	0	1
Minnesota	4	0	0
Oregon	4	0	0
Rhode Island	4	0	0
Texas	4	0	0
Missouri	3	0	0
Arizona	3	0	3
Guam	3	0	0
New Mexico	3	0	0
Virginia	3	0	0
Arkansas	2	0	0
Georgia	2	0	0
Louisiana	2	0	0
Maine	2	0	0
South Dakota	2	0	0
Tennessee	2	0	0
Utah	2	0	0
Alaska	1	0	1
Connecticut	1	0	0
Kansas	1	0	0
Montana	1	0	1
Oklahoma	1	0	0
Puerto Rico	1	0	0
Vermont	1	0	0
Virgin Islands	1	0	0
Wyoming	1	0	0
Kentucky	0	0	1
New Hampshire	0	0	0
Canada			
Nova Scotia	5	1	0
Quebec	3	0	2
Newfoundland & Labrador	0	0	1
Ontario	0	0	2
State/Province Unknown	0	0	1
Total	**524**	**46**	**66**

Figure 1-3. The seasonal spread of diving related fatalities recorded by DAN in 2019 (n=200).



consistently high mortalities in diving, DAN is working carefully with state officials to review as many cases as possible in an effort to further identify any trends that may lead to safer diving.

The U.S. Department of Health commissioned a study in 2019 (the Snorkel Safety Study) to investigate these unexplained drownings.[1] The report noted that the majority of drownings in Hawaii were snorkeling and ocean related, involving tourists over the age of 50. Of the mechanisms that may cause drowning in snorkelers, aspiration of water and hypoxia due to rapid onset pulmonary edema (ROPE) were thought by the authors to be the most common, and are indistinguishable from each other in postmortem examinations. The recognition of ROPE as a problem for snorkelers has been difficult to establish; accounts from survivors with related hypoxemia have been part of the investigation of this mechanism. It is thought that the increase in negative transthoracic pressure (NTP) required to maintain adequate volumes of ventilation during immersion while snorkeling promote ROPE and hypoxia. The chain of events that can lead to death involve the onset of pulmonary edema, and a resulting hypoxemia that then leads to weakness, loss of reflex responses, confusion, and reduced consciousness.

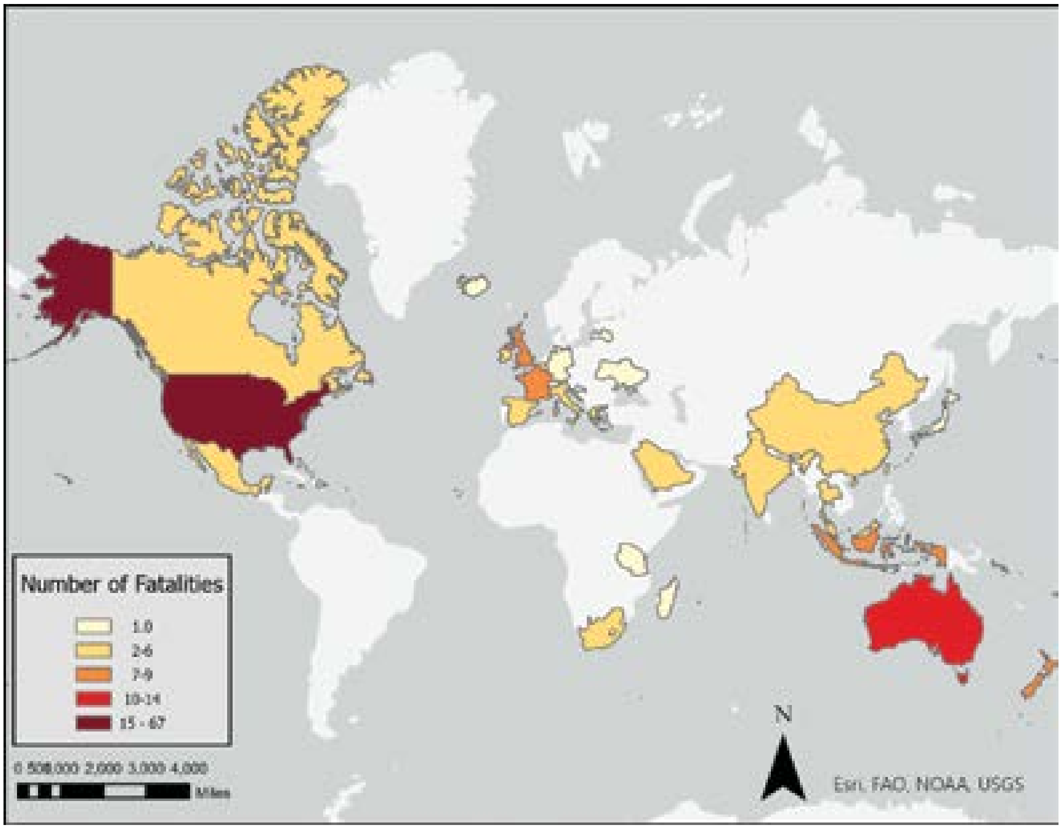
Immersion pulmonary edema is well known in scuba divers, but the Hawaiian report expressed that this process also exists in snorkeling. Varying types and models of snorkel equipment were investigated and the study revealed a huge variation in breathing resistance characteristics, with the negative pressures necessitated for ROPE to develop being undetectable by the user, especially at high work and ventilation rates. It is suspected that variation in equipment performance and the inability to determine their performance by inspection alone could be contributing to the increase of snorkeling accidents.

The following general risk factors when snorkeling were identified and made public:

- When jumping into the water from a boat there is little time to acclimate to the equipment, temperature, and conditions, and, once in, the snorkeler can't touch bottom so must exert extra effort. These are all risk factors so extra caution is advised.
- It is possible that recent prolonged air travel may be a risk factor.
- Heart conditions are significant risk factors, in particular diastolic dysfunction, which is an asymptomatic condition common in middle-aged people. A medical history of high blood pressure may be an indication of diastolic dysfunction.
- Snorkels with a higher degree of resistance to inhalation increase the risk of ROPE; avoid snorkels with constricted airways and the simpler the design, the better.
- Increased exertion can precipitate or accelerate ROPE.

Some publicity has been given to the potential dangers of full-face snorkel masks (FFM) as they are becoming more popular. The level of risk could not be established in the Hawaiian study as only four masks of the 50 tested were full-face. DAN has also been investigating the safety of this FFM equipment.[2] It was found that two of the three design types did not function as advertised but none provided problematic gas supplies to the user. However, some of the FFM models did increase breathing resistance with water intrusion and this could cause respiratory distress.[2]

Map 1-1. Distribution of global fatalities captured by DAN in 2019.



Map 1-2. Distribution of U.S and Canada fatalities captured by DAN in 2019.

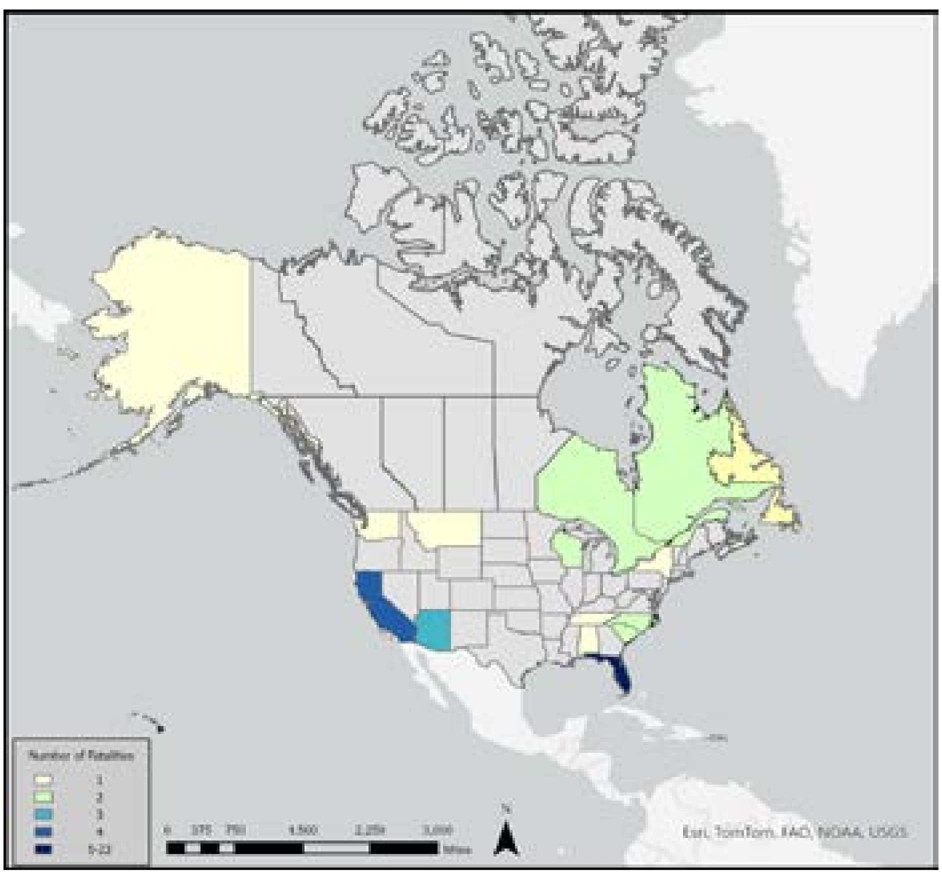


Figure 1-4. Age and sex distribution of reported diving fatalities in 2019 (n=172).

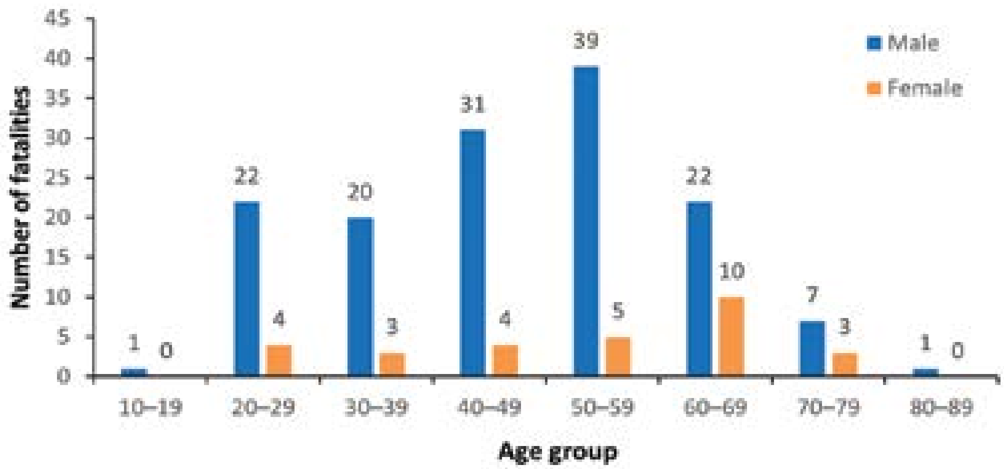


Table 1-6. Activities or type of accident leading to deaths in Hawaii.

Activity/mechanism of accident	
Snorkeling	11
Scuba	4
Breath-hold*	4
Killed by sharks	1
Unknown	2
Total	**22**

*Two of these cases were suspected to be breath-hold dives; although not confirmed, they are included here.

The 2018 data reported that the number of fatalities where follow-up was made in the U.S. was considerably reduced from previous years. In 2019 the total count was reduced considerably in comparison to the 10-year mean (40 for 2019 vs. mean of 52; Table 1-3.) but not to the same degree as the previous year, in part bolstered by the number of fatalities in Florida rising above the 10-year mean once again.

Follow-up fatalities in Canada remained similar to years previously. The number of fatal diving accidents for United States and Canadian citizens that occurred in countries outside the U.S. and Canada, and the country of incidence are reported in Table 1-7.

Overall, 2019 figures were increased from 2018 (total count of deaths abroad n=24 vs. n=15, respectively), and they were also increased slightly compared to the 10-year mean, particular in relation to the 2018 figure. It should be noted that mean values were rounded to reflect whole numbers as the data pertains to individuals. ‘Other’ for 2019 included Barbados, Dominican Republic, Fiji, Iceland, Jamaica, Solomon Islands, St Kitts and Nevis, and Tanzania, all of which had one case.

Table 1-7. Number of fatal dive accidents for United States and Canadian citizens occurring in the countries outside the United States and Canada.

Country	Total count (2009–2018)	10-year mean	Total count 2019
Mexico	47	5	5
Belize	13	1	3
Cayman Islands	27	3	3
Dutch Antilles	18	2	3
Bahamas	10	1	1
Indonesia	8	1	1
Philippines	4	0	0
Malaysia	1	0	0
Italy	1	0	0
Grenada	1	0	0
Other	86	9	8
Total	**216**	**22**	**24**

Historically, Florida and California are the U.S. states with the highest numbers of fatalities as they provide popular diver sites, and three counties within each are known for their high number of diving deaths. In 2018, these values had dropped, particularly for Monroe County in Florida from a mean of ten to two cases. Table 1-8 shows the values for 2019, where the Monroe County value had risen to 11 cases, although the other counties’ case rates have remained low. It was concluded that the total number of deaths for the United States and Canada in 2019 was slightly higher than in previous years.

Table 1-8. Number of U.S. cases in countries with historically high numbers of diving fatalities. Mean values are rounded to reflect the whole numbers as the data pertains to individuals.

State	County	2009–2018	10-year mean	2019
Florida	Monroe	88	9	11
	Palm Beach	27	3	1
	Broward	21	2	1
California	Los Angeles	48	5	0
	Monterey	20	2	2
	San Diego	18	2	0

DEMOGRAPHICS OF DECEDENTS

The distribution of fatalities worldwide described by age and sex are shown in Figure 1-4. Of the decedents, 81.5% (n=163) were male, 17.5% (n=35) were female, and 1.0% (n=2) were of unknown gender. Age was not recorded for 28 of the decedents; of the remaining 172, the mean age was 48 years and the median 50 years. Forty-four percent of the fatalities were divers aged 50 years or older, while the youngest deceased diver was 13 years, and the oldest 83 years. The age group having the highest number of fatalities was the age 50–59 bracket, having 44 deaths recorded in total.

Figure 1-5 describes the mean age of fatalities of each year from 2004, which in recent years had shown a trend towards an increase reaching a peak of 56 years in 2017. However, the data from 2019 show a relatively large reduction to 48 years. The previous DAN annual diving report questioned the increasing trend in age of fatalities seen. It noted that older age did not directly increase risk but added the caveat that increasing age may affect general health and physical fitness, both of which can affect risk while diving. It cannot be determined why the mean age of the 2019 fatalities fell to a level seen more consistently in the years prior to 2015, particularly as the overall number of worldwide fatalities has not fallen in concert.

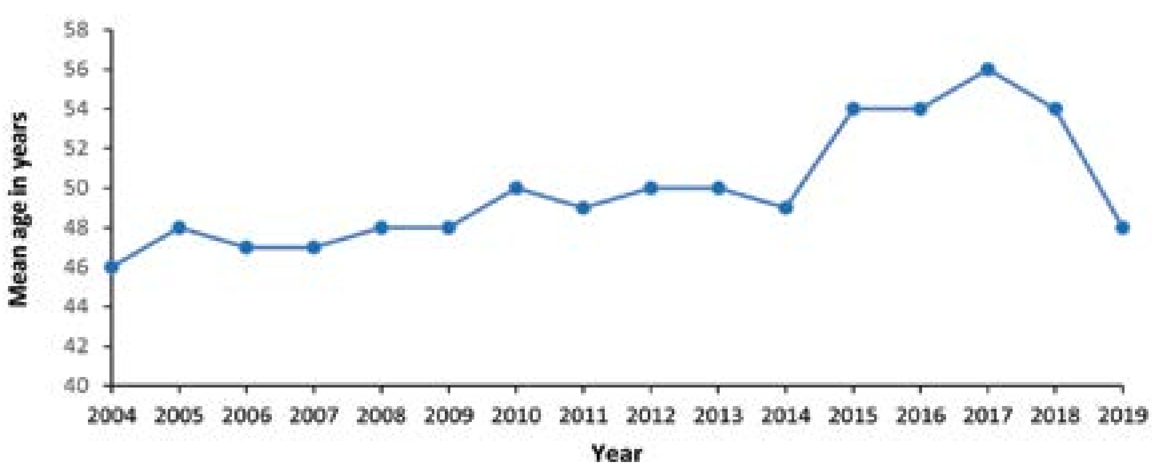
Of the 200 fatalities recorded, any data in terms of height, weight, medical history, and lifestyle etc., were relatively sparse. The records regarding certification of the divers were available for only 49 decedents and their certification type is shown in Table 1-9.

Table 1-9. Type of dive certification recorded across worldwide fatalities in 2019.

Certification	2019 count
Uncertified/Not Reported	151
Advanced/Specialist	28
Technical	7
Student	5
Instructor and Above	4
Divemaster/Assistant Instructor	3
Basic/Open Water	2
Rescue	0
Total	**200**

Relevant information on the decedents' experience in terms of years diving since certification went unreported in many of the records. Two records were notable in that they provided data on the number of lifetime dives that numbered 100 or over. One male decedent had recorded 300 lifetime dives; the death was recorded as diver error after the diver went missing. A female diver had logged 100 lifetime dives; her death appeared to be accidental, perhaps the result of equipment malfunction.

Figure 1-5. Mean age of diving fatalities by year (2004–2019).



CHARACTERISTICS OF FATAL DIVES

The characteristics of diving that are taken into consideration when assessing fatalities include: the activities that the divers were involved in at the time of the accident, for example recreational scuba or scientific diving; the environment in which they were located for their dive, for example in the ocean or a river; and the platform from which they made their dive, for example from a boat or pier.

Only 19 (10%) of the fatal dives reported worldwide in 2019 catalogued the type of dive activity being undertaken at the time of the accident, and these are detailed in Figure 1-6 (blue bars). Pleasure diving/sightseeing and spearfishing/game collecting were the activities being undertaken in most of these cases. When looking at the data from the U.S. and Canada alone, the same distribution of fatalities with activities was observed (Figure 1-6; red bars).

Worldwide only 69 records definitively recorded the type of diving apparatus used by the decedents; the majority were dives on open circuit equipment (Table 1-10.)

Table 1-10. Diving apparatus used by decedents worldwide.

Diving Apparatus	
Rebreather	24
Open Circuit	17
Unknown	17
Missing	5
Surface Supply	3
Other*	3
Total	**69**

*Includes one breath-hold diver, one snorkeler and one ‘other.’

With regards to dive environment, worldwide only 40 (21.5%) cases detailed this parameter with fatalities from dives made in a river/spring being most common (n=23, 57.5%), followed by the ocean/sea (n=16, 40%), and then pool diving (n=1, 2.5%). These data contrast with those reported for 2018, where most fatal dives occurred in an ocean/sea environment (75%), with only two in rivers or springs. Twenty-eight of these cases were reported from the U.S. or Canada, with n=19 reported for river/spring diving and n=9 in the ocean/sea.

There were slightly more cases detailing the dive platform from which fatalities took place worldwide (n=45), with dives made from the beach/shore being the most common (n=35, 77.7%), then followed by pier dives (n=7, 15.5%), and dives made in a chamber/private boat (n=3, 6.6%). The U.S. and Canada reported 34 of these dives, with 26 being made from the beach/shore, five from a pier, and three in/from a chamber/private boat.

CASES – PLEASURE DIVING/SIGHTSEEING

This category covers a broad range of activities from swimming and snorkeling, to taster dives, pleasure dives made by experienced scuba divers with many hours of diving under their belt, and divers using rebreathers to explore wrecks and caves for example. Of the 36 fatalities in this category, 15 did not report the cause of death (COD). Of the remaining 21, the COD for 11 cases was drowning. All diver fatalities/victims are referred to in the below cases, and throughout this chapter of the report, as Diver A.

CASE 2019-101 – Diver A was an experienced (61+ dives) male 43-year-old. He surfaced from a dive after approximately 10 minutes and deployed his surface marker. He was then picked up by his boat and came up the ladder onto the deck where he stood up and collapsed, hitting his head on the floor. The boat captain started cardiopulmonary resuscitation (CPR) immediately and Diver A was transported to the shore by the Fish and Wildlife Commission, then transferred to hospital where he was pronounced dead. He had no known medical conditions and had a negative drug blood screen. Cause of death was severe coronary atherosclerosis.

CASE 2019-102 – Diver A, a 13-year-old male, was taking part in a ‘discovery dive’ session. He started to panic while under the water and was assisted to the surface by his buddy. He became separated from his buddy while at the surface and slipped back underwater. The buddy signalled the boat for assistance and Diver A was found at the bottom at around 40 – 50 fsw with his breathing regulator out of his mouth. He was transported to hospital and pronounced dead. He had no existing medical conditions, with COD stated as drowning.

CASES – SPEARFISHING AND GAME COLLECTING

There were six cases where the COD was established following the activity of spearfishing/game collecting in the United States. Three were classified as drowning, one as drowning with barotrauma being a contributing factor, one as air embolism, and in one case, COD was ruled as due to hypertensive and arteriosclerotic cardiovascular disease.

CASE 2019-103 – Diver A, a man in his 60s, went with friends on their boat to snorkel/freedive in 6 to 10 ft of water for lobsters. After a few hours of free diving/snorkeling, Diver A and another friend moved to scuba diving in an area of approximately 40 ft depth. The dive lasted between 15 and 20 minutes. Friends noted that Diver A swam rather slowly back to the vessel and upon boarding stated he was having chest pains. He later collapsed and two of his friends began CPR while they returned to shore where emergency medics took over. Diver A had a history of high blood pressure and had a cardiac catheterization but was an experienced diver and had last dove three months prior. Cause of death was determined to be hypertensive and arteriosclerotic cardiovascular disease with a contributing factor of terminal submersion in water.

CASE 2019-104 – Diver A, a 63-year-old male was participating in a fishing tournament, using a rebreather. At 20–30 fsw, the victim signaled to his buddy that he was out of air so the buddy gave him his bailout tank. They had trouble inflating their buoyancy control devices (BCDs) and ended up sinking to the bottom at about 170 fsw, at which time the bailout tank was empty and they started buddy breathing. The buddy removed Diver A's rebreather and was finally able to surface with the unconscious victim. They were assisted to the boat and CPR was started but the victim did not recover. Attempts to recover the dive gear were unsuccessful. Investigation revealed that the victim was not certified to use helium mixed gas, nor for the depth of the dive. Witnesses said that the victim noticed a hose leaking before the dive trip and that during the transit to the site, he was observed to be replacing a hose. The buddy's dive computer noted that the dive lasted nine minutes. Cause of death was deemed to be drowning, with an insufficient supply of breathing gas and likely equipment malfunction contributing to the cause.

CASE 2019-105 – Diver A, a 54-year-old woman, was setting up her equipment when she complained of her regulator not working properly. She continued with the dive despite this, descended to 37 fsw and is reported to have surfaced approximately five minutes later complaining of being unable to breathe and in obvious distress. She was brought back onto the boat, and complained of nausea and abdominal pain with trouble breathing. On route back to shore Diver A lost consciousness and CPR was initiated. She passed away at the hospital a short time later. Analysis of her equipment revealed that her octopus was not functioning properly, the main regulator mouthpiece was missing a bite piece, and the tank was completely empty. Autopsy determined the COD to be drowning, due to pulmonary edema and congestion, with intra-alveolar hemorrhages. Barotrauma was listed as a contributing condition.

CASE 2019-106 – Diver A, a 56-year-old male, is believed to have drowned while scuba diving for stone crabs in an area he was known to frequent with a buddy. He chose to dive solo and was reported missing when he did not return home or arrive at work the next day. His dive flag was found unattached, and his body was found later. His scuba gear was recovered and inspected; the tank was found to be empty and the regulator and BCD were found to not be operating to standards outlined by the manufacturer, as both appeared to have leaks that would have necessitated increased effort from the diver to breathe and inflate the BCD. Weight pockets were found, but the weights were missing. Cause of death was determined to be air embolism due to barotrauma and drowning.

CASES – INSTRUCTING

The 2019 data report only one fatality occurring while the decedent was instructing.

CASE 2019-107 – Diver A was a 69-year-old female scuba diving instructor. It is unclear if this event was scuba related, as some reports said that she died while conducting 'swimming' lessons while other reports say 'scuba' lessons. Reportedly, the victim and her diving student were thrown onto the rocks by a large wave during sea conditions that were noted as having large swells that day. The COD was found to be drowning, with a blunt force head trauma causing an intracranial hemorrhage.

CASES – SCIENTIFIC

Worldwide, only one fatality was reported while participating in scientific diving.

CASE 2019-108 – Diver A was a 39-year-old male, an experienced diver, who was diving on a rebreather. He was part of a group surveying reefs at a remote location in the Solomon Islands. The divers were at approximately 70 msw (~230 fsw) when Diver A was seen to be flailing and twitching. When his buddy got to him, the regulator had fallen out of his mouth and his buddy was unable to get it back in, as his jaws were clenched. His buddy brought Diver A to the surface and was assisted by other divers and staff to bring the diver to the boat. CPR was initiated immediately upon surfacing and oxygen administered, however, the victim never regained consciousness. Cause of death was ruled as probable oxygen toxicity, with a contributing factor of arterial gas embolism (AGE).

ANALYSIS OF SITUATIONS AND HAZARDS

FATALITIES BY DIVE PHASE AND LIKELY TRIGGERS

The following dive phase categories were used to analyse the data:

- Pre-dive (on surface before dive)
- During the dive (underwater including ascent and descent)
- On surface post-dive
- Out of water

Worldwide in 2019, only 26 records that detailed the phase where loss of consciousness (LoC) took place were available (Table 1-11).

Figure 1-6. Activities undertaken at the time of the fatal dive accident.

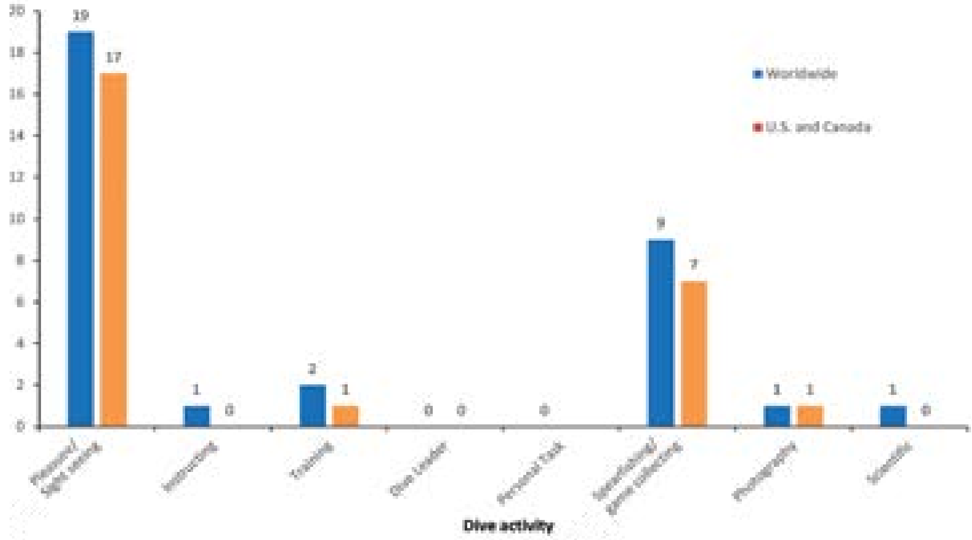


Table 1-11. Phase of dive where loss of consciousness was reported.

Where consciousness was lost	
Underwater	12
Surface post-dive	9
Out of water	3
Surface pre-dive	2
Total	**26**

SURFACE PRE-DIVE

Loss of consciousness at the surface before descent occurred in two cases, which calls into question the causality of the accidents; although both appeared to be triggered by the act of diving, one was classified as a health-related COD. The two cases are detailed below:

CASE 2019-109 – Diver A was scuba diving with a local company close to a wreck. He was observed at the surface having some difficulties prior to descending and spat out his regulator. His buddy reached Diver A and tried to replace the regulator but Diver A then passed out. The unresponsive man was then towed back to the boat where CPR was initiated. He did not regain consciousness and was pronounced dead at the hospital. Cause of death was reported to be thrombosis of the left anterior descending coronary artery, with the trigger event being loss of gas.

CASE 2019-110 – Diver A, who was observed to be morbidly obese, entered the water from a dive vessel. A fellow diver reported that Diver A's equipment was ill-fitted due to his body composition; on entering the water, his fins came off his feet and he started to swim towards them. After around five minutes in the water, he began to panic visibly and dislodged his scuba regulator from his mouth while attempting to swim on the surface. He had not inflated his BCD. A rescue diver went to Diver A but found him unconscious and apneic. Rescue breaths were given while Diver A was moved to the boat, then once onboard chest compressions were initiated as Diver A had no pulse at this point. He was profoundly cyanotic and had massive global edema. Emergency medical services retrieved Diver A but he was pronounced dead on arrival at the hospital. Cause of death was drowning triggered by equipment problems.

UNDERWATER

Of the 12 cases where the victim lost consciousness while underwater, 11 reported the COD. Eight were due to drowning, two involved cardiac problems, and one was reported as anoxic encephalopathy due to near drowning. Some of the cases are detailed below:

CASE 2019-111 – Diver A was a 30-year-old experienced male diver. He and his buddy were diving, descending to 170 ffw. Diver A indicated that he was 'leaking air' from his rebreather, which was set to open-circuit mode, although his buddy could not see evidence of this, so he suspected Diver A was suffering from narcosis and suggested they go up. Diver A signalled that he agreed, but then started to drop in the water again. His buddy tried to hold him but Diver A then slipped out of his hold and could not be seen, as the visibility was silty. The buddy then decided to surface to get help. A third buddy then saw Diver A lying motionless, face up, with blood in his mask at approximately 186 ffw; he also surfaced to call for help. Both buddies notified the emergency services. Diver A was recovered from the lake two days later from a depth of 184 ffw. Postmortem examination determined that Diver A had drowned in the setting of a rapid scuba descent and had probably experienced nitrogen narcosis, triggering the accident. His equipment was found to be fault free; his gas cylinders contained the intended gas mix, but the ratios were deemed inappropriate per industry standards for the intended diving depth.

CASE 2019-112 – Diver A was a 63-year-old male experienced diver. He was making his second dive of the day in cold water to a hydrothermal chimney in a lake at 29 meters depth (~95 feet). Having spent around 20 minutes at depth, he and his buddy ascended and had reached their safety stop at five meters. After three minutes, the victim started kicking to the surface. The buddy stayed to finish his decompression stop, and kept an eye on Diver A. He saw him stop kicking, then he seemed to float motionless to the surface. The dive support team recovered Diver A and brought him to the boat where they started giving chest compressions. Foam was said to have come from his mouth. Cause of death was deemed to be hypertensive heart disease, with a CT scan showing a considerable amount of air inside the arterial system of the brain and chest.

CASE 2019-113 – Diver A was a 51-year-old male dive instructor and public safety diver. Diver A went missing from the group that he was instructing and did not resurface with them. He was found unresponsive on the ocean floor tangled in kelp around 30 minutes after he was last seen by his group. His breathing apparatus was in place, with oxygen flowing. Following recovery from the ocean Diver A was in cardiac arrest and underwent resuscitation measures by medics during transport to the hospital emergency department. He arrived at the hospital in asystole with fixed and dilated pupils. Cause of death was asphyxiation and drowning, perhaps complicated by probably cardiac dysrhythmia.

SURFACE POST-DIVE

Of the nine reported cases where divers lost consciousness at the surface after diving, eight had COD established: four were due to drowning/asphyxia; one to arterial gas embolism; and three to cardiac problems. Several of the cases are detailed below; see also Cases 2019-103 (cardiac problems), 2019-102 (drowning), and 2019-105 (AGE) that are described in an earlier section of this report.

CASE 2019-114 – Diver A was a 67-year-old experienced male making a dive to a shipwreck in the Florida Keys. He was diving with a buddy to 25 fsw when he indicated that he was having problems with his regulator. He switched from his primary regulator to his octopus, and eventually had to share air with his buddy as they surfaced. The buddy saw Diver A inflating his BCD orally instead of using the power inflator. His buddy offered to assist the victim back to the boat, but Diver A refused and told his buddy to go back down and finish his dive, and that he would swim back to the boat. A boat crew member spotted Diver A at the surface, but he appeared to be unresponsive and 'not swimming'. The crew brought him back to the boat and CPR was started but Diver A never recovered. The COD was drowning, with severe heart disease being a contributing factor.

CASE 2019-115 – Diver A was a 55-year-old male who was an inexperienced diver, making a night shore dive with a large group. The group dived to approximately 60 feet. Diver A was reported to be wearing a new hybrid wetsuit that he was not familiar with (a semi-dry suit). Other divers noticed him waving his light back and forth; according to the witnesses and the decedent's dive computer, for unknown reasons at approximately nine minutes into the dive he ascended from 61 feet to 17 feet in about one minute, an unsafe rate of ascent per diving standards. This ascent may have been due to difficulty with buoyancy control. He then descended back down to 66 feet in about a minute. He was at that depth for about two minutes before the other divers recognized he needed assistance back to the surface. His behavior during the final, assisted ascent was described as "jerky/spasm-like/seizure-like". He indicated he was OK but would like to surface, so he was given further assistance. At the surface, he was conscious although rescuers said they noticed he had vomited, had froth from his mouth and was coughing. During the tow back to shore, the victim lost consciousness and CPR was initiated until an emergency medical team arrived. He was pronounced dead at the scene. Diver A was said to have died due to sudden cardiac death in the setting of scuba diving, hypertensive cardiovascular disease, and hepatic steatosis. His rapid ascent had also led to the contributing factors of pulmonary barotrauma and air embolism.

OUT OF WATER

Three cases reported on divers that left the water after diving and made it back on to their boat deck, only to lose consciousness at that point. All three had differing causes of death: complications of barotrauma; cardiac problems; and drowning/health problems. One case, 2019-120 (cardiac problems), is described earlier in the report.

CASE 2019-116 – Diver A was a man in his 40s who had been diving a shipwreck to 112 fsw (34 msw). During ascent Diver A stayed on the ascent line longer than his buddy because the buddy was ascending on a different profile. Diver A surfaced and returned to the boat where he passed out and was taken back to shore by the crew. He was later airlifted to hospital, where was pronounced dead. Cause of death determined to be complications of barotrauma from rapid ascent while scuba diving, however after the DAN Fatality and Injury Monitoring team reviewed the report the final interpretation contested this determination. The consulting pathologists confered that "Nothing in this report makes it barotrauma; the diver came up an ascent line. He also was on numerous prescription medications including narcotics and

Lasix", so perhaps the accident was more attributable to intoxication and its effects.

CASE 2019-117 – Diver A was a woman in her 70s, who complained of feeling unwell before she collapsed on the deck of her dive boat after snorkeling. She was taken to hospital, where she was pronounced dead. She had a history of breast cancer and was still in treatment at the time of the accident. Cause of death was given as drowning with a contributory factor of breast carcinoma.

TRIGGERS, MECHANISMS OF INJURIES, AND CAUSES OF DEATH

Official analysis of diving fatalities uses a chain-of-events methodology in the process of 'root cause analysis' to try and establish why a system failed. Although the available documentation and evidence is often scarce and insufficient for a robust analysis, studying the chain of events can still help towards establishing what went wrong, identifying targets for intervention, and then educating divers to try and prevent future accidents.

DAN collects as much information on contributing factors as possible for statistical analysis. Working back from the final COD, this report tries to identify disabling injuries, mechanisms and likely triggers that may have contributed to the accident.

CAUSE OF DEATH

Cause of death was specified for only 39 of the cases worldwide (Table 1-12), with an autopsy report available for 23 of these. Death certificates were available for three fatalities, in addition to the 23 autopsy reports. Drowning was responsible for 22 of the deaths, and heart disease or acute heart events for seven fatalities, with two episodes of sudden cardiac arrest and pathological substrates to cardiac disease (detailed in Table 1-11). Decompression illness (DCI) caused four fatalities, intoxication one fatality, and broncho aspiration one fatality.

Under the umbrella of DCI, two cases of AGE occurred; in one, autopsy found pulmonary edema, congestion, intra-alveolar hemorrhages, and barotrauma; in the second, multiple air bubbles were noted in pulmonary artery and anterior heart chambers, and in the leptomeningeal venous vasculature, while radiographs were obscured by a large air bubble in the stomach on trying to view the heart.

There was minimal hyperinflation of the lungs, minimal watery fluid in sphenoid sinus, stark contrast of gray and white matter of brain, and engorgement with generalized fluidity of blood. This decedent also had atherosclerotic coronary artery disease, with complex atheromatous lesions up to 75% in the left anterior descending branch, and a remote healed infarct in the anterior papillary muscle of heart.

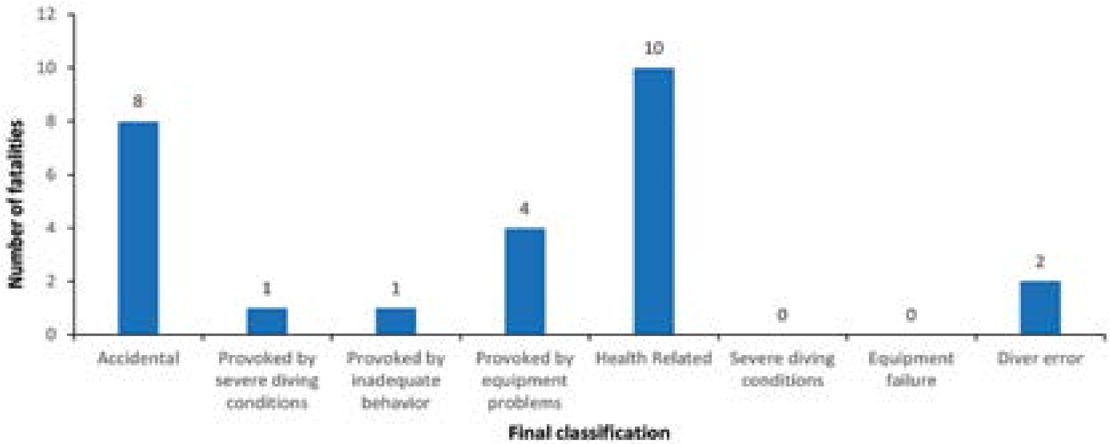
Another decedent with DCI died from complications of barotrauma associated with rapid ascent while scuba diving, with associated hypertensive and atherosclerotic cardiovascular disease. The final death classed as DCI was due to pulmonary edema, with the only details of the

Table 1-12. Cause of death determined by medical examiner.

Cause of death	Count	Category
Drowning	21	Drowning
Arterial gas embolism	4	DCI
Thrombosis of the left anterior descending coronary artery	2	Cardiac
Sudden cardiac arrest	2	Cardiac
Anoxic encephalopathy due to near drowning	1	Drowning
Barotrauma	1	DCI
Broncho aspiration	1	Broncho aspiration
Critical coronary atherosclerosis	1	Cardiac
Hypertensive and arteriosclerotic cardiovascular disease*	1	Cardiac
Hypertensive heart disease	1	Cardiac
Hypertensive heart disease and diabetes melllitus*	1	Cardiac
Intoxication	1	Intoxication
Pulmonary edema	1	DCI
Total	**38**	

*In these cases, heart disease was the primary cause of death with submersion in water cited as contributing factors. AGE, arterial gas embolism; DCI, decompression illness; IPE, immersion pulmonary edema.

Figure 1-7. Final classification of deaths (mechanisms of injury) (n=26).



accident being that the decedent was a 60-year-old female found unconscious in the water in Cozumel, Mexico.

One death was due to broncho aspiration; the decedent was also noted to have dilated cardiomyopathy. The final classification of deaths was given in 26 cases (Figure 1-7).

DISABLING INJURIES

Disabling injuries (DI) are those directly responsible for incapacitation and death in the water; when a death occurs upon leaving the water and drowning does not occur, the COD and disabling injury are often the same. Within the worldwide 2019 data, 25 reports detailed the DI (Figure 1-8).

TRIGGERS

Primary trigger events that started a chain of events leading to the accident and fatality were identified in only 17 cases, with loss of gas being the main problem (Table 1-12). Some secondary trigger events were also recorded, but only in ten cases.

CARDIAC CONDITIONS AS COD

A post-mortem description of decedents' hearts was provided in 22 cases. Cardiomegaly (enlargement of the heart) was mentioned in five of these cases. Of these, cardiac problems were cited as the primary COD in three cases, with the two remaining cases citing heart disease as a 'contributing factor'. Of the seven decedents where cardiac conditions were said to be COD (Table 1-10), all had an autopsy report detailing the condition of the heart; the adverse findings are described in Table 1-13.

Although drowning remains the primary COD for divers, pre-existing cardiac conditions or acute cardiac events remain an important risk factor, particularly if the victims have multiple health conditions; combined, they increase the probability of premature death. If any pre-existing conditions cause a problem while diving, then the underwater environment imposes a much higher risk to the individual than if they experienced such an event above surface where drowning is not an issue and CPR could be performed without a considerable delay.

Diabetes mellitus and hepatic steatosis (fatty liver) were examples of additional conditions that were attributed as COD alongside cardiac disease in some of the present cases (Table 1-14).

Table 1-13. Trigger events.

Primary trigger event		Secondary trigger event	
Loss of gas	11	Environment hazard*	2
Equipment problem	3	Hypertensive CVD	2
Contaminated gas	1	Intoxication	2
Health problem	1	Oxygen toxicity	1
O_2 valve closed	1	Nitrogen narcosis	1
		Overweighted	1
		Rapid ascent	1
Total	**17**	**Total**	**10**

While some of these victims may have been unaware of their cardiovascular status, given the risk factors associated with cardiac disease, it should be recommended that:

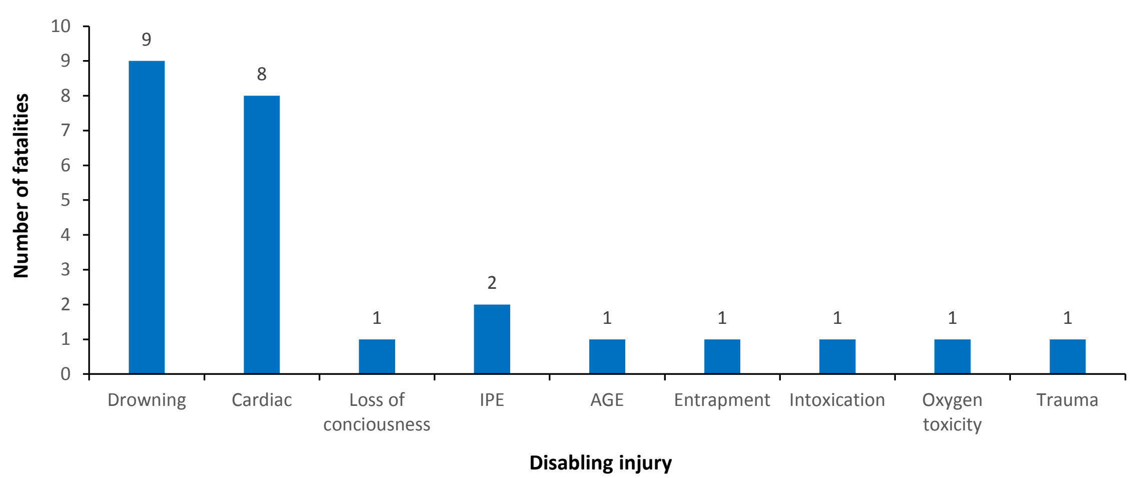
- Men over 45 and women over 50 should have periodic medical examinations
- Divers with multiple cardiovascular risk factors should be evaluated periodically
- Divers with a diagnosed heart condition should be thoroughly tested for exercise tolerance before being cleared for diving
- Divers with multiple manifestations of cardiovascular disease, especially if metabolic syndrome (diabetes, obesity) is present, should be advised not to dive

CASE 2019-120 (in Table 1-14) perhaps stands out as a cautionary tale, as the decedent was only 43 years-old and was fit and healthy. However, his COD was critical

Table 1-14. Adverse cardiac autopsy observations.

Case ID	COD	Autopsy – adverse cardiac comments
2019-118	Hypertensive heart disease and diabetes mellitus	Cardiomegaly. The aorta and its major branches are widely patent with moderate atherosclerotic change of its thoraco-abdominal portions.
2019-103	Hypertensive and arteriosclerotic cardiovascular disease	The lumen of the left anterior descending coronary artery is narrowed to a pinpoint by calcific atherosclerosis. The endothelial surfaces are rough, yellow and have a moderate amount of atherosclerosis.
2019-115	Sudden cardiac death with hypertensive cardiovascular disease and hepatic steatosis	Cardiomegaly.
2019-119	Sudden cardiac arrest	The proximal left circumflex coronary artery has focal, mildly calcified atherosclerotic stenosis of approximately 80%. The left anterior descending coronary artery has mild (up to 30%) non-calcified atherosclerotic stenosis. The proximal right coronary artery has non-calcified atherosclerotic stenosis of approximately 80% focally. The Mitral valve has some thickening and redundancy (myxoid degeneration). The aorta has moderate marked atherosclerotic changes.
2019-120	Critical coronary atherosclerosis	The right coronary artery has up to 95% stenosis by atherosclerosis.
2019-112	Hypertensive heart disease	Heart is slightly enlarged. At least 150 ml of air is drawn from the right side of the heart. In the back part of the right atrium where the atrium connects to the lower vena cava, a tear is visible on the inside of the atrium wall which does not reach through the wall and this area is up to 1.5 cm large. Coronary arteries are open, show normal width and show mild to medium coronary atherosclerosis without clear narrowing or clots. Permeation of the heart shows homogeneous rusty cardiac tissue. Left ventricle is 1 cm thick and the left ventricle wall is up to 2.2 cm thick – hence thickened. Aorta is undamaged and shows mild to medium atherosclerosis.

Figure 1-8. Disabling injury or medical condition preceding death (n=25).



coronary atherosclerosis, which was surprising given the decedent's background as a former marine and experienced diver. This highlights the fact that regular medical screening for divers in general is perhaps prudent given the environmental stressors they subject themselves too.

DROWNING AS THE DISABLING INJURY AND CAUSE OF DEATH

Drowning was established as COD in 22 cases and as the disabling injury in nine. Several cases of drowning as the disabling injury were reported previously – they include Case 2019-110, 2019-111, and 2019-113.

CASE 2019-121 – Diver A, a man in his 50s, was diving and spearfishing. He was wearing scuba gear including an air tank and carried a spear gun. Diver A and his buddy entered the water together, then became separated. Twenty minutes after entering the water Diver A was reported missing, his body was found around 2.5 hours later, floating face down. When he was located after the accident, neither the air tank nor the gun could be found and he was missing a dive glove and had an empty dive knife holder. Diver A had a history of hypertension, hyperlipidemia, anxiety, and was a known smoker. Cause of death was determined to be drowning. The toxicology report noted blood alcohol levels of 152mg/dL, the presence of cannabinoids and prescription medications.

CASE 2019-122 – Diver A, an experienced diver in her 20s, became trapped underwater in a cave. She was diving with friends in the main outflow area. Upon entering the cave, she was pushed into tree roots and became entangled; another diver in the group also became unconscious but was able to be rescued. Recovery of her body was difficult due to recent weather of the area causing increased outflow. COD was drowning, as her breathing gas had run out.

CASE 2019-123 – Diver A, a man in his 70s, was snorkeling. He was later found unconscious and supine in water after initially snorkeling/free diving with his brother. Their boat was anchored, flags were set, and Diver A entered the water with a weight belt, fins, mask, and snorkel. He then became separated from his buddy and was found moments later by witnesses face down, unresponsive and only wearing a mask and fins. Both men were brought back to the marina and paramedics performed CPR, but Diver A was pronounced dead at the scene. Autopsy revealed that COD was accidental drowning with hypertensive and arteriosclerotic cardiovascular disease as a contributing factor.

PULMONARY EDEMA AS THE DISABLING CONDITION

Pulmonary edema was the disabling injury in two cases, one (2019-105) being described earlier in this chapter.

CASE 2019-124 – Diver A , a man in his 50s, had gone diving alone. Other scuba divers in the area found Diver A face down in the water with his regulator still in his mouth and still attached to his tank and weights. The other divers began rescue breaths, dropped the weights, and inflated his BCD. A paddleboarder brought the victim to shore and called emergency services. The victim rented gear and performed a shore-entry solo dive that lasted 24 minutes to a maximum depth of 45 fsw, according to his dive computer data. A GoPro camera was with his belongings, but video evidence did not show anything directly related to the incident. Diver A had unspecified heart problems with intermittent chest pain and prior heart attacks, and was also in a bicycle accident one to two years prior, which resulted in an injured shoulder that recovered well. The dive equipment was examined, and all found to be in working order. The COD was drowning, with pulmonary edema the disabling factor.

LOSS OF CONSCIOUSNESS AS THE DISABLING CONDITION

One case involved loss of consciousness as the disabling condition:

CASE 2019-125 – Diver A was an experienced scuba diver and instructor, (>20 years) and closed-circuit rebreather diver. He and his buddy were diving and were reported to have entered the water together near a lock system but only one diver returned. He had reportedly been having some issues with his equipment, specifically his rebreather, shortly before his diving partner lost sight of him. His body was later recovered. Postmortem examination revealed a well-developed, muscular adult male in a black diving suit. There were early postmortem decomposition changes of the body that were more prominent in the exposed areas of the body (hands and face). There were marked immersion changes of the hands. There was no evidence of recent antemortem injuries on external of internal examination. Postmortem injuries with no apparent vital reaction were identified, which could be explained by trauma from hydroelectric dam turbines and/or impact with the bottom of the riverbed or shore. The cause of death was attributed to drowning due to unconsciousness, with malfunctioning equipment likely adding to the cause.

CONCLUSIONS

Worldwide the number of deaths recorded by DAN in 2019 remains similar to 2018, although there has been a slight upward trend since 2016. Follow-up figures remain much reduced when compared to the nine years prior to 2018. Around half of all victims were aged 50 years or over, and older age remains a risk factor related to health and fitness issues. However, the mean age of death was reduced considerably to 47 years from a peak of 56 years in 2017. The increased number of recreational deaths found in Hawaii has caused concern; research has found that the rise seems to be due to an increase in snorkeling accidents amidst the tourist population. The role of ROPE as a problem for snorkelers and the design of snorkeling equipment is an area that has been highlighted for further investigation to increase recreational divers' safety.

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SECTION 2. **DIVING INJURIES**

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The reporting and analysis of diving injuries remains a key element in any effort to improve diving safety. Two other types of reporting include diver incident and fatality reporting that are also important and reported in Section 1. Diving injury reports are often reported at onset with additional follow-up planned. Input from others such as the dive team, friends, rescue, law enforcement, health care professionals and most importantly, the diver, is always sought to increase the accuracy of the case. This leads to better immediate and long-term care advice as well as better case injury data to be analyzed anonymously with other cases later. An inability to contact the diver due to communication shortfalls or the diver's desire for no further contact can hamper this assistance. DAN always welcomes reporting and follow-up information from any type of diver from breath-hold to commercial/military. This includes anything from shallow depths to altitude exposures even from space.

INTRODUCTION

For over 40 years DAN's mission has been to help divers in need of medical emergency assistance, as well as promote dive safety through research, education, products and services. DAN medicine using DAN's Medical Services Call Center (MSCC) has been instrumental in providing real-time assistance, utilizing a 24-hour emergency hotline as well as responding to inquiries through the non-emergency line and emails. With a team of medics, nurses, and physicians, DAN is able to operate the MSCC in three strategic locations to provide the best assistance worldwide. Details on these specific locations are featured in Section 3 of this report. The assistance includes pre-hospital management, emergency room evaluation, treatment and disposition of injured divers and is conducted both with injured divers, witnesses, and treating medical personnel in real-time.

THE ROLE OF THE DAN EMERGENCY HOTLINE

The DAN Medical Services Department hosts the DAN Emergency Hotline, comparable to a poison control center but specializing in diving injuries. The hotline does not replace 911 services but supports and complements them. Even the most advanced medical systems have found the additional diving medical expertise helpful in the management of a dive injury, especially when they seldom see such injuries. The role of the DAN Emergency Hotline can be summarized in five functions:

1. **Telephonic Triage:** Evaluate whether reported symptoms might result from a diving injury. Detailed case history, including symptoms, dive history, event chronology, and relevant medical history are gathered to construct recommendations for the best course of action.
2. **First Aid Guidance:** Provide guidance on first aid treatment for scuba diving injuries. Effective first aid is crucial for maximizing the efficacy of definitive treatment. Recommendations depend on the availability of trained responders, adequate equipment, and DAN's knowledge of local resources. The situation is seldom ideal, and the best practical advice is given based on what resources are actually available. The better prepared and trained that a dive operation is prior to the injury, the better the options for care can be given.
3. **Encouraging Professional Medical Evaluation:** Persuade the injured diver to seek professional medical evaluation. Time to the nearest medical facility is critical for turning an injured diver into a patient within the healthcare system. Objective medical professionals armed with

diagnostic equipment are invaluable in eliminating serious non diving injuries from the differential. This evaluation can be important to evaluate which diving injury requires evacuation to a recompression chamber or to a higher level of care.

4. **Advising Non-Dive Expert Medical Professionals:** Aid doctors unfamiliar with diving injuries in making the best decisions for their patients once the diver is within the local healthcare system. Assistance in identifying a dive injury and it subsequent management can be challenging to any medical professional. Even experienced dive medical physicians call about unusual diving injuries they are managing for any additional insight to maximize the best outcome.
5. **Assisting with Medical Evacuations**: Aid DAN members with evacuations to suitable dive medicine facilities. DAN maintains a database of competent recompression facilities worldwide and assists with medical evacuations to ensure members receive necessary treatments at the closest and most appropriate facilities. This function is becoming increasingly important with the shortage of facilities available to provide hyperbaric oxygen treatment (HBOT) emergently.

DAN strives to provide the best possible recommendations to injured divers and those caring for them, despite the inherent limitations of telephonic communication. DAN's Emergency Hotline staff handles nearly 4,000 calls annually, with almost 2,000 of those calls related to divers experiencing symptoms post-dive. Most calls originate from laypeople (injured divers, fellow divers, dive leaders, family members, etc.) before any medical professional has been consulted. Calls regarding medically unstable divers may originate from sources including a boat, operating remotely anywhere around the world, or a call from a friend or family member at home on the other side of world relaying third-hand injury details about an injured diver in need of assistance. The initial assessment and thorough telephone triage are crucial for proper case management. DAN's medics, nurses, and doctors, trained and experienced in diving, strive to establish relevant information and provide the best advice.

Generally speaking, DAN medicines' goal is to assist a symptomatic diver to become a patient at their closest medical facility to expedite care. A number of calls come from healthcare professionals (ER physicians, nurses, or chamber staff) seeking expert dive medicine consultation. In these cases, DAN's role is less challenging as the information provided is typically more reliable than lay assessments who are dealing with the acute situation.

CHALLENGES AND LIMITATIONS

DAN accepts calls from members and non-members worldwide. While English is widely spoken in tourist destinations, language barriers can be a challenge. Increasing our coverage and expanding our team has helped tremendously in bridging that gap.

Because DAN assists with diving emergencies globally, our team understands the unique limitations involved in diving in remote locations. Calls from remote locations often suffer from unpredictable technical quality, adding to the difficulty of assisting someone in distress remotely. DAN must assume the worst-case scenario until the injured diver is properly assessed. Not all serious diver injuries involve bubble formation complications and may require emergent interventions that do not involve recompression. Those that do require recompression face additional challenges when it comes to finding open facilities with adequate staffing and optimal medical supervision, leading to situations where DAN is asked to assume a supervisory role. Advancements in telecommunications are bridging the gap between face-to-face interactions, but jurisdictional and medicolegal limitations are still major obstacles.

Due to the consistent lack of these in-person interactions between DAN and the injured diver, it is impractical and unwise to establish a physician-patient relationship between DAN's medical staff and a diver calling the hotline. Managing expectations about what DAN can do over the phone can be challenging. DAN does not admit patients to medical facilities or provide direct/indirect patient care, medical evaluations, diagnostic processes or treatment decisions. DAN mainly provides consultation and advice. Professional medical assistance starts with local emergency medical services (EMS) personnel.

CALLS TO MSCC

Maintaining a system where we can monitor the number of interactions with divers contacting us through phone calls or emails can be quite the undertaking. Our MSCC assists with emergency medical scenarios, travel assistance and non-emergency medical information.

In 2019 DAN had 20,931 interactions that serviced 3,692 cases, which is approximately 18% higher than the 3,127 cases serviced in 2018. Divers can contact our DAN medicine for emergencies by calling our 24-hotline, or for non-emergencies by sending us an email or calling our information line.

Each inquiry is categorized and recorded. This section focuses on those contacts classified as illness/injury.

Of the cases that were classified as illness/injury, they are further divided into diving and non-diving related categories. There were 3,692 illness/injury contacts made in 2019 with 1,865 cases found to be diving related and 1,827 non-diving related. A table of illness/injury breakdown showing the mean from 2014 to 2018 compared with 2019 is presented in Table 2-1.

These cases were broken down further into the type of dive injury incurred by the diver. and presented in Table 2-2.

Most calls continue to be received during the summer months. This is unsurprising as peak diving season is generally between May and September. Figure 2-1 shows the number of calls per month during 2019.

DIVER DEMOGRAPHICS

Roughly 64% of the calls received by DAN medicine were from DAN members, however DAN services all divers and will not refuse a call from any diver in need of assistance. In 65% of the inquires, the sex of the diver was provided with 37% male, 28% female, and 35% not recorded.

GEOGRAPHIC DISTRIBUTION

DAN receives calls worldwide and manages the geographic location of calls to better understand any additional challenges in receiving care divers might face. In 2019, the majority of the calls were from within the United States and Canada. In addition to the North American region, Central America has utilized DAN services with an annual average of 394 calls since 2014. Australia and some Pacific regions involved DAN medicine 137 times while Asia increased its utilization of services to 227 times in 2019. Figure 2-2 shows the trend in number of contacts from specific regions between 2014 and 2019. Map 2-1 shows the volume of calls by country for 2019.

Within the United States we were able to break down the number of calls by each state. Florida maintains the highest number of calls, with 258, making the total number of calls from Florida 1,692 from 2014 to 2019. This is an average of 31.5% of all United States calls

Table 2-1. Number of Illness/injury cases for 2014–2018 compared to 2019.

ILLNESS/INJURY	2014–2018 (mean)	2019
Diving Related	2,107	1,865
Non-Diving Related	1,480	1,827
Total	**3,588**	**3,692**

Table 2-2. Number of dive injuries evaluated between 2014–2018 compared to 2019.

DIVING RELATED	2014–2018 (mean)	2019
Barotrauma	1,017	835
Decompression Sickness	609	680
Marine Envenomation	228	149
Pulmonary Edema - IPE	46	49
Arterial Gas Embolism/AGE	40	40
Fatality	36	31
Non-Fatal Drowning	21	23
Gas Contamination	21	16
Finfoot	17	7
Motion Sickness	16	10
Mask Squeeze	13	16
Loss of Consciousness	10	5
Cardiac Arrhythmia	6	2
Nitrogen Narcosis	3	2
Total	**2,083**	**1865**

Figure 2-1. Number of telephone calls per month in 2019.

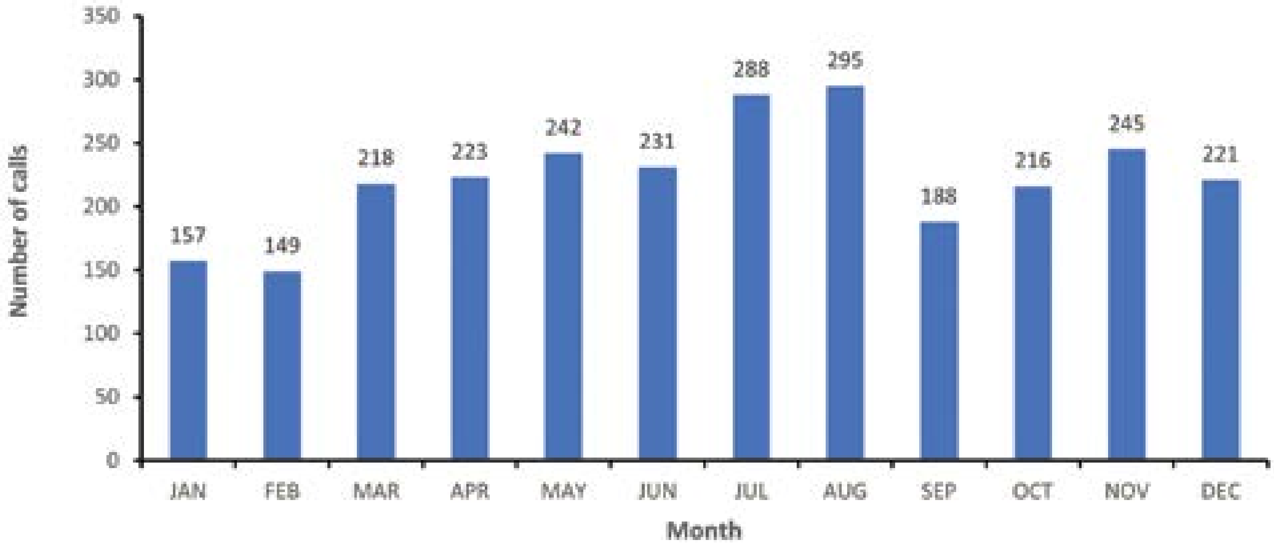
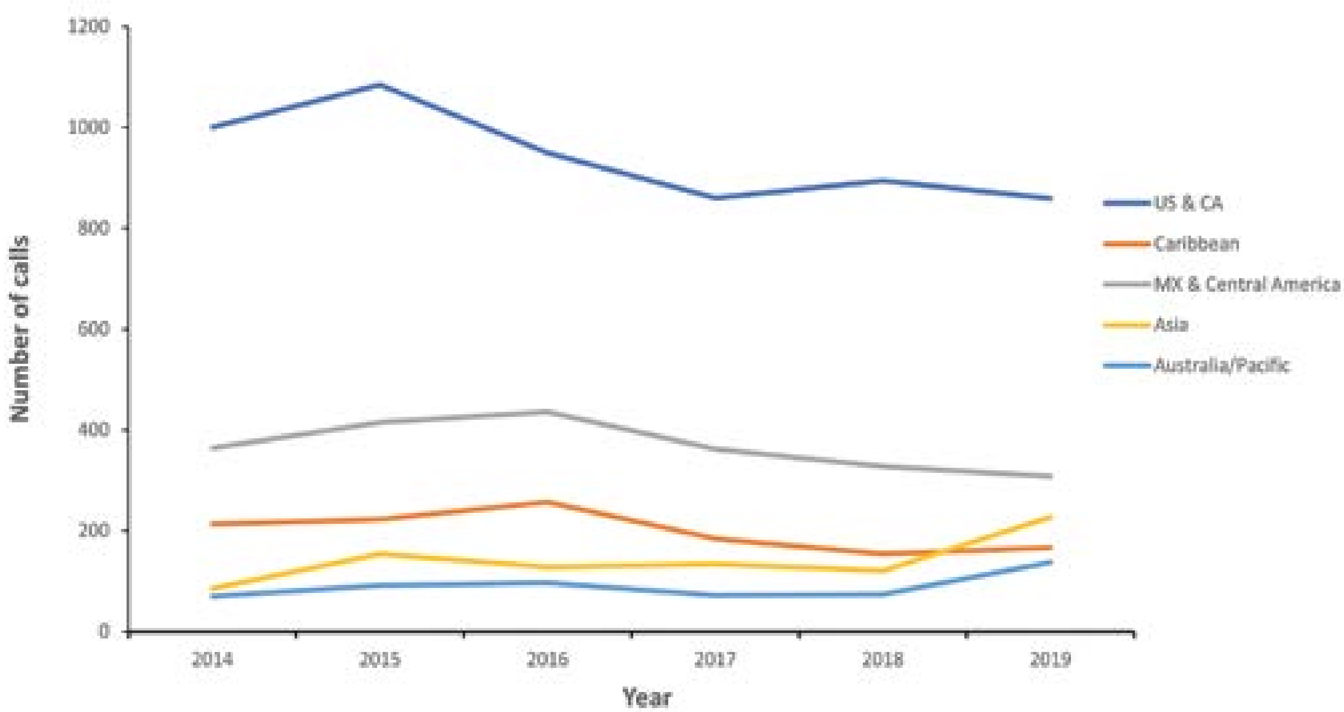
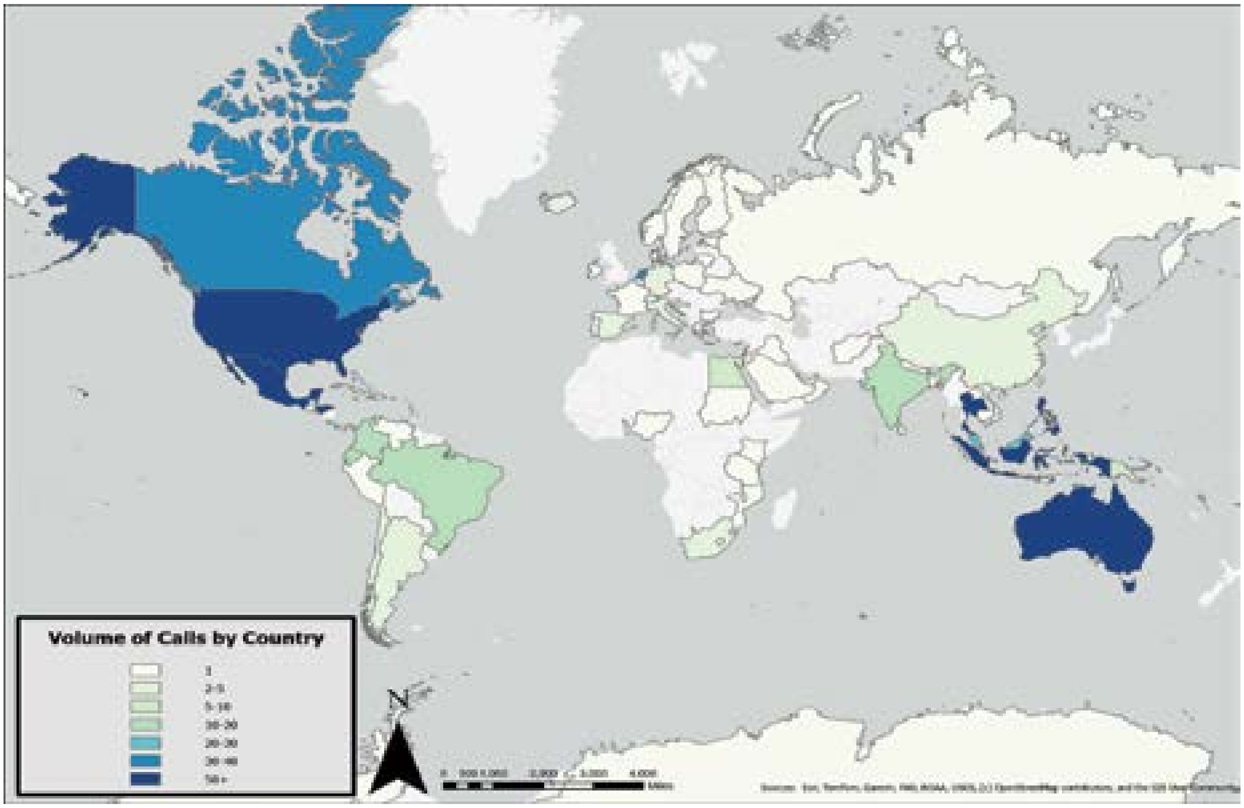


Figure 2-2. Trend in numbers of contacts from specific regions between 2014 to 2019.



Map 2-1. Volume of telephone calls by country in 2019.



to DAN medicine during that time frame. South Florida, including the Keys, were the origination of most of these Florida calls. Figure 2-3 below depicts the number of calls greater than 15 per year by state.

CASE SUMMARIES

BILATERAL HEARING LOSS

DISTAL SYMMETRICAL UPPER AND LOWER PARESTHESIAS

CASE 2019-201 – A 26-year-old female recreational diver completed eight dives in three days in a remote diving location. Her dives were within NDL and included safety stops. Her last dive was 25 m (82 ft) for 39 minutes. Approximately one hour after her last dive, she felt fatigued and anxious. She then began to experience tingling in both her distal upper and lower extremities. After taking her to an ER and giving her supplemental oxygen the patient felt better and experienced relief from her troubling distal paresthesias. She was later discharged. She was doing well and began online research of her condition and became increasingly distressed. Still concerned, two days later began to have mild distal paresthesias again. She found a chamber that felt her initial presentation could have been DCS and was now again symptomatic. She received a TT-6 with gradual relief.

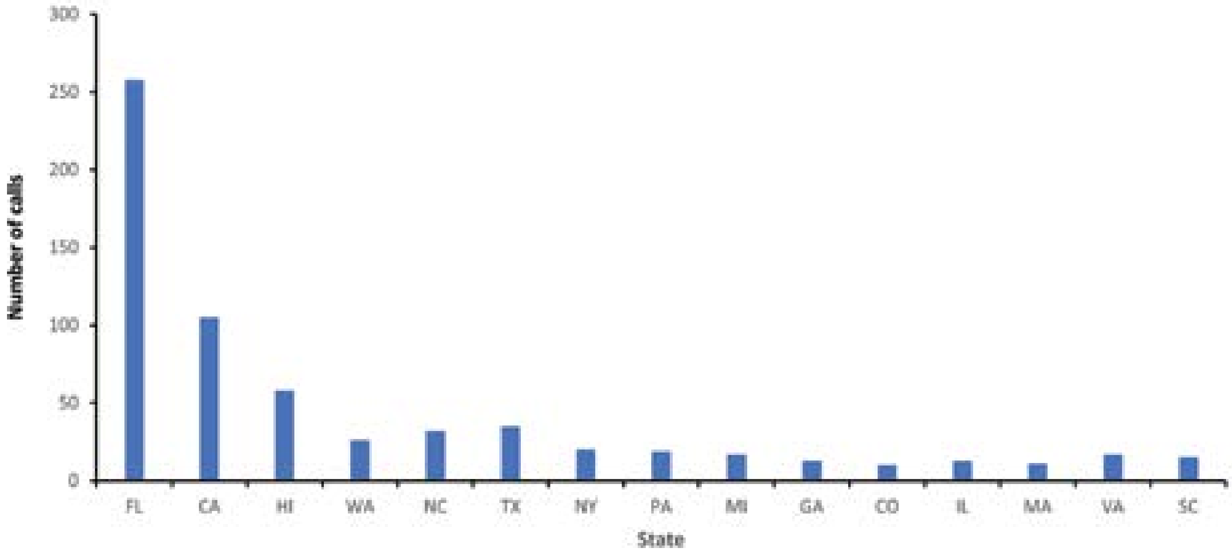
It can be an unusual DCS CNS lesion that symmetrically only affects the distal, bilateral upper and lower extremity tingling. Tingling resolved with surface oxygen and HBOT. Other causes were not ruled out including hyperventilation.

FOOT PAIN

CASE 2019-202 – A mother enrolled her 12 year old son in an open water certification course. The mother called DAN to relay the events. To complete the course he had obtained rental gear from the shop for his open water dives. He had trouble equalizing during his open water dives. During a routine drill, he panicked, spat out his regulator and had to be stopped from ascending while replacing his regulator. Upon reaching the surface the instructor determined he was fine and proceeded to another dive without additional incident reported. Two days later, he was brought back for his final open water dive from a boat where he continued to have difficulties. Following his single dive within NDL to 46 fsw (14 msw) for 51 minutes with a safety stop, he also complained of left big toe pain for suspicion of pain only DCS. He was taken to ER where a blister on the left toe was seen.

This young child may have required additional training in the pool both for additional skill development as well as assessment for his ability to equalize. The mental and physical maturity of this child needs to be reevaluated prior to awarding certification. An argument to wait or at

Figure 2-3. 2019 telephone calls by state.



least a repeat of the course could be made. Proper fitting of rental gear especially for a child where appropriately sized gear may not have been available. No medical assessment of this child was conducted that would include neuro, otoscopic exams and possible chest x-ray following his attempt at a panicked ascent without his regulator as well as his difficulty equalizing. Sole focus on left toe pain/blister was only a priority after extensive google search about DCS highlighted this as a possible diagnosis.

BILATERAL INNER EAR BAROTRAUMA

CASE 2019-203 – An ER physician called about a 65 year old newly certified diver who had just returned from a dive trip. He did only one day of diving as he was having considerable difficulty equalizing his middle ear on both dives that were both 35 fsw (11 msw) for 30 minutes. The bilateral ear pain was worse during the first part of the descent and somewhat improved once at depth. He had the sensation of water in his ears after both dives that persisted over the next day. Sounds appeared muffled. He denied any nausea, vomiting, or vertigo. His neuro exam was normal, a conductive hearing loss bilateral, erythematous TMs with serous fluid in the middle ear space was seen. He was given decongestants and an ENT consultation.

Inner ear barotrauma is associated with difficulty equalizing the middle ear space. This can be due to inadequate training or poor technique that is commonly seen in new divers who are also distracted by other issues on their beginning open water dives conducted on their own. Congestion due to allergies or recent upper respiratory tract infection can cause the mucosa to be edematous and difficult to consistently open when equalization is attempted. It is rare that anatomic abnormalities affect eustachian tube function and there should be no further diving until recovery that includes normal inner ear function. In addition, equalization techniques need to be reviewed and conducted under supervision by his instructor to ensure that correct techniques are being used and are effective, once cleared by his physician to return to dive.

MIDDLE EAR BAROTRAUMA WITH TYMPANIC MEMBRANE RUPTURE

CASE 2019-204 – A diver reported difficulty equalizing on his prior dive. He experienced muffled hearing from his right ear but felt he could equalize enough for his next dive. Unfortunately, he experienced significant difficulty equalizing his middle ear on descent, but he continued despite severe pain, then heard a distinct pop and had immediate pain relief. Upon surfacing, he noted significant serosanguinous drainage from that same ear. He had a conductive hearing loss in the affected ear. ER confirmed middle ear barotrauma with TM rupture with hearing loss. He was sent home with decongestants and given an ENT consultation. The diver was told to keep his ear clean and dry. He was also told no diving until his hearing was returned to normal and his TM had healed.

Tympanic membrane (TM) or ear drum rupture unfortunately is commonly seen in divers who continue their descent despite the inability to equalize. Increasingly severe pain is felt with each foot of further descent until a sudden relief occurs with an associated pop.

Bubbles have been seen flowing from the ear of a diver who continues attempts at equalization, a practice to be discouraged. Avoiding descent when unable to equalize *is important. If difficulty equalizing occurs and especially if TM rupture is suspected, safely abort the dive to avoid any water entering the middle ear space that may cause incapacitating vertigo or an infection from the non-sterile saltwater entering the middle ear space.*

CUTANEOUS DECOMPRESSION SICKNESS

CASE 2019-205 – A 38-year-old female diver performed two dives on the day prior. On the day of her injury she conducted her first dive to 22 m (73 ft) for 74 minutes with a 90 minute surface interval before she conducted her second dive to 24 m (79 ft) for 76 minutes. Both dives were on air, with safety stops completed and reportedly within NDL. Thirty minutes post-dive, before reaching shore she became nauseated. This was followed by a tender, pruritic rash the covered her abdomen and upper arm. She was placed on oxygen that relieved her symptoms over the next several hours. She was seen at a hyperbaric facility, where her neuro was normal and found to be without a rash. She was offered hyperbaric oxygen therapy which she refused. She later flew back home four days later reportedly without issue. She had previous bariatric surgery and no prior history of DCS in the past.

The diver was engaged in multi-day, repetitive dives. Her dives may appear to have significant missed decompression if her depth/time profiles are taken as purely square dive profiles. But these reported exposures often include safety stops and the dive is usually conducted at a shallower depth if a typical multi-level dive. Dive computers account for both factors in determining the need for decompression stops. For those whose mild, type 1 symptoms that resolve spontaneously or after surface oxygen, recompression is recommended if available. If recompression therapy was not obtained, following post-treatment guidelines of waiting at least three days before flying home commercially after physician evaluation is prudent.

TYPE 1 DCS WORSENED BY CONTINUED DIVING

CASE 2019-206 – A 55-year-old female was liveaboard diving, attempting to participate in all dives offered in a puzzling quest to distinguish herself from the other divers by performing the most dives. After the third day of four dives per day she experienced nausea after her second dive. Feeling somewhat better, she made a third dive then found a mottled rash over her abdomen. The crew placed her on oxygen. The rash resolved by that evening. A nurse and physician guest reportedly found her physical exam to be normal. As vacation trip leader, she insisted on diving the following day. After the first dive, she again complained of nausea in addition to a tender marbled rash extending from abdomen to shoulder. In addition, she experienced occasional bouts of dizziness. Upon calling DAN, the recommendations to hydrate, high flow oxygen and proceed to nearest medical facility were given. Upon arrival, she still had a painful rash though the nausea was nearly resolved. Tingling of the shoulder was intermittent. The chamber was readied, and staff assembled in this remote location. However, the diver did not arrive at the chamber whose staff waited into the evening. Reportedly her dizziness did not resolve for several weeks and no follow-up or ENT consultation was obtained.

This case highlights several issues. Scuba diving should never be a competition for the deepest, fastest ascent, etc. Dives should be planned to include consideration of age, fitness, environmental conditions etc. Once an injury occurs, prompt medical attention should be sought and clearance given before returning to dive. A cascade of events occurs with injury, and they may compound a diving injury if returning to soon. Your diving is sometimes copied by those around you, especially if you are the leader of an expedition. So, your diving should be exemplary to avoid mimicry by those less experienced. And finally, not respecting the staff at recompression chambers who standby while we dive should we have an issue is unacceptable. Diverting, taking your time to arrive or just not showing up may not only impact your treatment outcome but affects the personnel at the chamber who are attempting to maintain its 24/7 availability for divers in that location.

LOWER BACK PATHOLOGY

CASE 2019-207 – A 59-year-old male tec diver was wreck diving to a depth of 36 msw (118 fsw) for 34 minutes. The dive was uneventful. Shortly upon surfacing he complained of a backache, dizziness, and confusion. He was placed on oxygen and had to be carried off the boat secondary to his back pain. In the ER, he also stated that he was confused after the dive but later stated that mental status change occurred at depth and later improved. He was given three liters of IV fluids, neuro exam was significant for saddle anesthesia difficulty evaluating gait due to his ongoing low back pain (LBP), and bladder dysfunction. CT of his head and back x-rays were normal. Minimal change was noted after recompression on a TT6. He was sent for imaging of his spine and emergency consultation that diagnosed cauda equina syndrome with neurogenic bladder, spondylosis that required emergent spine surgery including laminectomy, foraminotomy, and fixation. The diver improved with ongoing physical rehabilitation. He later relayed episodes of moderate low back pain associated with physical activity.

This case demonstrates two important points: first, the importance of relaying a good history. The diver relayed mental status impairment after surfacing instead of at depth where it occurred. Since the confusion resolved with ascent and at surface quickly, the possibility of *nitrogen narcosis may have been a possibility. His onset of LBP, neuro deficits, and confusion following a deep, square dive supported the possibility of DCS and prompt recompression. The diver's subsequent clarification of his symptom onset, h/o low back pain and minimal change with recompression therapy quickly prompted his physician team to identify his operable back condition. Fortunately, local availability enabled this prompt recognition and expert surgical treatment prevented long term impairment.*

INNER EAR BAROTRAUMA

CASE 2019-208 – A 55-year-old diver took a quick resort course to dive with friends while on vacation. The friends chose ideal conditions and made two dives to less than 12 m (40 ft) max depth for 30 minutes with full safety stops. She could not equalize and forced herself to depth on the second dive. Upon surfacing she experienced muffled hearing, vertigo, and nausea/vomiting. A local hyperbaric center who did not regularly treat dives performed four full treatment tables without benefit and hearing became more muffled. After three days she traveled home without change in symptoms. She felt more nitrogen bubbles remained and obtained another treatment that made her condition worse. She called DAN who recommended a medical evaluation that reported evidence of middle ear barotrauma and fluid behind both eardrums with conductive hearing loss and minimal nystagmus noted. No further recompression was obtained, and ENT evaluation five weeks later was normal with a diagnosis of inner ear barotrauma.

This case illustrates the importance of differentiating inner ear barotrauma from inner ear DCS. She gave a convincing history of a novice diver struggling with equalization and subsequently injuring both middle and inner ear. The dives were very conservative and conditions ideal. Recompression is not indicated and may worsen the condition by exposing the injured ear to additional pressure induced barotrauma. Bubble sensation in and around the ear may be experienced with middle ear barotrauma and is NOT pathologic nitrogen bubbles causing DCS. Certainly no benefit for recompression warrants its discontinuation and search for other etiologies. Fortunately, any damage to the inner ear appears to have resolved per her ENT consultation. No further diving should be conducted until her physician team ascertains she has healed and can effectively equalize before undergoing retraining to include equalization mastery.

MEDICATION EFFECTS

CASE 2019-209 – A 35-year-old diver made two uneventful no-deco dives with safety stops and normal ascent to surface. The next morning, no diving was planned, and he removed his sea sickness patch then replaced his contact lenses, which he had forgotten to do the previous night. His wife noted one pupil was clearly larger than the other and he appeared forgetful. He called DAN for nearest chamber for possible recompression for arterial gas embolism. A history of an uneventful dive, healthy diver, normal neuro exam, no extrapulmonary air, lead to a scopolamine side effect being considered.

The consideration of a pulmonary overinflation syndrome should be considered in a diver who has underlying pulmonary issues, has experienced rapid emergent ascent especially if breath-holding demonstrates mental or neuro changes, and evidence of extrapulmonary air occurring shortly after a dive. None of these occurred in this case. The possibility that small findings may have been missed is a slight possibility. In this case, mild amnesia and unequal pupils needed to be evaluated for other findings, and none were found. History revealed that his anti-nausea prophylaxis was the scopolamine patch that can cause some degree of amnesia in some divers. In addition, he described the improper handling of the scopolamine patch and handling contacts before thoroughly washing his hands. After a day, his symptoms resolved.

SUMMARY OF THE DAN MEDICAL SERVICES CALL CENTER (MSCC) OPERATIONS AND INSIGHTS

The Divers Alert Network (DAN) Medical Services Call Center (MSCC) was established in 1980 to assist injured divers. Originally a single medic operation, DAN has evolved into a 24/7 call center staffed by medics, nurses, and physicians in three global locations. Through its services, DAN continues to provide and enhance diver safety, refine emergency response systems, and support global diving communities. In 2019, DAN handled 20,931 interactions, categorized as:

- Cases (emergency assistance)
- Inquiries (non-emergency information)
- Follow-ups

Among diving-related cases, the most frequent issues included:

- Barotrauma (e.g., ear or sinus injuries)
- Decompression sickness (DCS)
- Marine envenomation
- Pulmonary edema (immersion-related)

Non-diving-related cases continued to rise with the need for medical evacuations by commercial aviation and medical air ambulance. A majority of these medical evacuations originated from both the Caribbean and Southeast Asia.

DAN's telecommunication-based support faces challenges, including:

- Reliance on verbal communication for diagnosis and advice.
- Variability in the technical quality of calls and language barriers.
- The need to clarify DAN’s role as advisory rather than providing direct medical care.

DAN assists both members and non-members, ensuring prompt emergency response and guidance for diving-related and non-diving incidents. It's broader mission emphasizes injury prevention, diver education, and collaboration with medical professionals to improve outcomes.

SECTION 3. **INTERNATIONAL DIVING INJURIES & FATALITIES**

INTRODUCTION

As mentioned in the previous chapters, DAN is diligent about retrieving the most up-to-date information on diving injuries and fatalities that occur around the world. While our follow-up process is limited in certain regions, other DAN offices and outside organizations collaborate to work on fatality and injury monitoring initiatives. For this report we recieved contributions from DAN Japan, DAN Europe, and DAN Southern Africa. The New Zealand Underwater Association's 2020 Annual Report excerpt on diving fatalities is also incorporated in this section.

DAN EUROPE

DAN Europe collects injury and fatality data from only DAN Europe members. Data is collected from calls to their Medical Services Call Center (MSCC) and their insurance claims. In 2019 they recieved a total of 2,349 calls, 1,332 of those were diving related, 1,017 were non-diving related. This is an increase of 370 total calls from the 1,979 total received in 2018.

Map 3-1 highlights the countries where each call originated, which were global in scale and not just from European nations. Indonesia, Thailand, Egypt, and Italy all saw more than 200 calls from afflicted DAN Europe members with both diving and non-diving accidents serviced by the MSCC.

Of the emergency calls serviced, 315 were confirmed cases of decompression illness (DCI), while 170 were suspected cases of decompression illness, and 20 related to a fatal dive accident in 2019. Table 3-1 highlights the type of diving related medical emergencies collected in 2019.

Table 3-1. Diving related medical emergencies collected in 2019.

Diagnosis	Number of Calls
DCI	315
Suspected DCI	170
Ear barotrauma	178
Suspected ear barotrauma	101
Ear infection	132
Diving trauma – dry	58
Diving trauma – wet	108
Pulmonary suspected barotrauma	13
Pulmonary barotrauma	10
Pulmonary edema	8
Other barotrauma (dental/sinus/mask)	36
Other suspected barotrauma (dental/sinus/mask)	25
Marine-life-injury	60
Near-misses	12
Other diving related emergency	86
Diving death	20
Total	**1,332**

Of the DCI cases (both confirmed and suspected), the specific type and number of cases are outlined in Table 3-2. The majority of confirmed cases were skin bends (Type I DCI) comprising a reported 91 emergency calls, followed by neuro-sensorial DCI with 82 calls.

Table 3-2. Number of DCI and Suspected DCI (Susp DCI) Cases reported to DAN Europe in 2019.

Type of DCI	DCI	Susp DCI
Skin	91	45
Neuro sensorial	82	31
Neuro Motor	39	19
Oto vestibular	39	11
Pain Only	32	22
Omitted deco stop	3	12
Cerebral	5	-
Pulmonary	1	3
AGE	7	1
CAGE	-	1
Taravana	2	1
Not enough information	14	24
Total	315	170

DAN SOUTHERN AFRICA

DAN Southern Africa also manages a MSCC and in 2019 they recieved 220 calls and emails ranging from non-diving related inquiries to fatal dive accidents. Of the 220, 117 were non-emergency calls, 96 were email inquiries, and seven were emergencies (Table 3-3).

Table 3-3. Category of call serviced by DAN Southern Africa in 2019.

Category of call	Number of calls serviced
Emergency	7
Email Inquiry	96
Non-emergency	117
Total	**220**

In conjunction with DAN and DAN Europe, DAN Southern Africa assigns a sub-category based on the caller's chief complaint and overall assessment of the individual case. Table 3-4 displays the number of emergency and non-emergency calls in each sub-category. A majority of the calls recieved in 2019 were from divers seeking general medical advice, with 160 calls combined. Of the 220 total calls, only five serviced by this office were in connection to suspected DCS

DAN JAPAN

The following is a summary on recreational dive accidents and fatalities that occurred in Japan from January to December, 2019, based on the published data collected by the Japan Coast Guard (JCG) and other agencies including DAN JAPAN. The term 'fatality' includes missing cases.

Map 3-1. Call origins

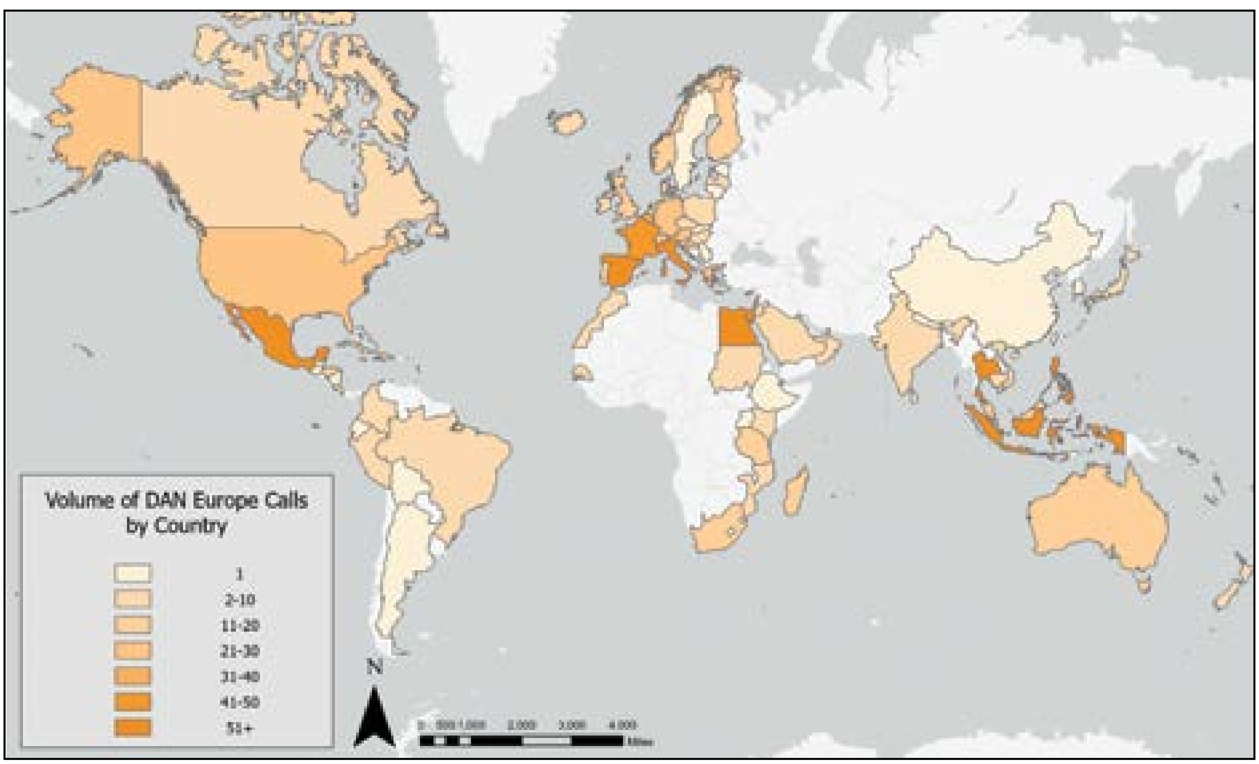


Table 3-4. Sub-category of calls serviced by DAN Southern Africa in 2019.

Sub-Category	Category			
	Non-emergency	Email Query	Emergency	Total
Medical advice	93	65	2	160
Assistance	3	8	4	15
Information request	4	6	-	10
Dive physician information	1	6	-	7
Ears	6	-	-	6
Suspected DCS	3	1	1	5
Evacuation options	1	3	-	4
Claim	3	-	-	3
Claim request	-	1	-	1
Chamber information	-	3	-	3
Chamber testing	2	1	-	3
Scientific and research dives	1	-	-	1
Commercial dive plans	-	1	-	1
Deep dive notifcation	-	1	-	1
Total	**117**	**96**	**7**	**220**

GENERAL TENDENCY

The trend across the past ten years (2010–2019) is illustrated in Figure 3-1, which shows a total of sixteen fatalities (nine male and seven female, including one missing value) in 2019, with 15.5 fatalities per year (red line). The percentage of male fatalities in 2019 was 56.3% versus a ten-year-mean of 64.6%, indicating that the male fatality rate is gradually decreasing, as described in the previous report.

It is thought that the Japanese dive population is between 300,000 to 500,000 people. Based on these values, the fatality rate per 100,000 divers in 2019 is estimated to be around 3.1–5.2.

The previous ten-year figures reported 467 dive accidents (including survival cases) involving emergency medical services, and of these 157 were fatal (33.6%)

AGE GROUP DISTRIBUTION

Figure 3-2 shows the number of fatalities by age group. Of 16 fatalities, seven were in their 50s and accounted for 43.8% of all fatalities. Adding the over 60 age group fatalities (four cases), the fatality rate increased to 68.8%. This trend towards older age fatalities was also evident in our recent data: i.e. from 2014 to 2019, the fatality rate over 50 was 57.1% (total fatalities 84 cases; over 50s 48 cases), and when expanded to cover age over 40, the fatality rate was 78.6% (over 40s; 66 cases).

These data suggest that as mentioned in the previous report, older divers may have underlying conditions, for example cardiac disease or stroke, hypertension, and/or high cholesterol, which can increase the risk for diving-related fatalities.

CAUSE OF DEATH

The causes of death diagnosed by physicians are shown in Figure 3-3. Two cases of illness/injuries were reported, one myocardial infarction and the other a hypoxic encephalopathy (brain damage from lack of oxygen); both were in divers aged over 50 years. One missing case is included in the unknown category.

In 11 cases of drowning, nine decedents (81.8%) were over 40 years of age and six (54.5%) were over 50 years, while two were over 60 years. These data also support the assumption that comorbidities in older divers could trigger the fatal accidents.

Figure 3-1. Number of fatalities from 2010 to 2019 reported to DAN Japan.

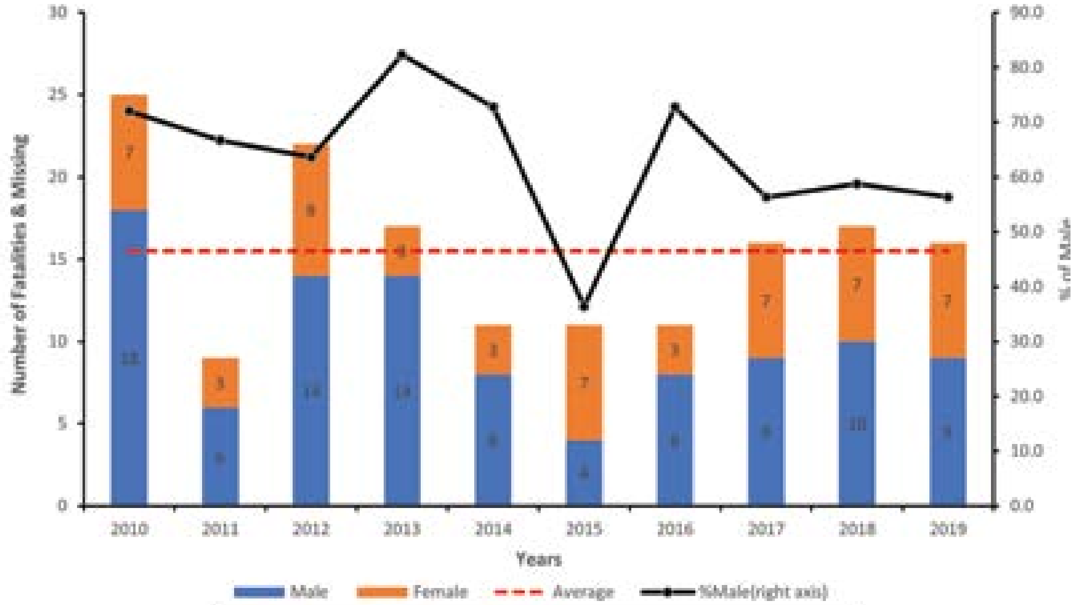


Figure 3-2. Age group distribution of fatalities reported to DAN Japan in 2019.

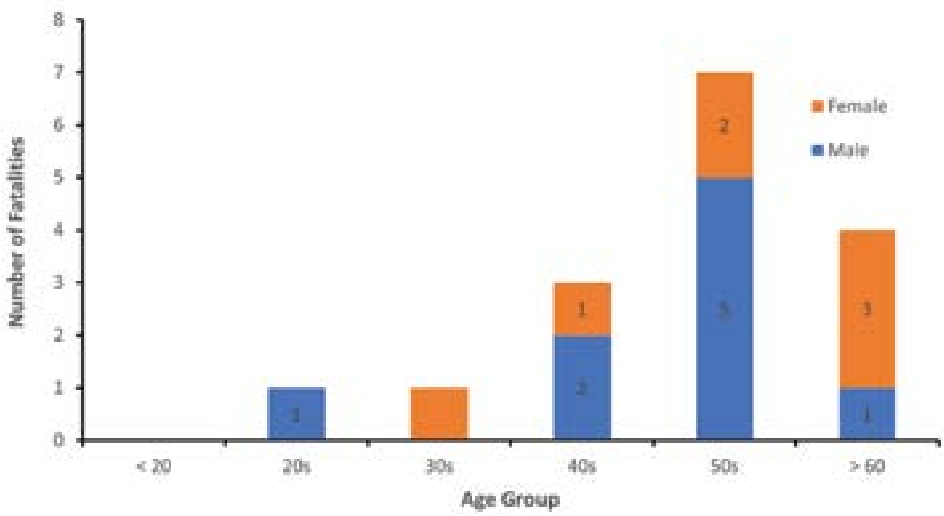


Figure 3-3. Distribution of cause of death in fatal dive accidents reported to DAN Japan in 2019.

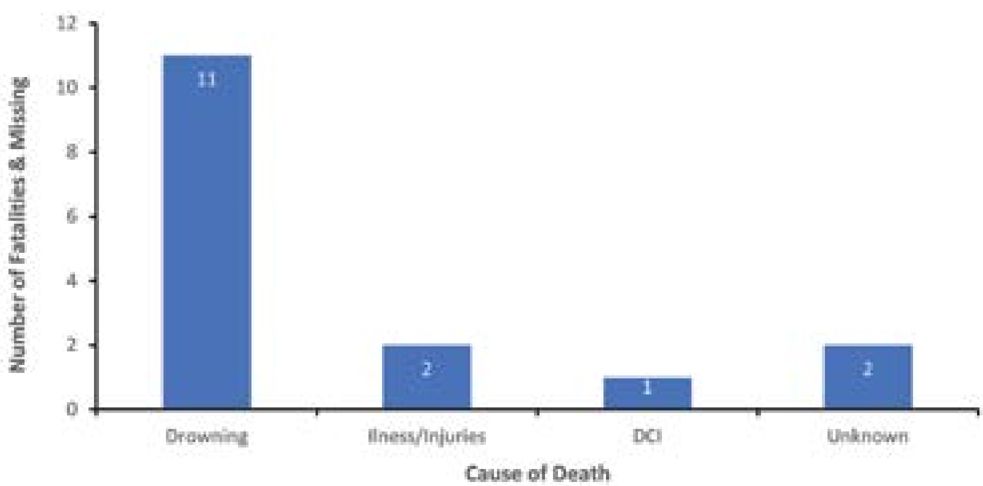
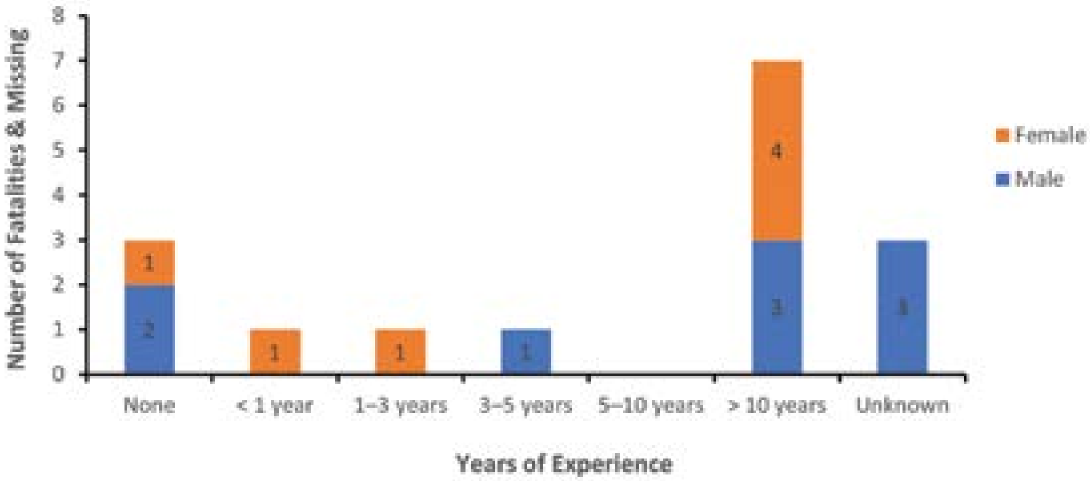


Figure 3-4. Distribution of fatalities by years of dive experience.



DIVER EXPERIENCE

GENERAL EXPERIENCE BY YEARS OF DIVING

Figure 3-4 shows number of fatalities by years of dive experience. These limited data suggest that dive experience itself does not necessarily guarantee safety. For safer diving, divers should maintain physical and mental fitness, dive conservatively, and follow the safe diving practice. Unfortunately, the denominators of each section were unknown, so the fatality rate could not be calculated.

One serious problem must be pointed out. Three deaths occurred in the 'no dive experience' category, indicating the deaths took place during a introductory diving course or open water diver training, where the instructor had full responsibility.

ESTIMATED NUMBER OF LIFETIME DIVES

In considering the cases from a slightly different point of view, Figure 3-5 describes the number of lifetime dives completed before an accident. A large total number of lifetime dives does not necessarily ensure dive safety.

ESTIMATED NUMBER OF DIVES WITHIN ONE YEAR

Figure 3-6 shows the number of dives each diver had made in the year previous to the to the accident. The Unknown category was the most numerous (eight cases, 50.0%), while fatalities in those who did not dive in the past year comprised four cases (25.0%).

Figure 3-5. Number of total dives completed before fatal accident.

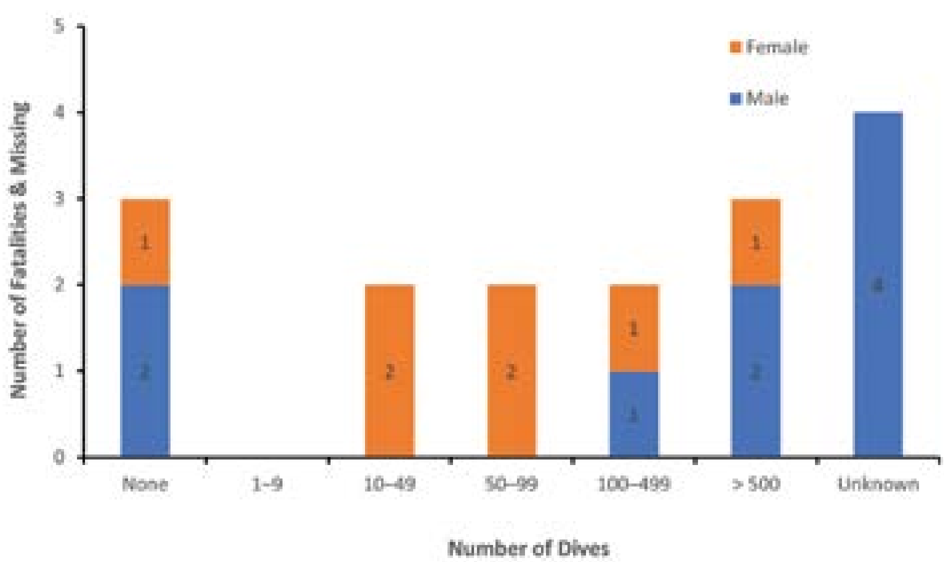
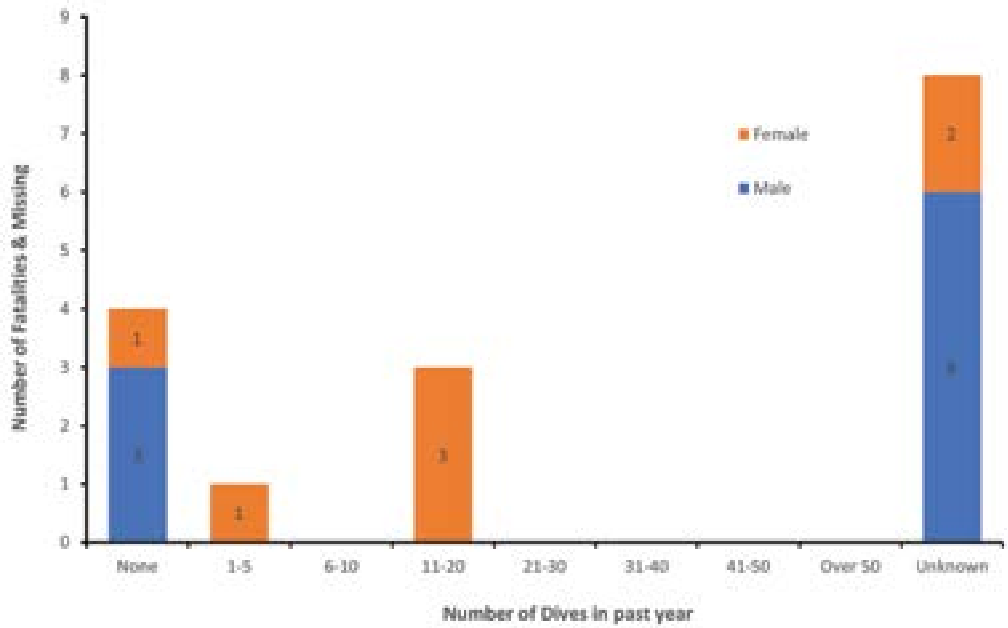


Figure 3-6. Number of dives completed in the year previous to a fatal accident.



FATALITIES BY MONTH AND ORGANIZATION OF DIVERS

Fatal accidents occurred throughout the year, with the majority (37.5%) of cases occurring during the summer season (June–August), and 6.3% in the autumn (September–November); these two periods are high season for diving in Japan. In winter (December–February), 31.3% of cases were reported, while in springtime (March–May), only 25.0% occurred. Figure 3-7 outlines the month and number of dive accidents reported.

Dive activities in Japan are most often made with a dive leader(s) who organize and guide their underwater dive tours. The tours are usually organized by dive shops or local dive services at dive sites. As a consequence, guided dive activities with instructor(s) and/or dive guide(s), such as a Dive Master or Assistant Instructor had the most numerous fatalities (31.3%), alongside solo dives (31.3%), then followed by entry training/experience excursions (18.8%). Group or buddy dive activities had the lowest number of fatalities (6.3%). These numbers are highlighted in Figure 3-8.

Figure 3-7. Distribution of fatalities reported by month in 2019.

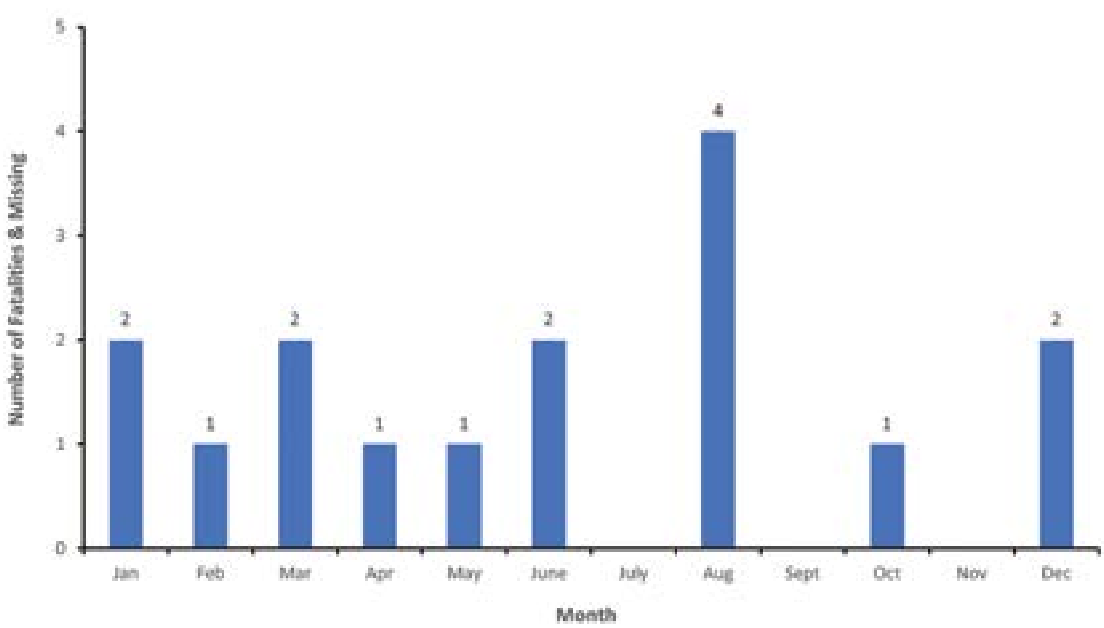
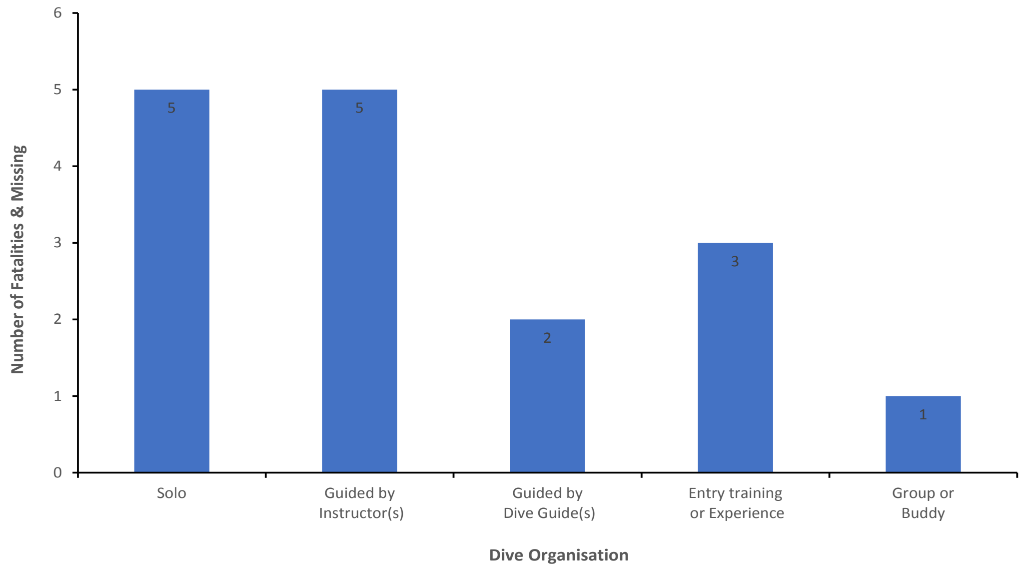


Figure 3-8. Number of fatalities by dive organization.



NEW ZEALAND UNDERWATER ASSOCIATION

The following is an excerpt from the New Zealand Underwater Association (NZUA) 2020 Annual Report (featuring 2019 data). We thank the team at NZUA for providing us with this information and collaborating with us on dive our safety efforts.

WATER SAFETY NEW ZEALAND

NZ Underwater continues to work closely with sector lead and key safety funding partner, Water Safety NZ.

New Zealand has one of the highest per capita fatal drowning rates in the Organization for Economic Cooperation and Development (OECD). In 2019, New Zealand's total per 100,000 preventable drowning death rate was 1.8, an increase on the 5-year rate of 1.6. Divers remain a high priority for the organisation.

KEY OUTTAKES FROM THE PROVISIONAL DROWNING REPORT 2019

There were 82 preventable drowning fatalities in 2019, an increase of 24% on the 66 recorded in 2018. The 2019 total is higher than the five-year average of 79 and less than the the peak of 91 recorded in 2017.

OBSERVATIONS

- The over-representation of men in the statistics worsened from 78% to 81%.
- The under-fives age group fatalities jumped to seven from three.
- The 55–64 age group doubled to 12 from 6.
- The over – 65 cohort reduced by two to 15, but remains the highest age group classified.
- Regionally, and based on numbers, Auckland (18), Northland (16), Waikato (7), Otago (7), and Southland (6) presented the highest number of drowning fatalities in 2019.
- West Coast (5) and Wellington (5) have shown an increase in fatalities – two each were recorded in 2018.
- Significant increases in incidences occurred in Land Based Fishing (12).
- Significant increases in incidences were recorded for Underwater Diving (11) activities.
- Beach numbers spiked to 27 in 2019 compared to 20 in 2018, and 18 for the 2014–2018 five year average.
- River numbers have increased to 19 in 2019 compared to 12 in 2018 and 17 for the 2014–2018 five year average.
- Domestic and home pool numbers have reduced with three each.

References: 2019 Provisional Drowning Report – available on the WSNZ website.

MARITIME NEW ZEALAND

NZUA appreciates Maritime NZ's continued financial support of its safety-related activities.

While the use of lifejackets and two forms of communication remains central to Maritime NZ's recreational sector safety messaging, the organisation is increasing its emphasis on the consumption of alcohol on vessels; a position the NZUA supports.

Priority areas for the 2019– 2020 year were as follows:

- Failure to wear lifejackets, particularly in boats under six metres (a factor in up to two thirds of boating fatalities).

- Failure to carry communication equipment so that the skipper can call for help when in trouble.
- Failure to check a marine weather forecast before venturing out on to the water.
- Consumption of alcohol.
- Lack of skipper knowledge of boating safety rules – particularly vessel speed and the 'rules of the road'. The strategy also focuses largely on males – in particular males over 45 years of age who make up the majority of boating fatalities.

NO EXCUSES

The No Excuses campaign ran again this past Summer. Supported by funding from Maritime NZ, participating councils issues infringment notices up to $300 for boaties not carrying lifejackets or speeding in controlled areas.

REPORT FROM SENIOR SERGEANT BRUCE ADAMS – POLICE NATIONAL DIVE SQUAD

The Police National Dive Squad is currently investigating nine fatalities, one of which is a double fatality. The statistics below include 2019 and 2020 (nine in 2019, five in 2020 at the time of this report). Five of these fatalities were free divers and all instances included recreational activities.

We have seen a continuation of contributing factors from previous years as below; and these cases involved several factors occurring at once – as opposed to a single contributing factor which on its own, would likely be manageable by the diver.

Of the 78 fatalities investigated since 2006, 17 were free divers. This appears to be an area of diving that is increasing in popularity.

The 20 main contributing factors identified include the following:

- 56 had not abandoned their weight belt.
- 37 were not diving actively with a dive buddy. This includes free divers operating ‘one up one down’.
- 28 were not medically fit to dive.
- 26 were over-weighted (carrying too much buoyancy weight).
- 24 did not service their equipment before the dive.
- 21 did not run pre-dive checks on equipment.
- 21 had run out of air supply.
- 20 had not planned to end their dive when cylinder contents reached 50bar.
- 18 were not carrying a knife (despite this, entanglement was not a factor).
- 16 did not have a dive plan, especially an emergency plan.
- 15 had started the dive knowing there was a fault with equipment.
- 15 had exceeded dive experience or qualification.
- 12 were not familiar with the equipment being used.
- 12 had consumed alcohol.
- 11 had taken prescription medication or recreational drugs.
- 11 cases had catch-bags attached to the diver.
- 10 cases had changes in health which should have been discussed with their doctor.
- 10 had exceeded safe ascent rates.
- Nine cases where the diver appeared unaware or ignored warnings/alarms/ recommendations by their dive computer.
- Eight cases where the diver had an extended break from diving and refresher courses were recommended.

It is also worth noting that in almost all cases, the dive flag ‘alpha’ was not displayed. Although not a direct contributing factor in the previous fatalities, it is only a matter of time before the absence of a flag will result in an unfortunate event. The ‘alpha’ flag is essential to warn others that people are diving below.

These tragic events, like any accidental loss of life, have a horrifying impact on family, friends and the community. Once again we wish to reiterate the importance of best practice in diving, including keeping up-to-date with training; monitoring one’s own health and capabilities; checking and servicing equipment regularly; and always diving with a buddy. These key learnings must be acknowledged to allow us all to create a safer environment for everyone involved in this sport.

DIVE EMERGENGY SERVICE (DES)

The Diver Emergency Service (DES) is a 24 hours, seven days a week hotline for advice and treatment of all diving related incidents, accidents, or injuries, including the emergency management of decompression illness.

The phone number (0800 4 337 111), is manned by medical professionals with a diving doctor on call and remains a crucial part of diver safety management in New Zealand.

SURVIVE THE DIVE – FIT, CHECK & SIGNAL

For the 2019–2020 year, NZUA centralised its messaging around the Survive the Dive banner, with Fly the Flag still present as a stand-alone promotion. Funding for the campaign was applied for jointly from Water Safety NZ and Maritime NZ. Both applications were successful.

The ongoing campaign is anchored by a repository of diving and boating safety knowledge hosted on the NZ Underwater website – www.survivethedive.nzunderwater.org.nz

The information on the site has been produced and/or advised by qualified diving and boating experts and is reviewed, refreshed and added to by the NZUA editorial team.

Promoted under the headline 'Survive the Dive', the 2019/2020 campaign wraps multiple safety issues affecting the underwater community engaged in SCUBA, spearfishing and snorkelling activities, within the headline pillars of Fit, Check and Signal.

The campaign's key message can be summarised by the following voice-over created to support 60-second video executions launched in the Summer of 2019:

SURVIVE THE DIVE – 60 SECOND VOICE-OVER –

All NZ SCUBA, spearfishing, and food-gathering divers are reminded to Survive the Dive by following the principles of Fit, Check and Signal.

WHY FIT?

Poor heart health and a lack of general fitness are a primary cause of diver fatalities with divers over the age of 40 most at risk.

A committed cardiovascular program supported by regular medical check-ups is central to a safe diving plan. 'Fit to dive' means sober too! Alcohol and drugs do not mix with diving. Even a hangover can cause serious diving trouble.

NZ Underwater says, "Get real about your physical state before taking a splash to put a feed on the plate."

WHAT'S CHECK?

- Check the weather.
- Check the boat.
- Check the gear.
- Check your mate's gear.
- Check everything and anything.

Visit www.survivethedive.nzunderwater.org.nz for checklist tips and remember Weather – Boat – Gear before Go!

AND SIGNAL?

- Signal the boat – A legal dive flag flown on every boat is mandatory.
- Signal you – Numerous devices are available to signal spear divers and snorkellers in the water as well as SCUBA divers on the surface.
- Signal the trip – report the trip to an external party like the NZ Coastguard, as well as friends and family.
- Being safe is being seen! And signal first to get found fast!
- Fit, Check and Signal to Survive the Dive!"

DIVING AND BOATING SAFETY PRIORITIES ADDRESSED INCLUDE:

- Health and fitness.
- Medical checks.
- Training.
- Refresher courses.
- Equipment checks and maintenance.
- Diver best practice.
- Boating safety and on-water best practice including:
  - Avoiding the consumption of alcohol and drugs, even to the point of considering the effects of hangover.
  - Checking and understanding weather forecasts.
  - Pre-trip boat checks including: general seaworthiness, lifejacket condition and use, bilge-pumps, and use of at least two communication devices.
  - Signalling with dive flags.
    - Signalling divers in the water with various devices.
    - Signalling the trip – filing trips reports with Coastguard and other third parties.

ACKNOWLEDGEMENTS

The editors of this report at DAN would like to thank:

Tetsu Nozawa – DAN Japan

The New Zealand Underwater Association

DAN Europe

DAN Southern Africa

for sharing their injury and fatalitiy statistics with us so that we may inform the diving community of the global trends in dive safety.

SECTION 4. **BREATH-HOLD DIVING**

S. Lesley Blogg PhD, Frauke Tillmans, PhD

INTRODUCTION

Humans have held their breath to dive for food and materials in seas and lakes long before the advent of scuba diving facilitated breathing underwater. For over 1,500 years to the present day distinct freediving populations such as the Ama of Japan and Korea, and the Bajau of Indonesia have used breath-holding techniques to harvest pearls and sea food,[1] while in the Mediterranean, generations of Greeks living on the Dodecanese Islands harvested sponges in the same way.

The definition of breath-hold diving is holding your breath in any form while submerged underwater and engaging in an activity. Examples still include collecting fish and other treasures from the sea floor for subsistence or commercial purposes, while there are many recreational breath-hold pursuits including playing and swimming underwater in a pool, making underwater excursions while snorkeling, and sports including competitive freediving, synchronised swimming, and underwater rugby. Given the range of underwater activities that already exist and are emerging, as well as the diverse variety of people that undertake them, the incidents that take place while breath-holding are very varied. DAN aims to monitor these incidents to produce safety guidelines and inform participants about possible risks and how to avoid them.

As with any activity, those that participate in and practice breath-holding on a regular basis will have some advantages over those that are untrained. At the extreme level, genetic adaptations to diving underwater have been found in breath-hold harvesting populations who may sometimes spend more than five hours a day submerged.[2,3] In a study on the Bajau divers, it was found that natural selection pressures on the PDE10A gene has meant that this population have larger spleens than ‘normal’, allowing them to increase the amount of circulating oxygenated red blood cells in their body when breath-hold diving.[2,4]

The same study also found evidence that selection had modified a gene affecting the human diving response,[2] which is not as extreme as some other mammalian and avian divers, but serves to slow the heart rate (diving bradycardia), reduce the flow of blood to limbs, and increase mean arterial blood pressure thus maximising blood supply to essential areas such as the brain and core for optimal survival in the absence of breathing.[5]

Further work has shown that both spleen and lung volume can predict performance in competitive freedivers, and that apnea (breath-hold) training can increase the length of time a person can hold their breath and their diving response.[6] Thus, experienced breath-hold divers will not only exhibit a better performance, but their training will also benefit their safety, while untrained breath-holders will be at greater risk. Response to breath-holding is also highly individual, and once again preparedness and training will influence performance and safety.

Untrained individuals can usually hold their breath for a maximum of one minute and this obviously limits any excursions underwater. Another curb to breath-holding underwater is ear pain, which is caused by differential pressures between the middle and external ear as a diver descends, influencing maximum reachable depth. Once a diver can equalize this difference, they may then exceed their previous limits. Other obstacles exist once a diver goes deeper. For example, at 30 m (99 ft) underwater the lungs of an average person are squeezed to their residual volume. At these depths, the urge to breathe often prompts a diver to rush to the surface before additional troubles can occur, although this is not true for all divers and especially not for those attempting to accomplish a task underwater, such as fishing or harvesting. The pressure to complete a task may push a diver past his or her limits and they may experience a blackout due to hypoxia.

Not all breath-hold diving involves achieving great depths; during competitive underwater rugby or hockey, a player must be able to repeatedly submerge themselves in a pool of depth 3.5−5 m (11.55−16 ft) and swim throughout the game. For both sports, the game lasts for two 15 minutes periods with a five-minute break at half time, so the ability to perform repeat breath-holds is most important.

Competitive freedivers are particularly driven to improve their breath-hold limits, and there are a range of competitive categories that require different abilities. Table 4-1 describes the categories and lists the current depth/time records (to December 2019) for each.

OVERVIEW OF CASES

Since 2004, DAN has collected and analysed breath-hold incidents. The sources of information are public media, calls to the DAN emergency or help line regarding voluntary reports from witnesses or divers experiencing problems, and DAN's online Diving Incident Report System (DIRS). The amount of data captured is only a fraction of all incidents that occur each year.

There is no regulation of common breath-hold activities such as snorkeling, spontaneous breath-hold diving, and recreational spearfishing, nor is there a formal reporting system for related incidents and injuries. Even so, the amount of data collected by DAN continues to increase each year. Figure 4-1 shows data captured annually by DAN since 2004. The mean number of fatalities recorded across this period is 52 deaths, and this was also the number recorded in 2019; no injury data were collected in the reports for this year.

DEMOGRAPHICS

The mean age of breath-hold victims reported in 2019 is shown in Figure 4-2 (the age of two of the decedents was unknown). Unlike Scuba divers, where the age group with highest number of fatalities is usually over 50 years, the age distribution of breath-hold divers in 2019 was focused more on those 20–50 years of age, meaning that age-related health issues might be less likely to play a role in the cause of the accident.

GEOGRAPHICAL DISTRIBUTION

The citizenship of breath-hold victims was recorded in 39 cases, with the majority being from the United States (Figure 4-3). The location of the fatal accidents was recorded in all bar one case (n=51) (Table 4-2 and Map 4-1), with the United States (including Hawaii) being the location for 22 of these deaths, the same number as for the 2018 data.

Figure 4-1: Total number of breath-hold diving fatalities recorded by DAN worldwide 2004–2019.

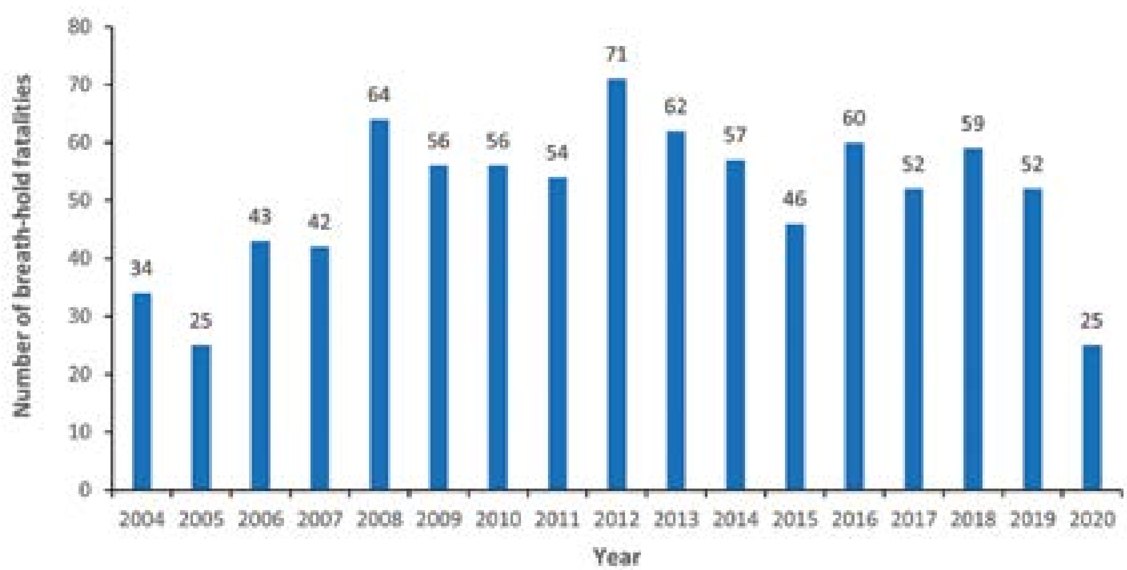


Table 4-1: AIDA recognized competitive freediving disciplines and records (to December 2019).

Discipline	Description	Record Performance			
		Women		Men	
Static apnea	Resting, immersed breath-hold in controlled water (usually a shallow swimming pool).	9:02 min	21 June 2013	11:35 min	8 June 2009
Constant weight	Vertical self-propelled swimming to a maximum depth and back to the surface; no line assitance allowed.	114 m	7 Nov 2020	130 m	18 July 2018
Free immersion	Vertical excursion propelled on a rope during descent and ascent; no fins.	98 m	16 Oct 2019	125 m	24 July 2018
No limit	Vertical descent to a maximum depth on a weighted sled; ascent with a lift bag deployed by the diver.	160 m	17 Aug 2002	214 m	14 June 2007
Dynamic without fins	Horizontal swim in controlled water.	191 m	1 July 2017	244 m	1 July 2016
Constant weight without fins	Vertical self-propelled swimming to a maximum depth and back to the surface; no line assistance allowed.	73 m	22 July 2018	102 m	21 July 2016
Variable weight	Vertical descent to a maximum depth on a weighted sled; ascent by pulling up a line and/or kicking.	130 m	18 Oct 2015	146 m	1 Nov 2015
Dynamic with fins	Horizontal swim in controlled water.	257 m	13 Oct 2019	300 m	2 July 2016

Figure 4-2: Distribution of breath-hold fatalities by age group in 2019 (n=50).

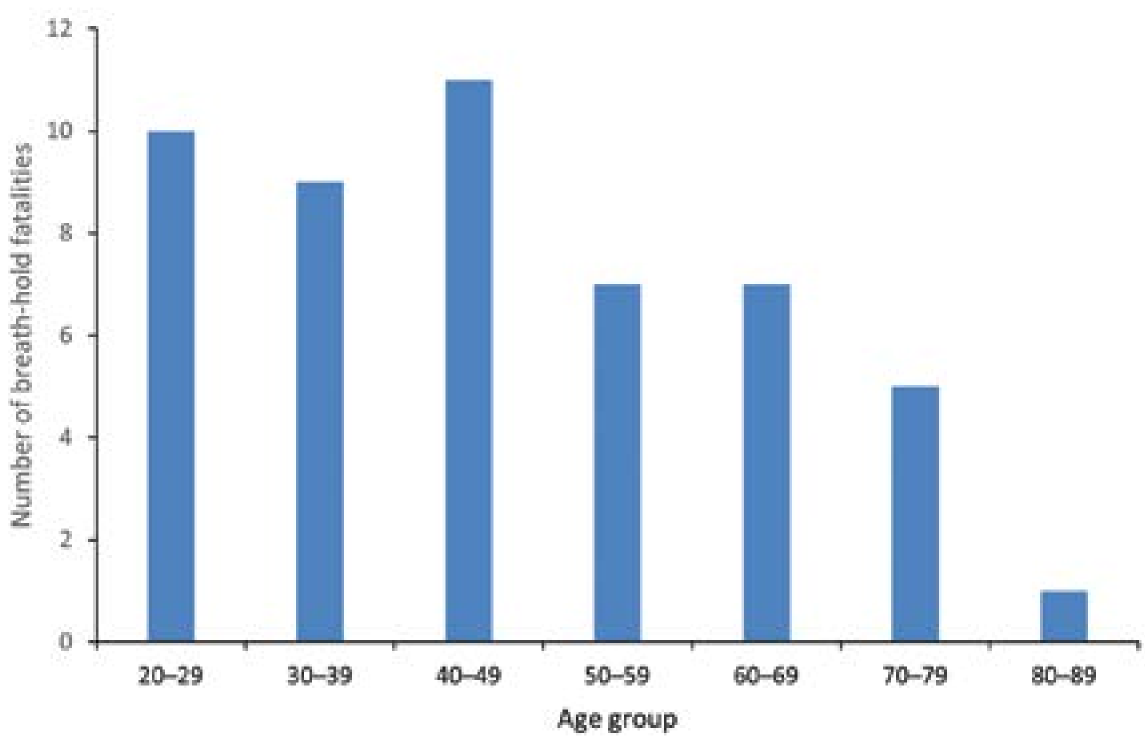


Table 4-2: Country where fatal breath-hold accident took place in 2019.

Country	Number of Fatalities
United States	22
Australia	4
New Zealand	4
Belize	3
Maldives	3
Cayman Islands	2
Bahamas	1
Croatia	1
Fiji	1
Greece	1
India	1
Indonesia	1
Madagascar	1
Maritius	1
Saint Kitts and Nevis	1
Saint Lucia	1
Saudi Arabia	1
South Africa	1
Tanzania	1
Total	**51**

ACTIVITIES WHILE BREATH-HOLD DIVING

In most of the fatal breath-hold dives (n=50) the activity at the time of the accident was known, with the majority taking part in snorkeling activities (n=31); only 19 were participating in freediving of some kind. This split should probably be expected, given that worldwide there are far more people participating in snorkeling than freediving.

In 2023, the International Association for the Development of Apnea (AIDA) had 2,889 freedivers registered to compete and reported that 20,000 people have become certified freedivers in recent years.[7] By comparison, in 2020 the Sports and Fitness Industry Association estimated that 7.7 million Americans alone participated in snorkeling, with a probable 27 million snorkelers worldwide.[8] The numbers reported here are too small to make accurate representation but given the several orders of magnitude larger participation numbers for snorkelling, the ratio of freediving vs. snorkelling deaths perhaps indicates the higher degree of risk associated with freediving.

As mentioned in this report previously, there were an unprecedented number (n=11) of snorkeling deaths in Hawaii in 2019; a rise in tourist snorkeling deaths in Hawaii has been evident for some time and has led to investigations into the cause of this worrying trend, including equipment use and design. The conventional snorkel design consists of a mask, snorkel tube, and mouthpiece and has been in evidence since the 1940s.[9] Recently, full face masks (FFM) of varying design and function, which are modified from gas masks, have entered the market and are sold as being easier to use for the beginner. However, multiple fatalities have been recorded for snorkelers using FFMs, so as reported in Chapter 1, the safety and utility of these masks is being investigated. DAN has funded one of these studies designed to determine how the use of a FFM varies physiologically from a conventional snorkel and thus any variation in risk to the user.[10] Ten volunteers were enrolled to the study and dived using a range of seven FFMs while their blood oxygen saturation, inspired airway pressure, and inspired/expired levels of CO_2 and O_2 were measured in real time. Two of the FFMs did not function as suggested but gas supply to the divers remained sufficient. However, some of the masks allowed water ingress, and did show an increased breathing resistance that could potentially increase the work of breathing and thus respiratory distress to a diver,[10] suggesting that caution should be used when using these types of masks.

Figure 4-4 shows the distribution of breath-hold activities across age groups. The majority of freedivers were from the younger age groups (20–49 years), which is consistent with earlier reports, while snorkeling is easily accessible and appeals to a broad age range of participants, young and old.

The specific freediving activity being undertaken at the time of the accident is shown in Figure 4-5. As in previous years, spearfishing/harvesting was the most common activity, although the 2019 data do show that the number of accidents happening while freediving for pleasure or sightseeing rose. However, these numbers are so small that it is difficult to draw any meaningful conclusions from them; it must also be remembered that these data are not a comprehensive report of all freediving accidents across the world in 2019, as many will not be reported or recorded.

SELECTED CASES

CASE 2019-401 – Diver A was snorkeling when he became seperated from his group. A witness recalled they had been parted for 20–30 minutes when they heard the order to get back on the boat due to an emergency. Diver A had been recovered to the boat having been found unconscious in the water and CPR was being performed; he was then transported to hospital and later pronounced dead. Autopsy revealed the suspected cause of death to be drowning with ischemic stroke of the basal ganglia and hypertension as an underlying factor.

CASE 2019-402 – Diver A was with friends on a snorkeling tour. The boat had between 15 and 20 guests on board for

Map 4-1: Number of breath-hold fatalities by country of accident in 2019.

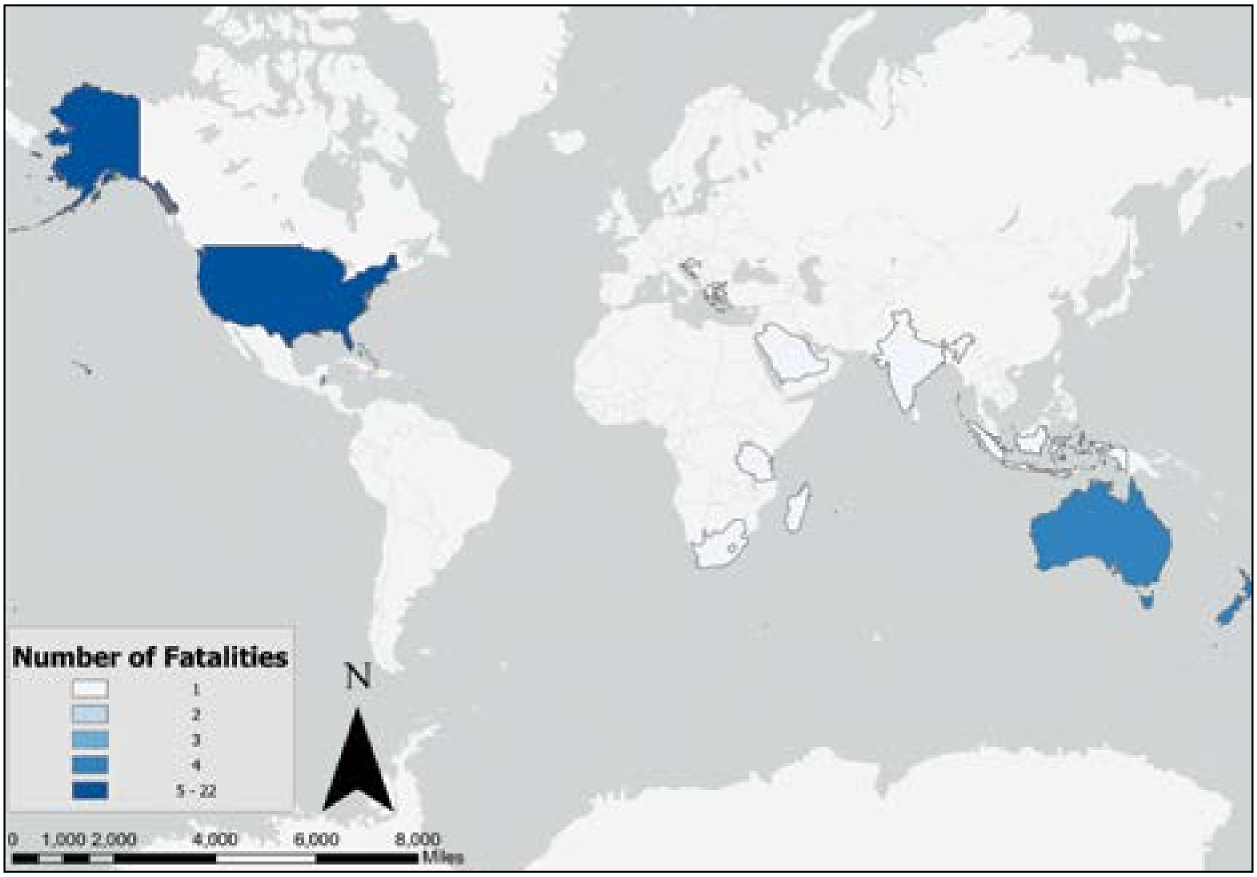


Figure 4-3: Citizenship of the breath-hold victims (n=39).

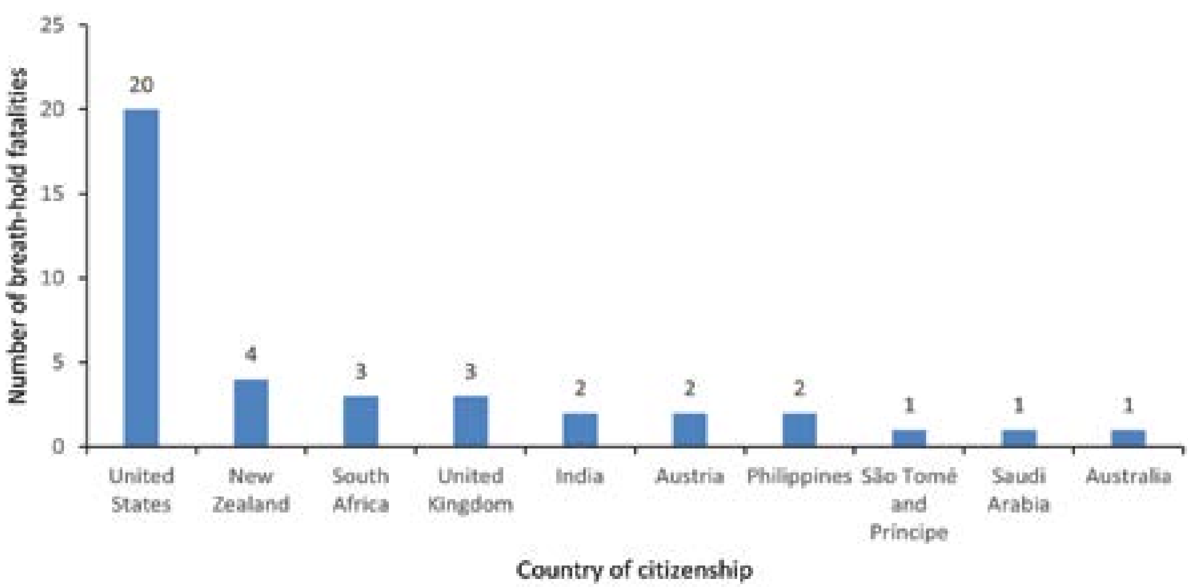
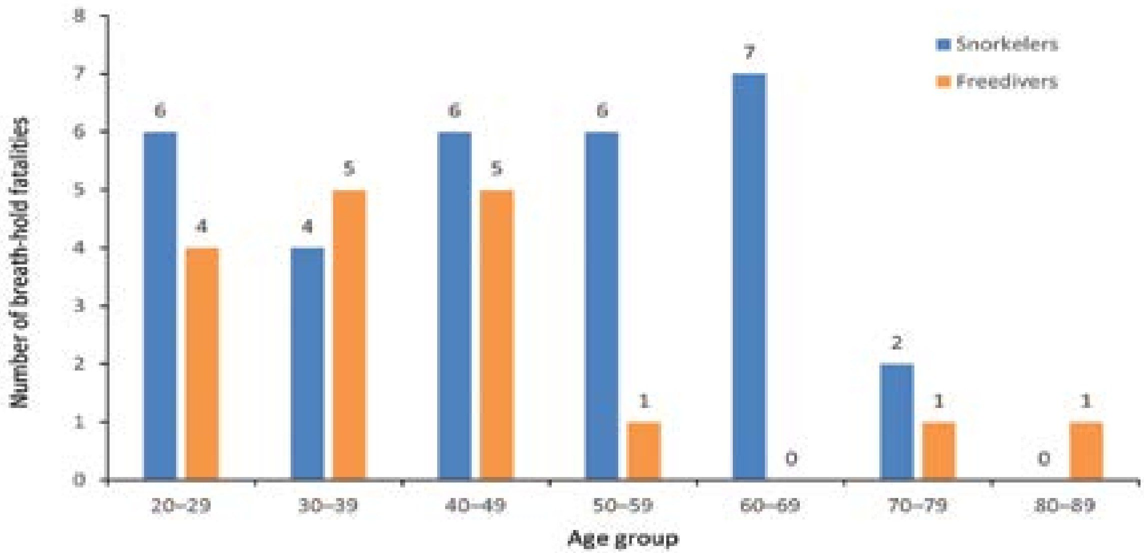


Figure 4-4: Distribution of breath-hold fatalities split by age group and activity in 2019 (n=38).



the snorkeling trip. Concern was expressed to the captain that the group were not particularly strong swimmers, and the friends made a request for life jackets but instead were given personal floatation devices (PFDs) that fit around the neck and were orally inflated, rather than life jackets. The friends did not have experience with these PFDs and they were not checked for fit or correct inflation by the crew before entering the water. Diver A entered the water before the rest of the friends, and he was observed to be face down with the snorkel in the proper position by the captain and appeared to be snorkeling properly. Diver A then began drifting farther away from the boat; the captain asked the mate to check on him who found that he was unconscious. The mate began rescue breaths and signaled for help. CPR was performed on the boat and Diver A was transported to the nearest hospital but did not recover. Autopsy reported the cause of death to be drowning and accidental with no other notes on previous health history or medications.

Commentary: this case highlights the need for safety briefings and checks to be made thoroughly, particularly when dealing with a large group of people going snorkeling; this accident could have been preventable if more care had been taken.

CASE 2019-403 – Diver A was an experienced spear fisherman who was in the water with friends. His friends raised the alarm when he failed to surface. Rescue services and friends with scuba equipment tried to locate him. After one hour his body was recovered and the accident was said to be a fatal drowning. He was wearing his weight belt when he was found and was a distance away from his spear and belt reel.

CASE 2019-404 – Diver A, a 44-year-old male was on a surf trip. He entered the water to go snorkeling next to the boat he was using but reports then say he suffered from shallow water blackout and drowned while still close to the vessel.

Commentary: this accident shows that snorkelers as well as freedivers are at risk of shallow water blackout if they make excursions from the surface.

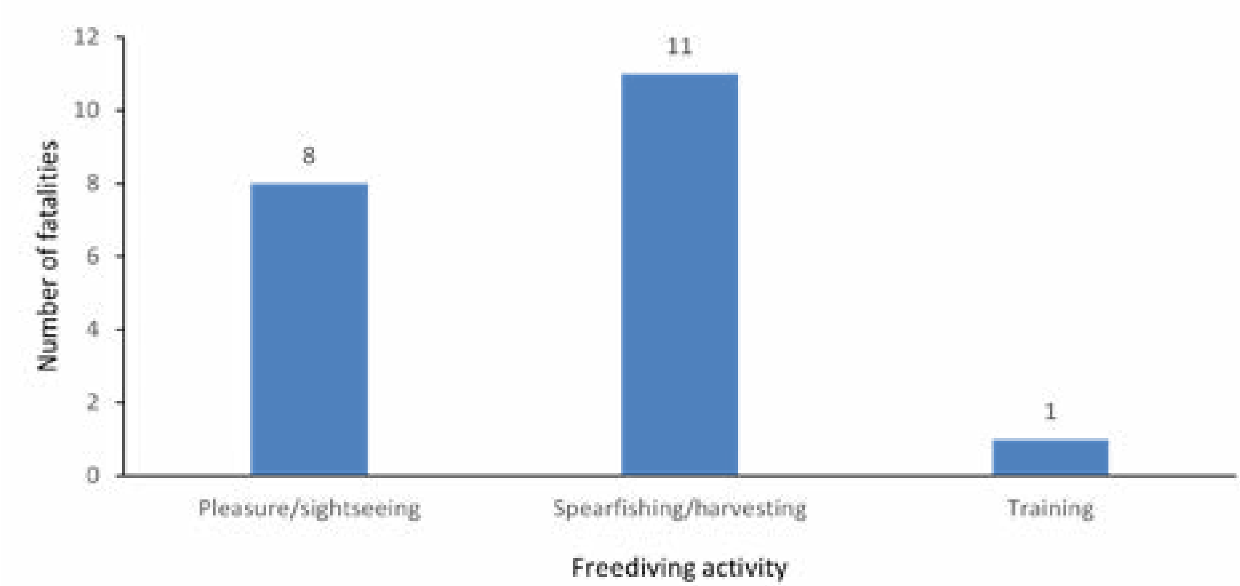
CASE 2019-405 – Diver A was an experienced scuba and freediver. Diver A and her buddy went to a dive site based on a recommendation from a local shop. The site was around 200 m (656 ft) from shore. They were equipped with a one meter (3 feet) wide safety buoy to mark where they were diving. During the dive a large speedboat came towards them and got too close. Diver A's leg was severed by the boat propeller and the diver began to sink. Despite the buddy's best efforts she could not be saved.

CASE 2019-406 – Diver A was on holiday snorkeling and was reportedly swept away by strong currents, then drowned.

Commentary: This accident highlights the importance of being aware of rip tides when swimming from shore and how to swim out of them – a rip is always limited in width, so swimming parallel to the shore and not back to it will usually allow swimmers to exit the flow. Officials were warning tourists to take extra caution following the accidents, with strong currents present due to the north-eastern monsoon at that time.

CASE 2019-407 – Diver A was participating in training dives for a forthcoming competition. He was reported missing by his team during the session, who said that he had gone missing from the 80-meter marker (262 ft). A

Figure 4-5: Distribution of freediving fatalities by activity category in 2019.



search operation was launched but was delayed due to the depth Diver A was diving to, as technical trimix divers were needed. More than 24 hours passed before Diver A's body was found at 81 m (266 ft) underwater. Cause of death was drowning.

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SECTION 5. **TECHNICAL DIVING**

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INTRODUCTION

Technical diving, or 'tec diving', evolved in the late 1980s when recreational divers began exploring deeper depths and longer durations underwater. The term gained prominence around 1990 with the launch of Aquacorp magazine, which specifically covered this burgeoning area of diving. Originally used by the Royal Navy to describe rebreather diving, Bill Hamilton later redefined technical diving to encompass diving with multiple breathing gases or using a rebreather system.[1]

Today, the definition of tec diving varies among different training agencies. In the 1990s, nitrox diving was considered a form of technical diving, but it is now commonly regarded as a recreational specialty akin to night diving or other specialties beyond basic open water training. For the scope of this chapter, technical diving is defined as diving that includes:

1. Penetration of a wreck or cave beyond the visibility of the entrance.
2. Diving below 40 meters (130 feet) that requires decompression stops.
3. The use of multiple gases on a single dive.
4. The use of a rebreather.

The rebreather market has grown in the last decade from an estimated 2,000 certified rebreather divers in 2013 to 3,000 in 2022, with around 25,000–35,000 units on decompression illness, divers of this nature are more the market today. This is a growing market with an susceptible to hypoxic events, hypercapnic events, estimated 1.8–3.8 deaths per 100,000 closed-circuit and overall stress on the human body due to increased rebreather (CCR) dives.[2,3]

For technical diving, deep diving ranges from 40 m (130 ft) to depths below 60 m (196 ft) where hypoxic breathing gas is required to avoid oxygen toxicity. The limit for divers certified by the major training agencies is 100 m (328 ft).

The deepest recorded open circuit scuba dive on air is recorded at 156 m (512 ft) in July 1993, and the deepest open circuit scuba dive on record with mixed gas to 332 m (1,089 ft) in September of 2014.[4] The deepest cave dive was performed on closed circuit rebreather (CCR) to 312 m (1,024 ft) in January of 2024[5] and the deepest open water dive on CCR was to 316 m (1,037 ft) in October of 2018.[6] In 2023 the first hydrogen/oxygen (hydrox) rebreather dive was conducted to a depth of 230 m (750 ft) by Richard Harris.[7] The deepest wreck dive on record was in 2008 to the Milano lying at a depth of 236 m (774 ft) in Lake Maggiore.[8]

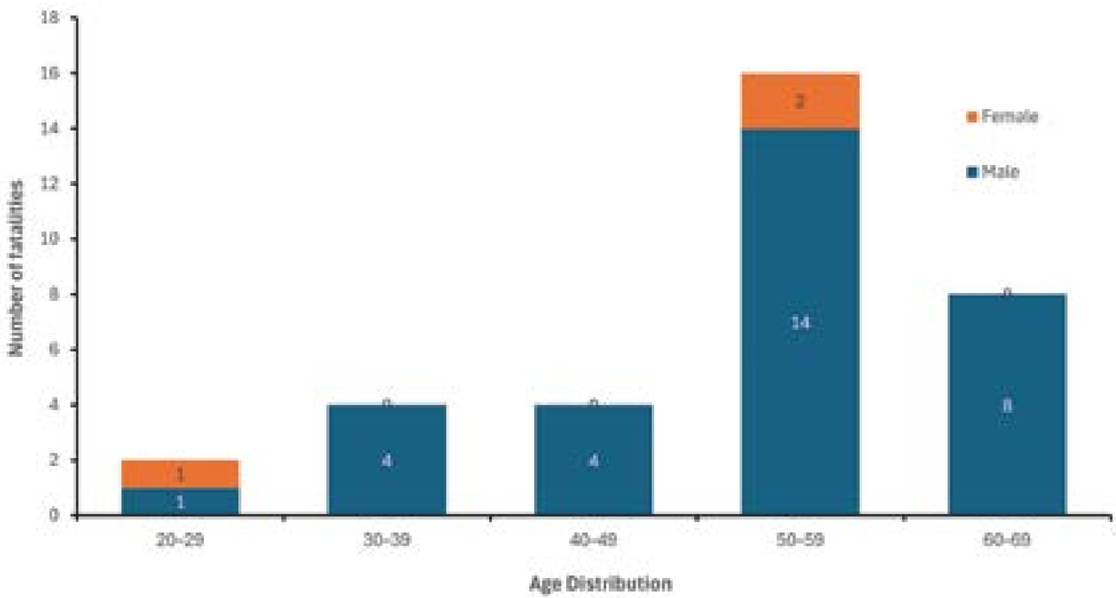
ADDITIONAL CONSIDERATIONS

Technical diving requires extensive advanced training and knowledge of diving physics and human limitations. To be able to execute a technical dive safely, divers of this calibre are considered avid divers that practice in harsh conditions with additional equipment. These divers are also diligent in their planning and dive preparations.

The use of specialized equipment, mixed gases and additional depth pose serious physiological risks for human divers. In addition to considering the risk of decompression illness, divers of this nature are more susceptible to hypoxic events, hypercapnic events, and overall stress on the human body due to increased atmopsheric pressure. Overhead environments also increase these risks as access to surface support is limited and can delay treatment.

Because of these considerations, it is inadvisable to partake in a technical dive without the proper certification. Do not dive beyond your training and physical limitations.

Figure 5-1: Age distribution of technical diving fatalities reported to DAN in 2019.



TYPE OF TECHNICAL DIVING

The dives were classified as; Deep, Rebreather, Cave, and Wreck. Many involved more than one of these disciplines for example the exploration of a deep wreck using a rebreather (6/40). The majority (28/40) of technical fatalities reported to DAN in 2019 include the use of a rebreather. Table 5-1 highlights the type of technical dives that were being conducted at the time of the fatality. Figure 5-2 displays the overlap between specialty dive and the number of fatal accidents collected in 2019.

Table 5-1: Type and number of technical dives conducted at the time of the fatality as reported to DAN in 2019.

Type of technical dive	Number of fatalities
CCR	13
CCR/Wreck/Deep	6
Mix/deep	4
CCR/Mix/Deep	3
Wreck	3
CCR/Wreck	2
CCR/Cave	2
CCR/Cave/Deep	2
Cave/Mix/deep	2
Wreck/Deep	2
Cave	1

Note: Mix refers to mixed-gas

DIVER DEMOGRAPHICS

Of the 200 fatalities reported in 2019, a total of 40 (3 female, 37 male) met the criteria of technical diving. The age range was from 23 years to 69 years of age, the average age was 52 with the majority (16 cases) being between 50–59 years of age (Figure 5-1).

Information regarding a decedent's certification level is not always available. It must be noted that not all technical diving fatalities are amongst trained and certified technical divers. DAN examines the facts surrounding each case as they become available. Further investigation is necessary to identify any trends in certification levels amongst technical diving fatalities.

LOCATION AND DEPTH OF DIVE

Information for 30 of the 40 dives was available for the depth of the dive. The majority (21/30) were deep dives greater than 40 m (130 ft). The deepest was 200 m (656 ft) and shallowest was to 4 m (13 ft). Table 5-2 displays the distribution of deep dives amongst fatalities reported to DAN in 2019.

Most fatalities occurred in the USA and France at 7 fatalities each, followed by the UK and Greece at 4 each. Map 5-1 highlights the number of fatalities by region. Canada, Italy, and Belgium each had two and the remaining locations each had one. Table 5-3 describes these numbers by location.

Map 5-1: Location of fatal technical dive accidents reported to DAN in 2019.

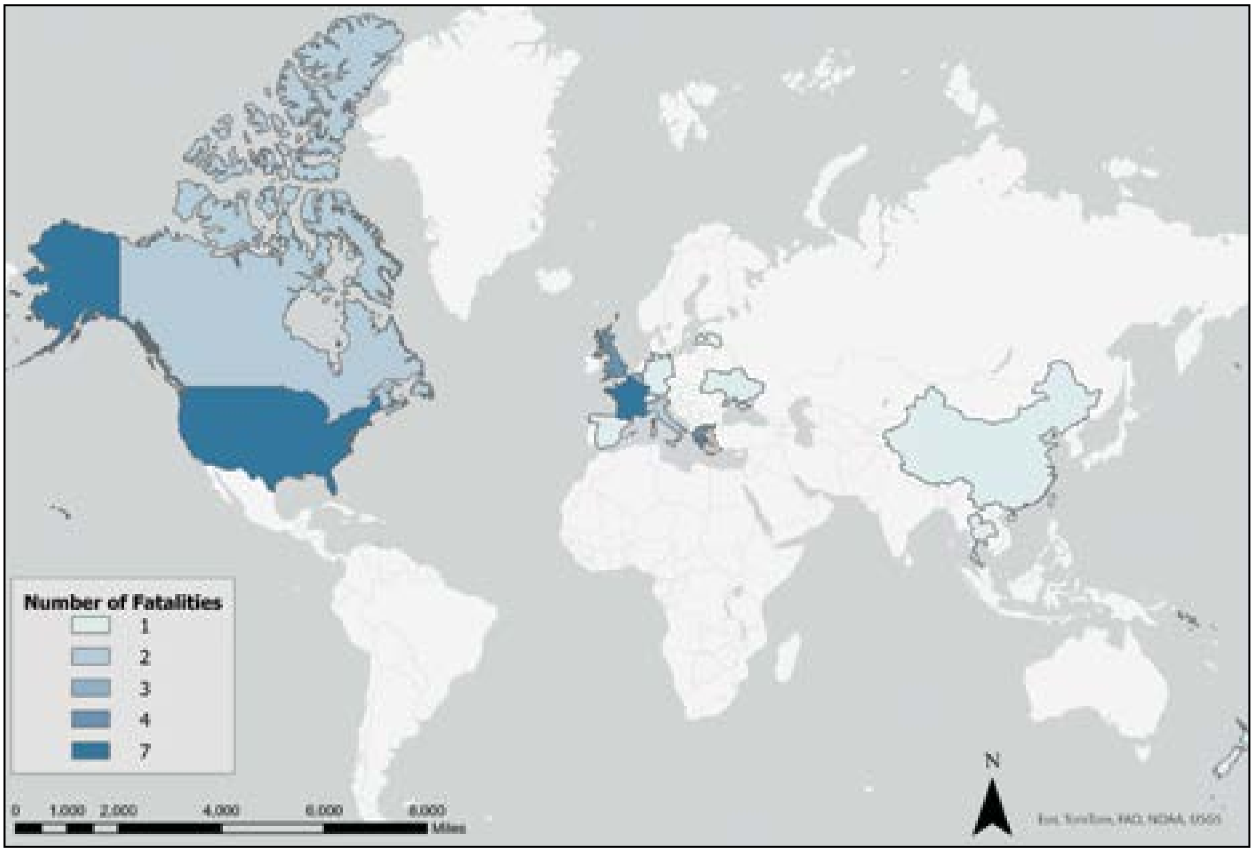


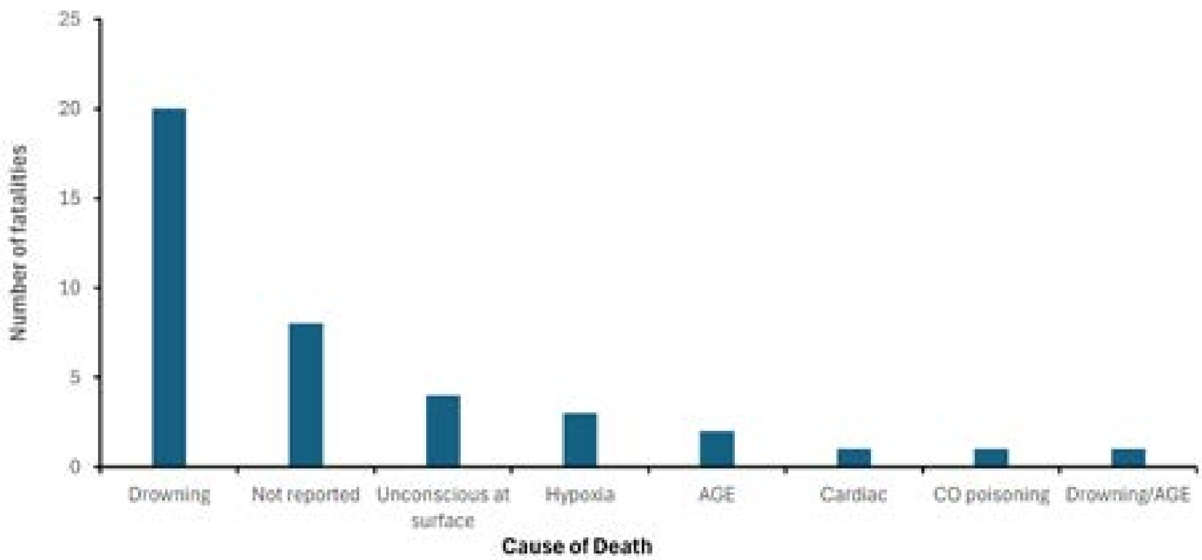
Table 5-2: Maximum depths of fatal technical dives reported to DAN in 2019.

Depth	Count of Depth
Not reported	10
200 m	1
125 m	1
120 m	1
117 m	1
115 m	1
90 m	3
80 m	1
70 m	5
60 m	2
50 m	5
35 m	1
30 m	3
18 m	1
10 m	1
7 m	2
4 m	1
Total	**40**

Table 5-3: Location of technical diving fatalities reported to DAN in 2019.

Location of accident	Number of fatalities
France	7
United States	7
Greece	4
United Kingdom	4
Belgium	3
Canada	2
Italy	2
Bonaire	1
China	1
Germany	1
Latvia	1
New Zealand	1
Soloman Islands	1
Spain	1
Switzerland	1
Tahiti	1
Thailand	1
Ukraine	1
Total	**40**

Figure 5-2: Cause of death of technical diving fatalities reported to DAN in 2019.



DISABLING INJURIES AND CAUSE OF DEATH

A paucity of fatality data is available, with most collected from insurance claims and the emergency calls received by DAN America, DAN Europe, and the DAN fatality surveillance project that scans media and news outlets for possible fatalities. Frequently in diving related incidents, the cause of death (COD) is difficult to establish and is most often ruled drowning in the medical examiner reports submitted to DAN.[2]

In this data set 28/40 cases reported a COD with the majority being drowning (20/28). In the 10 that did not report the cause of death, four made it to the surface before becoming unconscious. Hypoxia accounted for three of the cases and two were due to arterial gas embolism. Cardiac incidents, carbon monoxide poisoning and a co-cause of drowning with arterial gas embolism each accounted for one case.

The disabling injury that most likely contributed to the chain of events that lead to the fatal outcome/drowning was established for 16 cases. There were two cases of entrapment, one in a cave the other in a wreck. Equipment issues occurred on two events on rebreathers. Hypoxia occurred twice, once on a rebreather where the oxygen was not turned on the other was observed to have a rapid ascent followed by a seizure.

Other disabling events included missed decompression obligations, narcosis, increased work of breathing, hyperoxia, hypercapnia, carbon monoxide poisoning, suspected immersion pulmonary oedema, and lack of training for the equipment and type of diving. These are listed in Table 5-4.

CASE SUMMARIES

CASE 2019-501 – Divers A and B were both age 53, with significant experience in deep diving, rebreather diving, and mixed gas. They were on a charter with three other divers to explore a wreck at a depth of 90 m (300 ft). One hour after the divers descended the boat captain noticed Diver A floating face up at the surface unresponsive. The captain retrieved Diver A, initiated CPR, and the use of an AED. The captain signaled to the other divers to return to the boat as soon as possible, however the remaining divers all had significant decompression time to complete. A mayday call went out and the Coast Guard responded by helicopter and by ship. Diver A was transported by Coast Guard to the base where paramedics continued life saving measures. Two hours after surfacing Diver A was pronounced dead. The charter boat remained on scene to collect the other divers as they surfaced after decompression. Diver B did not surface with the others. Three days later the body of Diver B was recovered by the local Sherriff's Office. It remains unclear what occurred and the other divers on the trip report they did not see the two divers during the dive.

CASE 2019-502 – Diver A, 54 years old was an experienced rebreather mixed gas diver diving with two other divers to explore a wreck at a depth of 120 m (394 ft).The divers ascended to a depth of 90 m (300 ft) together when the divers lost visual contact with Diver A. Due to the decompression obligation and limited gas supply the divers could not conduct a search and assumed that Diver A was conducting his decompression and ascent out of view and would be reunited on the surface since their decompression schedule was identical. Upon surfacing it was discovered that Diver

A was missing, and an accident had occurred. Rescue services was alerted immediately. The search for Diver A included cadaver dogs and an ROV. Two weeks after their disappearance his body was discovered by technical divers at a depth between 70–75 m (230– 246 ft) It was subsequently recovered by technical divers.

CASE 2019-503 – Diver A, a 56-year-old male was an experienced rebreather mixed gas diver on a planned wreck dive to 70 m (230 ft) with two other divers. The three divers entered the water and conducted a bubble check at 9 m (30 ft) before descending the shot line when one diver lost contact with the shot line due to current and was entangled in a fishing net. Diver A came to his assistance and untangled the divers gear and they returned to the shot line and completed their descent. When they reached the wreck Diver A signaled that his handset that controlled the rebreather was malfunctioning and indicated he was going to return to the surface with two other divers. They ascended together completing their decompression stops. At their final stop the divers deployed their surface markers and left the shot line. At this point the divers lost sight of Diver A. Once on the surface they noticed Diver A had not surfaced. A diver donned mask and fins and swam to the surface marker of Diver A where it was discovered that he was not holding the reel that was hanging 8 m below the marker. Due to nitrogen loading divers could not descend to conduct a search. An extensive search was undertaken using sidescan sonar and technical divers. Diver A was located in 67 m (220 ft) of water by divers who photographed the body and noted that Diver A had his heads-up display (HUD) flashing low oxygen warning. They moved the body to the shot line to arrange recovery of the body. Inspection of the equipment revealed a flooded handset due to a crack in the front screen. Data recovered form handset shows the power was failing, stopping O_2 addition. Diver A then failed to either monitor, see, or believe his HUD, and failed to add sufficient oxygen. Diver A went unconscious due to hypoxia at end of deco and sank.

Table 5-4: Disabling event recorded for fatal technical dives reported to DAN in 2019.

Disabling Event	Number of fatalities
Entrapment	2
Equipment issues	2
Hypercapnia	2
Hypoxia	2
Missed decompression	2
Hyperoxia	1
Improper compressor used	1
Increased work of breathing	1
Lack of training	1
Narcosis	1
Suspected IPE	1

CASE 2019-504 – Diver A was on a wreck dive. He was discovered by other divers on his back without his mouthpiece in place. There was blood coming from his mouth and his teeth were clenched. Upon inspection of his rebreather, it was noted that several alarms had alerted Diver A to a spike in oxygen levels. It is presumed oxygen toxicity caused Diver A to convulse and loose his mouthpiece resulting in drowning.

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APPENDIX A: **BREATHING GAS CONTAMINENTS**

SAFETY SERVICES

Francois Burman MSc, PE

INTRODUCTION

A significant amount of literature exists concerning the quality of breathing gases, what contaminants we should be concerned about, how to analyze them, and their toxic effects on humans.

Standards and guidelines are published that set safe limits, including the results of various occupational health and safety studies determining the effects of being exposed for an extended amount of time. In many cases, the information has been developed through practices and lessons learned.

However, much of this information, and certainly the occupational health and safety studies, are based on breathing compressed air at or around sea level – one atmosphere absolute (ATA). Commercial and navy diving experts have based their limits on divers being exposed to contaminants for an extended period of time while at depth.

Yet we do not know the effects on the average scuba diver. What are the realistic and safe limits for this population of diver? In addition, divers often use enriched or mixed gases where acceptable contamination levels are not well described.

We cannot ignore the reality that scuba divers may not be as fit to dive as commercial or navy divers would be. We need to consider those that are vulnerable to certain contaminants, yet still declared as fit-to-dive.

Medical and industrial science, technology, and experience have empowered us to better understand the effects of decisions on air quality. This provides us with better rationale behind making such decisions.

International published and regulatory standards contain discrepancies as to air purity contaminant limits. So, which of these limits are safe and in fact, what do the numbers even mean?

A safety-conscious diver should know how to review a filling station's air-quality analysis certificate with some idea of what to look for and be able to discuss concerns about whether standards are being met, whether a contaminant level is significant, or if there is surrounding environmental pollution.

Are existing, published air-quality standards applicable and will they ensure safety for scuba divers? We will examine which contaminants may be present, how contaminant levels introduce risks to a diver, and finally what sensible limits should be regarded as realistic, best, and safe practice in scuba diving.

Of particular interest and concern to scuba divers, the most commonly found elements listed under air purity standards include carbon dioxide (CO_2), carbon monoxide (CO), oil and particulates, moisture (H_2O), and odor. We will devote a good deal of the discussion in Appendices A through C to unravel what is real and what is less relevant for some of these.

A SURVEY OF INTERNATIONAL PRACTICES

Before entering into any sensible discussion, a survey is required of existing practices and established standards that are in force in various operating and geographical areas.

Source data is available in standards, specifications, occupational health and clinical regulations, industry practices, as well as in the original repositories of knowledge for underwater breathing air (gas) systems. These are referred to as the 'rules' published by the international maritime classification societies.

Table A1 provides a summary of the available information on air quality standards that apply to diving on air compressed to typical scuba cylinder pressures.

Table A1: Maximum limits for contaminating substances in breathing air.

Region	Reference	CO_2	CO	H_2O*	Oil†	Odor‡	Other
Europe[1]	EN 12021	500 ppm_V	5 ppm_V	62 ppm_V	0.5 mg/m³	NS	- §
USA[2]	CGA Gr E	1,000 ppm_V	10 ppm_V	24 ppm_V	5 mg/m³	None	THC¶ 25 ppm_V
USN[3]	Diving Manual	1,000 ppm_V	10 ppm_V	24 ppm_V	5 mg/m³	None	THC 25 ppm_V
Canada[4]	CSA Z180.1	600 ppm_V	5 ppm_V	34 ppm_V	1 mg/m³	Slight	THC 10 ppm_V
Australia[5]	AS/NZS 2299.1	600 ppm_V	5 ppm_V	62 ppm_V	0.5 mg/m³	None	NS
UK[6]	HSE DVIS 9	500 ppm_V	5 ppm_V	62 ppm_V	0.5 mg/m³	NS	-
UK[7]	LR 5-4 8.4.1	500 ppm_V	15 ppm_V	25 ppm_V	1 mg/m³	None	NO_2, NO 1 ppm_V
DAN[8]	RAG	500 ppm_V	10 ppm_V	62 ppm_V	0.5 mg/m³	None	THC 25 ppm_V

The term ppm (parts per million) in this article refers to the unit of measure relative to volume: that is, parts per million by volume of ppm_V.

The information applies to commercial, technical, and recreational scuba diving.#

These data are by no means exhaustive but do serve to provide a baseline for further evaluation. Note that contaminant levels have been converted to the most quoted international units, and in some cases may be extrapolations. In addition, where there was duplication, only the most internationally accepted standards are included.

Other notable toxic or debilitating elements have found their way into breathing systems. This includes sulfur dioxide (SO_2), nitrous fumes (NO_X), and even more infrequently, compounds such as xylene, toluene, and various halogenated solvents (sometimes used in cleaning piping systems). Limits for these are based primarily on health effects, and published in occupational health regulations and specifications, usually expressed as an 8-hour weighted average exposure.

Lastly, when it comes to the production of enriched air for nitrox and technical gas mixtures, the amount of residual oil – both in vapor and condensed form – is noted in the literature as a specific fire hazard. The concentration of oxygen defining enriched air varies between 21% and 40%. However, when dealing with high pressure equipment, specifically all air (gas) up to the high pressure section of the first stage regulator, specific literature applies and a realistic level of 25% has been deemed applicate in this discussion.[9, 10, 11] To this end, several standards list the limit of oil in compressed oxygen-enriched gas mixtures to 0.1 mg/m³.[1, 5, 6, 8, 12]

PRACTICAL CONSIDERATIONS OF AIR QUALITY ANALYSIS:

When establishing specifications for contaminants in air for use in scuba diving, consideration of the available analytical techniques is necessary to ensure that suitable analysis can be done in practice. Clearly, techniques that provide accuracy and resolution appropriate to the limits being imposed are necessary, but analyses that require expensive and/or elaborate testing methods are not going to provide practical solutions, nor is the degree of accuracy necessary.

Assuming commercially available field-testing methods, applicable to the most commonly stated purity limits, the data for breathing air purity instruments found in Table A2 applies.

While there are a range of other toxic and debilitating compounds that have been detected in breathing air, it would be deemed impractical to demand analysis except where a risk assessment clearly shows that this is a likely hazard in a specific location or situation.

*The requirement for stored air depends on circumstances, varies between publications, and some standards do not state specific limits. As general rules, (1) Where conditions are unknown, a PDP limit of 12°F (-11°C) applies; or (2) PDP to be 9°F (5°C) below the lowest likely temperature; or, (3) at atmospheric pressure, the limit for air stored between 580 – 3,000 psi (40 to 200 bar) is 50 mg/m3 (62 ppmv or -51°F, -46°C ADP), (4) air stored above 2,900 psi (207 bar) is 35 mg/m3 (44 ppmv or -56°F, -49°C ADP), and (5) air supplied to high pressure cylinders is 25 mg/m3 (31 ppmv or -61°F, -52°C ADP).

In this table, we assume that compressed air is nominally 3,000 psi (207 bar) to specify PDP.
Dew point temperatures are indicated as pressure dew point (PDP) or atmospheric dew point (ADP) above.

†Oil is sometimes regarded as a particulate in mg/m3 and is combined with all other particulates.

‡NS – not significant

§Free of any other harmful or toxic substances

¶THC – total (volatile) hydrocarbons, sometimes including methane (CH4) where stated in some standards

#Unless otherwise stated, the limits apply to air at standard temperature and pressure (STP): 32°F, 14.7 psi(a) (0° C, 102kPa).

Table A2: Gas Purity Analysis.

		CO_2	CO	H_2O	Oil
Detection methods	Manual	Detector tube	Detector tube	Detector tube	Detector tube
	Electronic	NDIR*	Electro-chemical	Dew-point meter	(VOC) PID†
Accuracy‡	Lower	± 15%	±15%	± 20%	N/A§
	Higher	± 2%	± 1%	± 0.2°C	± 2%¶
Detection limit	Lower	100 ppm_V	2–5 ppm_V	± 6 ppm_V	0.1 mg/m^3
	Higher	10 ppm_V	0 ppm_V	± 10 ppm_V	0.01 mg/m^3

Note: Analysis of purity levels in breathing gases are most accurate where the contaminant levels are within typically expected maximum levels and the balance of the gases in air. Where levels are orders of magnitude higher, accuracy is negatively impacted.

The lower values apply to the most commonly used method, i.e., the detector tube, which has been the accepted practice in the breathing air analysis since the standards were first set, while higher values are achieved using industrial breathing air electronic (sensor-based) instruments. The accuracy of laboratory analysis equipment is not included.

A RISK ASSESSMENT APPROACH TO IDENTIFYING CONTAMINANTS[12]

GENERAL

The three primary reasons for considering the assessment of breathing air quality, listed in a normally accepted order of concern, may include:

1. the risk to human health;
2. the risk of fire; and
3. the risk of equipment failure.

Elements of potential concern can then be divided into three categories, prioritized by the likelihood of occurrence, namely:

4. those most commonly found in compressed air (CO_2, CO, H_2O, condensed oil, particles, and odor);
5. those found in certain operational areas (volatile hydrocarbons and organic compounds, such as CH_4); and
6. relatively rare, but reported toxic substances (for example vapors from cleaning products and halogenated solvents, emissions from motor vehicles, SO_2), and NO_X fumes).

The production process for compressed air can theoretically introduce oil (vaporized or condensed), particulates, and some amounts of CO_2 and CO. All other contaminants, including larger amounts of CO_2 and CO, need to be present in the ambient environment in order to be present in the final product.

As a general rule, occupational health practices require that we analyze environmental conditions in the vicinity of where we are aware of potential hazards. Compressors used to produce breathing air will require a thorough risk analysis prior to selection and purchase. Installation of compressors, the compressed air lines, and all interface connections will require compliance with the applicable codes and standards governing the installation of gas systems. Site selection of the compressors' intake should receive a careful risk analysis with consideration given to weather conditions, potential local toxic fumes, and exhausts from buildings or internal combustion engines.

Lubricating oils for breathing air compressors are selected on the basis of their high temperature stability and acceptability to human exposure.

It remains an accepted fact that we do not monitor or analyze the air that we normally breathe unless we have reason to be concerned.

These considerations are mentioned to provide a degree of pragmatism in any debate on the quality of compressed breathing air. In the ideal world, where all the appropriate selection criteria are applied, and where a thorough risk analysis is made of the operating area and changes not expected, these requirements for analysis and quality control could be reduced by design and intent. However,

*Non-dispersive infrared sensor

†Photoionization detector used to determine the amount of volatile organic compound (VOC), in vapor phase, associated with a specific oil type. Correction factors need to be applied to determine the concentration of the applicable oil in use.

‡Accuracy is generally stated as a percentage of the actual reading.

§Oil-detection by detector tube or equivalent provides a simple pass or fail outcome only and is assessed in condensed form and not vapor form.

¶Online oil detection requires highly sophisticated equipment, impractical to use in a scuba air-production plant. Gravimetric analysis in a testing laboratory provides greater accuracy for oil contaminant detection but is not a real-time method. VOC detection has been shown to be a good indicator of oil content in vapor phase with affordable PID sensors being available for online, real-time monitoring.

CONSTITUENT POTENTIALLY AFFECTING AIR PURITY [13,14]

GROUP 1: CONSTITUENT USUALLY PRESENT IN COMPRESSED AIR

Constituent:	**Carbon dioxide (CO_2)**
Sources	Ambient environment, internal combustion and cooking processes, human and animal respiration, microbial breakdown of organic matter, and conversion of CO to CO_2 in compressor filters and in motor vehicle exhaust systems.
Human safety	Elevated levels stimulate respiratory center, increasing rate of breathing; increase in depth increases respiratory risk; patients with high partial pressure of O_2 are at greater risk of oxygen-induced seizures with elevated partial pressure of CO_2; elevated levels lead to minor perceptive changes, discomfort, dizziness or stupor, and finally to unconsciousness and even death.
Fire safety	No concerns.
Equipment	No concerns.
Detection methods	Discrete field detection through detector tube or continuous detection using an infrared sensor. Laboratory measurement using GC-M-FID[12].
Constituent:	**Carbon monoxide (CO)**
Sources	Ambient environment, internal combustion processes, furnaces, gas burners, cigarette smoke, or overheated compressor oils.
Human safety	Decreases the carrying capacity of hemoglobin resulting in a decreased amount of oxygen available to the tissues leading to hypoxia. A highly toxic contaminant with environmental levels magnified by increased depth.
Fire safety	No concerns.
Equipment	No concerns.
Detection	Discrete detection through detector tube or continuous detection using an electrochemical sensor. Laboratory measurement using GC-M-FID*
Constituent:	**Moisture (H_2O)**
Sources	Ambient environment (humidity), drying processes (laundry), combustion, and other processes.
Human safety	Elevated levels of moisture are desirable (comfort and reduced dehydration), whereas dry air inhibits growth of bacteria.
Fire safety	Very dry conditions enhance production of static electricity.
Equipment	Excessive moisture may cause regulators to freeze as Joule-Thomson cooling takes place during pressure reduction through a small orifice. Regulators may fail open, causing downstream over-pressurization of piping and equipment and potentially resulting in free flow. Excessive moisture enhances corrosion and oxidation (rust) of air storage vessels. Excessive moisture causes filtration elements and chemicals to saturate, resulting in reduced filtration efficiency and effectiveness, as well as elevated pressure drops. Excessive moisture can interact with some ultra-fine carbon filtration units, generating strong chemical odors and resulting in nausea and respiratory irritation.
Detection	Discrete field detection through detector tube or continuous measurement using a dew point meter (electronic hygrometer). Laboratory detection using GC-MS[13]
Constituent:	**Oil (condensed and vaporized)**
Sources	Mostly compressor lubricating oil (introduced internally); but also: ambient evaporated oil from compressor oil leaks and surrounding equipment, motor vehicle exhaust fumes, and pollens – all introduced through the compressor intake, and even contaminated air pipes between the air processing plant and the cylinder.
Human safety	Larger condensed particles removed by body's clearance mechanisms; smaller particles are retained and may be hazardous depending on type and amount (symptoms include inflammation or even rupturing of alveoli).[14]
Fire safety	Significant fire concerns, irrespective of type or phase of oil.
Equipment	No concerns at the levels usually controlled for. A maximum level of 5 mg/m^3 equates to a liquid dew point temperature of -64°C, or 6 ppm_V; significantly lower than the lowest required levels for H_2O.
Detection	Field: Discrete detection of condensed oil using a detector tube (Impactor†) or continuous detection through measuring the primary VOC associated with the oil in use. Laboratory detection of condensed oil gravimetric analysis. Oil in vapor form detected using GC-MS§.

Constituent:	Particulates
Sources	Ambient environment (micro-particles of dust and pollens); breakdown products in compressors, piping systems,and filtration media; as well as post-construction debris in pipes and controls.
Human safety	Particles larger than 5µm have the potential to cause upper respiratory tract inflammation and distress; particles smaller than 5µm may result in shortness of breath, especially in patients with respiratory conditions (e.g. asthma and bronchitis), as well as a reduction in the ability to resist infection.
Fire safety	Larger concentrations of particulates can serve as a source of ignitable fuel.
Equipment	Larger particles are known causes of failures in pressure regulators, may cause valves not to seal when closed, and may erode valve seats, discs, and seals.
Detection	Field detection is not a practical option; however, filtration is highly effective where properly sized, located and maintained. Laboratory detection using gravimetric analysis. Particle size assessed using microscopy.
Constituent:	**Odor**
Sources:	Ambient environment, overheating compressors, and cleaning compounds used on air supply systems.
Human safety	Generally related to comfort levels only. Odors from volatile, toxic, or otherwise harmful substances indicate potential safety issues related to these contaminants.
Fire safety	No concerns from odor itself. Contaminants with fire risks (oils, VOC, etc.) are discussed under the relevant contaminant sections.
Equipment	No concerns.
Detection	Field detection – subjectively through the human sense of smell. Laboratory detection for odors using an olfactometer. Identified odors measured using GC-MS[§].

GROUP 2: CONSTITUENT PRESENT IN SPECIFIC AREAS

Constituent:	**Volatile hydrocarbons and Volatile Organic Compounds (VOC)** – include but are not limited to toluene, xylene, benzene, ethane, styrene and acetone.
Sources	Ambient environment as a result of exposure to building materials, plastic materials, industrial chemicals and cleaning compounds, adhesives, furniture, flooring, heating and combustion processes. Overheating compressors reported as a potential source.
Human safety	Generally hazardous in terms of carcinogens, neurological and narcotic effects, organ damage and general distress. Initial symptoms include fatigue, headaches, confusion, numbness, cardiac irritation and depression.
Fire safety	Significant fire concerns in terms of low ignition temperature and low flashpoint fuels.
Equipment	No significant concerns at the expected levels.
Detection	Field detection – odor usually detected through the human sense of smell. Identified compounds measured discretely using detector tubes or GC-MS
Constituent:	**Methane (CH_4)**
Sources	Ambient environment, especially prominent in certain geological areas as well as near decaying or fermenting organic matter, landfills, or domestic animals (cattle). CH_4 may permeate buildings and enter the compressor intake.
Human safety	Not toxic (may be an asphyxiant where oxygen is reduced to below 16%)
Fire safety	Significant fire concerns with CH_4 being a highly flammable fuel.
Equipment	No concerns.
Detection	Discrete field detection using detector tubes or continuous monitoring using PID sensors. Laboratory detection using GC-M-FID.

[*]GC-M-FID: Gas Chromatography - Methanizer - Flame Ionization Detection

[§]GC-MS: Gas Chromotography - Mass Spectrometry

[†]Impactor is a Dräger Safety product enabling field detection of all oil types with reproducible results expressed in the ranges: <0.1 mg/m_3, 0.1 to 0.5 mg/m_3 and >1.0 mg/m_3

sampling should be performed where changes or system maintenance activities are known to have taken place.

Exposures to contaminants in compressed air have occurred due to a loss of controls, external influences and incidents, and where equipment has been neglected.

Finally, while it is possible to provide a consensus and even a mandate of maximum exposure limits for all potential hazardous contaminants, the practicalities of online, real-time analysis, affordable measuring instruments, and the accuracy achievable in the field, have in the end a large determining influence on what can and should be required.

A discussion on air quality to derive safe, realistic, achievable and sustainable standards therefore needs to be done in the context of the imperfect world, but with a sensible dose of realism. Below is an outline of three groups of elements that may potentially affect air purity.

Group 1 highlights common elements usually present in compressed air.

Group 2 may be significantly broader than discussed below, but the following analysis serves to indicate where potential hazards may exist for scuba diving filling stations.

Volatile hydrocarbons include organic compounds. However, methane (CH_4) is the most commonly occurring of these compounds and is separated from the analysis here. Some standards require that all hydrocarbons be grouped as a total hydrocarbon (THC) limit. This does not allow for easy identification of potential sources.

Group 3 contains rare but reported contaminants, however this group is too diverse and extensive to discuss in a similar fashion to the previous two groups.

Typical contaminants include vapors from cleaning products or solvents not covered under Group 2 above, as well as environmentally present compounds including hydrogen sulfide (H_2S), sulfur dioxide (SO_2), nitric oxides (NO, N_2O, NO_2, etc.) fumes, ozone, lead compounds, asbestos, and many others.

Each of these has specific deleterious effects on humans, but no significant fire or equipment issues – at least not in the concentrations expected in the air.

Nitric oxide products, loosely referred to as NO_x, are associated with decreases in lung function, increased severity of respiratory problems, chronic inflammation, and irreversible structural changes, amongst other related respiratory conditions and complications.

Most occupational health and safety regulations for any public enterprise provide regulations, limits, and guidelines for identification and exclusion.

In terms of this discussion, we will exclude several of these from the requirements for acceptable air quality and accept that these will be controlled by occupational hazard identification and risk assessment (HIRA) practices.

PRACTICAL LIMITS

The following limits outlined in Table A3 have been extracted from the literature based on the effect on human physiology, fire risks, and risks to equipment.

Consistent units of measure have been used throughout the table as far as possible for easy of reading, but are not necessarily the units used by some measurement devices.

All human exposure limits are expressed as the surface equivalent value (SEV) and for the purposes of air diving, a maximum pressure of 190 fsw (7 ATA or 60 msw) is assumed. Limits tabulated are generally stated as the "no-effect level", that is the dose with no known toxic or debilitating effects.

The exact conditions under which air quality analysis should be done are not discussed, but from a practical perspective, any analysis should be done such that the worst case can be detected.

DISCUSSION

As somewhat of a generalization, the scuba industry has accepted published purity limits as being the results of relevant research. However, most of this research is based on commercial diving, military diving, and occupational health and safety in the workplace where air is breathed under normobaric applications.

The average scuba diver does not fall into any of these working groups; the scuba diver also breathes air under elevated environmental pressures.

While it is unlikely that any changes to current standards will be considered, it is of interest to examine what the actual risks to the scuba diver are as a result of exposure to the most common of the purity requirements. These include CO_2, CO, oil, and particulates, all of which are present in breathing quality air (as defined by the US Environmental Protection Agency (EPA) in hazardous air quality indices (AQI)) and have been shown to negatively impact divers through cases reported to DAN.

An important note here is that national regulations will continue to manage minimum purity levels regardless of what may truly apply to a scuba diver. However, what is also true is that the capabilities of modern compressor breathing-air filtration systems used in the scuba industry, if appropriately selected, maintained, and exchanged as indicated by manufacturer's specifications, should ensure that the levels of common contaminants such as CO, moisture, and oil and particulates will meet specifications.

Unless very specific CO_2 filtration systems are employed, the final levels of CO_2 will likely match those of the ambient air once the filter elements have reached about

25% of their service life. Issues surrounding CO_2 levels are further discussed in later on in Appendix A.

Other less common contaminants will not be removed unless clearly identified prior to production and where the relevant filtration systems have been installed. Once again this highlights the need for a thorough risk assessment of the location of the air intake.

In depth and scuba air quality specific investigations into the effects of CO_2, CO, and oil and particulates are described in Appendices A to C, providing the basis in determining actual safe levels and the basis upon which these are determined.

CONCLUSIONS

A review of international standards, the consideration of the practicalities of both field and independent laboratory analysis, an analysis of actual safe limits of the most common potential contaminants, and a dose of realism, provide suggested maximum limits as contained in Table A4.

No consistent, standard guidance is given as to what an acceptable testing frequency might be. Best practice here would be to test:

1. When there is any reason to be concerned, such as complaint of taste, odor, headache, nausea or any other related reaction from divers, and in this case focusing on the contaminant of concern; or
2. After any servicing requiring access to the air flow path; or
3. After breathing air filter changes; or
4. When an environmental change occurs where the air intake could have been affected; or
5. Whenever there are significant changes in air quality test results – in this case, analysis should be repeated, regardless of whether purity limits are exceeded, until results stabilize; or
6. As required by the compressor and/or filter manufacturer; or
7. As per regulatory authorities; or
8. If site-testing by the dive operation is realistic, then and as applicable, either continuous testing or weekly testing if electronic analyzers are available, or monthly testing if detector tubes are being used, or if none of the above applies, then
9. At least quarterly.

Where samples are sent to an independent testing facility, this should be regarded simply as post-production quality control or regulatory compliance, as independence does not provide any guarantee of air quality other than at the time the test sample was drawn.

The essential steps in ensuring safe breathing air are ongoing risk assessments of the operation and surroundings, and an awareness of what can potentially result in contamination of the air.

APPENDIX A: WHAT IS A SAFE LEVEL OF CARBON DIOXIDE IN OUR BREATHING AIR?[15]

The most abundant potential contaminant found in breathing gas is CO_2.

Almost all divers have some degree of knowledge about how CO_2 affects them, whether it be in rebreather diving, shallow-water black-out in free diving, skip-breathing, or hyperventilation underwater due to strenuous activities.

In terms of limits, however, we find more significant discrepancies in international publications, which leads to the question: if in the USA the amount of CO_2 in compressed air we can allow for recreational diving is double the European Norm*, does this mean that the US Navy or the CGA† standards do not really apply to recreational diving?[1, 2, 3]

A good starting point is a review of the basics. We used some of the same content in the Appendix B discussing safe levels of CO, repeated here to allow the individual appendices (A through C) to be extracted and used independently.

Depth has a direct impact on partial pressure; Dalton's law tells us that the deeper we dive, the greater the partial pressure of all the constituents (separate gases that make up the air we breathe) of the breathing gas at depth. In practical terms, this means that the actual number of gas molecules in a unit volume of gas increases proportionally.

Let's say, for example, that your cylinder was filled at the dive shop with a gas mix containing a CO_2 level of 500 ppm_V‡ (which corresponds to a partial pressure of 0.0005 ATA). If you were to use this cylinder on your dive down to 130 fsw (40 msw) or 5 ATA, the CO_2 partial pressure would rise to 5 times the surface value, or 0.0025 ATA (2,500 ppm_V). This theoretical elevated level is known as the surface equivalent value, or SEV.

When producing nitrox, either by gas separation (using a permeable membrane) or gas generator (using pressure swing absorption or PSA technologies), we further inadvertently increase the number of undesirable molecules in the final breathing gas.

*The current applicable standard for the EU is EN 12021 (2014), with the CO2 contaminant limit for breathing and enriched air reflected in Table 1, i.e., ≤ 500 ppm_V.

†The current applicable reference in the USA is CGA G-7.1-2018, the commonly referred to Class E (SCUBA) air specification of ≤ 1,000 ppm_V.

‡The use the term ppm (parts per million) in this article refers to the unit of measure relative to volume: that is parts per million by volume or ppm_V.

Table A3: Published contaminant safe limits.*

Contaminant	Human exposure	Fire risk	Equipment risk	Detection Limit†	Achievable Limit‡
CO_2	5,000 ppm_v for $pO_2 \geq 3$ ATA 15,000 ppm_v for $pO_2 \leq 1.6$ ATA	Nil	Nil	10 ppm_v	< 500 ppm_v Normal air contains ±421 ppm_v§
CO	70 ppm_v¶	Nil	Nil	1 ppm_v	≤ 5 ppm_v
H_2O	RH#: ≤ 50% – 60% Based on control of bacterial growth	RH5 > 30% Dew point > 3°C	HP: Lowest ambient less 44°C LP: Lowest ambient less 6°C	Dew point -64°C based on 5 mg/m³ (6 ppm_v)	-48°C or ≤ 35 mg/m³
Oil	≤ 5 mg/m³	≤ 0.1 mg/m³	None at ≤ 5 mg/m³	0.01 mg/m³	≤ 0.5**mg/m³
Particles	≤ 50 mg/m³ No particles ≤ 10 µm	≤ 5 mg/m³	No limits determined	0.01 mg Size 0.5 µm	0.5 mg/m³ for particles > 5 µm
Odor	None	None Detected	Nil	None	None
VOC	≤ 5 ppm_v	LEL ≤ 1 % Limit 1000 ppm_v	Nil	5 ppm_v	≤ 5 ppm_v
CH_4	≤ 5% (5 x 104 ppm_v)	LEL†† ≤ 5 % Limit 5,000 ppm_v	Nil	10 ppm_v	≤ 25 ppm_v
H_2S	≤ 50 ppm_v	Nil	>> Human limit	1 ppm_v	≤ 1 ppm_v
SO_2	≤ 5 ppm_v	Nil	Nil	1 ppm_v	≤ 1 ppm_v
NO‡‡	≤ 10 ppm_v	Nil	Nil	1 ppm_v	≤ 2 ppm_v

For example, producing 40% nitrox using either of the above technologies could increase the concentration of CO_2 by a factor of up to three.

Air contains just under 21% oxygen, and we need to almost double this to get to 40%. The standard membrane separators we use in the dive industry are not efficient enough to achieve this without wasting even more air. This means that we need to use up to three times more air through the separator to produce the volume of nitrox we desire. However, in this process, we are not removing CO_2.

This means that the 500 ppm_V in the air being drawn into the compressor could end up being as high as 1,500 ppm_V in the cylinder. When we consider the SEV at a maximum diving depth of 80 fsw (24.3 msw or 3.4 ATA), the SEV could be 3.4 times this, or 5,100 ppm_V.

One way to mitigate the amount of CO_2 that will enter breathing gas during nitrox production is the use of an appropriate molecular sieve desiccant in the high-pressure compressor filter cartridges. This has been the subject of several medical studies and clearly works in

*Sources include NIOSH (National Institute for Occupational Safety and Health in the United States), the EPA (United States Environmental Protection Agency), the HSE (Health and Safety Executive in the UK), the HSWA (Health and Safety at Work New Zealand) and the WHO (World Health Organisation). The information is all open access. In addition to these, references already listed include levels relevant to diving. [16] [31] [30]

†Limit applicable to what can be detected in the field – either online analyzers or discrete sampling for laboratory analysis (where applicable).

‡Limit that can be realistically achieved based on current filtration, catalytic, and elimination methods, assuming typical CO_2 levels in the vicinity of the compressor intake.

§The US National Oceanic and Atmospheric Administration (NOAA) average world-wide CO_2 level published in May 2022.

¶A SEV value of 70 ppm_v at 7 ATA arises from a value of 10 ppm_v at 1 ATA.

#RH: Relative humidity at normal temperature and pressure: 68°F/20°C and 1 ATA (14.7 psia/101.325 kPa).

**Some equipment suppliers state the limit contained in EN 12021 [1] for condensed oil. Using available and economically viable equipment, a limit of ≤ 0.1 mg/m3 is realistically achievable.

††LEL: Lower explosive limit – fire codes usually recommend a limit of ≤ 10% of LEL. 10% of 1% LEL = 0.1% or 1,000 ppmv.

‡‡NO represents all nitrogen oxide compounds (NO, N_2O, NO_2, etc.).

Table A4: Suggested contaminants for HP compressed breathing air.

Group 1[*]: Contaminants always potentially present should be limited to:		
CO_2	Scuba air	1,000 ppm$_V$
CO	Scuba air	5 ppm$_V$[†]
H_2O	Scuba air	Stored at 3,000 psi (207 bar): 62 ppm$_v$ (50 mg/m^3) Stored above 3,000 psi: 44 ppm$_v$ (35 mg/m^3) Supplied to cylinders: 31 ppm$_v$ (25 mg/m^3)
Oil	Scuba air Oxygen compatible air	$\leq$ 0.5 mg/m^3 $\leq$ 0.1 mg/m^3
Particles	Scuba air	$\leq$ 0.5 mg/m^3 for particles > 5 µm
Odor	Scuba air	None, or faint and not objectionable
Group 2[‡]: Contaminants present in specific areas should be limited to:		
VOC	Scuba air	$\leq$ 5 ppm$_v$
CH_4	Scuba air	$\leq$ 25 ppm$_v$
Group 3: Rare but reported contaminants should be limited to:		
H_2S	Scuba air	$\leq$ 1 ppm$_v$
SO_2	Scuba air	$\leq$ 1 ppm$_v$
NO_X	Scuba air	$\leq$ 2 ppm$_v$

practice, however we cannot yet predict the exact amount of CO_2 that will be captured in the filter media.

For the sake of simplicity, molecular sieves (such as MS 5A and MS 13X) can effectively remove up to 20% of the CO_2 in the air or gas passing through. This is an observation, but has been somewhat verified by industry experts, and the author has been provided with physical evidence a few times where filter cartridges were within run-hour specifications and were not saturated with water. Other air-testing laboratories have stated that this reduction of up to 20% only occurs during the initial use of a replacement filter.

In contrast with the case for CO, where the elevated partial pressure of oxygen at depth significantly offsets toxicity, with CO_2, a similar elevated partial pressure of oxygen does not appear to benefit the diver. It actually seems to increase the amount of diving narcosis, which leads to increased impairment at deeper depths.[§] It appears that the combination of increased partial pressures of oxygen and CO_2 is what increases the sensitivity to narcosis as well as potentially increasing a risk of oxygen toxicity seizures where the partial pressure of oxygen is elevated.

Finally, and despite what critics of climate change might say, the data shows the world is in a state of increasing CO_2 levels in the atmosphere. As recently as 2000, the average global CO_2 level was around 370 ppm$_V$[¶]. This matched well with dive shop and recompression chamber facility air quality analyses. The average level is now 421 ppm$_V$[#], and a continued rise is predicted unless something changes. It should not be long before the average level of CO_2 in the atmosphere reaches the maximum limit for breathing air allowed under EU guidelines.[1]

The next phase of this discussion is connecting CO_2 levels and human physiological effects, specifically how this might affect divers while underwater.

The physiological effects of elevated CO_2 in occupational (working) situations have been widely studied and the results (usually expressed in terms of TLV, PEL, TWA, and REL[**]), amongst other global regulatory measures published in health and safety standards and codes of

[*]The caveat to this being that national or other regulatory requirements, if stricter, take precedence.

[†]These contaminants should be monitored regularly, as discussed under best practice, by means of either on-site or laboratory analysis.

[‡]Up to 10 ppm$_v$ would be acceptable to dive with, if analyzed on the day. However, air quality testing should use 5 ppm$_v$ as the limit.

[§]A HIRA survey should be performed to determine the likelihood of any of these or other potentially toxic elements being present in the environment during the air compression process.

[§]This was evident in a US Navy funded study by Dr J Freiberger, although the participants there were fit navy divers, rather than potentially compromised recreational divers. [30]

[¶]The global average values referred to here are as published by NOAA's Earth System Research Laboratory (ESRL) and account for season and geographic variances. The average value shown on the date this article was written is 421 ppm (May 2022). NOAA is the US National Oceanographic and Atmospheric Administration - a recognized international authority.

[#]There are several acronyms found in occupational health and safety standards and guidelines, some indicating instantaneous levels and others the accumulated exposure during an 8-hour working day throughout the life of a worker. TLV, the Threshold Limit Value, is used to describe the upper exposure limit for work in hazardous environments. PEL, the Permissible Exposure Limit, is the legal limit allowed in specific regions or countries. The 8-hour derivative of PEL is the TWA, Time Weighted Average. REL, the Recommended Exposure Limit, is simply a recommended guideline but is intended to supersede the PEL once adopted.

practice throughout the world – focused on the 8-hour working day. However, due to much shorter exposures, recreational divers could, in theory, easily manage significantly higher levels.

The NOAA Diving Manual describes the relationship between concentrations, exposure limits, and symptoms in terms of zones.[16] Table A5 (based on Figure 1) provides a brief correlation between these zones and the units of measure used. The last column indicates the level of CO_2 in a scuba cylinder that would produce the corresponding maximum SEV level. For example, a cylinder containing 1,950 ppm_V of CO_2 would achieve a SEV of 15,000 (the upper limit for zone 1) at a depth of 220 fsw – 67 msw or 7.7 ATA.

Table A5: NOAA zone values after the initial equalizing phase and for a 1-hour exposure.

Zone	PCO_2	% CO_2 at 1 ATA	ppm_v at 1 ATA	ppm_v in cylinder*
I	0–0.015	0–1.5	0–15,000	1,950
II	0.015–0.023	1.5–2.3	15,000–23,000	2,990
III	0.023–0.066	2.3–6.6	23,000-66,000	8,570
IV	0.066–0.100	6.6–10	66,000-100,000	13,000
V	≥ 0.100	≥ 10	≥100,000	>13,000

Although these are not trivial values, unless they are associated with the effect on a diver during a typical dive, they have no real meaning to us.

Figure 1 shows the effects of a 60-minute dive, based on the SEV levels of CO_2 contained in a charged scuba cylinder. The graph in Figure 1 indicates the resulting physiological conditions by zone based on US Navy research. This does not correlate well with published data from other sources. One reason could be that US Navy divers are expected to be at a much higher level of fitness than the average occupational worker or recreational diver. However, the value of Figure 1 lies in the trend of resulting conditions with time of exposure.

Before deciding on realistic, safe and achievable levels, it should be noted that reactions to elevated levels of CO_2 vary depending on the individual. In addition, the amount of physical activity during a dive has a direct relationship with CO_2 production in the tissues and is independent of the levels in the compressed gas being inhaled.

Limits should therefore be based on what is safe for a recreational diver who is considered to be fit-to-dive by a qualified physician, with diving activities assumed to be relatively strenuous. This leads to a very broad and subjective assessment. However, a review of the research that has gone into acceptable CO_2 levels at pressure (submarine and navy diving medicine), the standard, long term 8-hour working environment (occupational health and safety) levels, as well as long-term, continuous exposure levels (NASA in terms of space capsule environments) appear to point to similar levels that can be tolerated in most cases.

Maximum depth and bottom time are also important criteria to consider when determining maximum exposure levels to CO_2. The deeper we dive, the shorter the bottom time (which is determined by the decompression time and the gas used to decompress with). A dive to 220 fsw (67 msw) will usually not exceed 15 minutes, unless a longer decompression obligation is accepted. A shallower dive to 60 fsw (20 msw) with a 50-minute bottom time extends exposure, but also allows a higher CO_2 level to remain within the safe SEV.

This is, however, complicated by the fact that over time, CO_2 accumulates in our tissues – see Figure 1. The longer the dive, the more CO_2 we accumulate and the closer we move towards the next, higher zone.

In order to remain in Zone I after 60 minutes and be symptom-free, the CO_2 SEV should be no more than 15,000 ppm_V. To keep within Zone II, where minor symptoms may be perceived, the CO_2 SEV should be no more than 25,000 ppm_V.

A CO_2 limit would have to apply to all dives (other than where very specific planning takes exposure and time into safe consideration). Limits are there to keep people safe under all expected conditions.

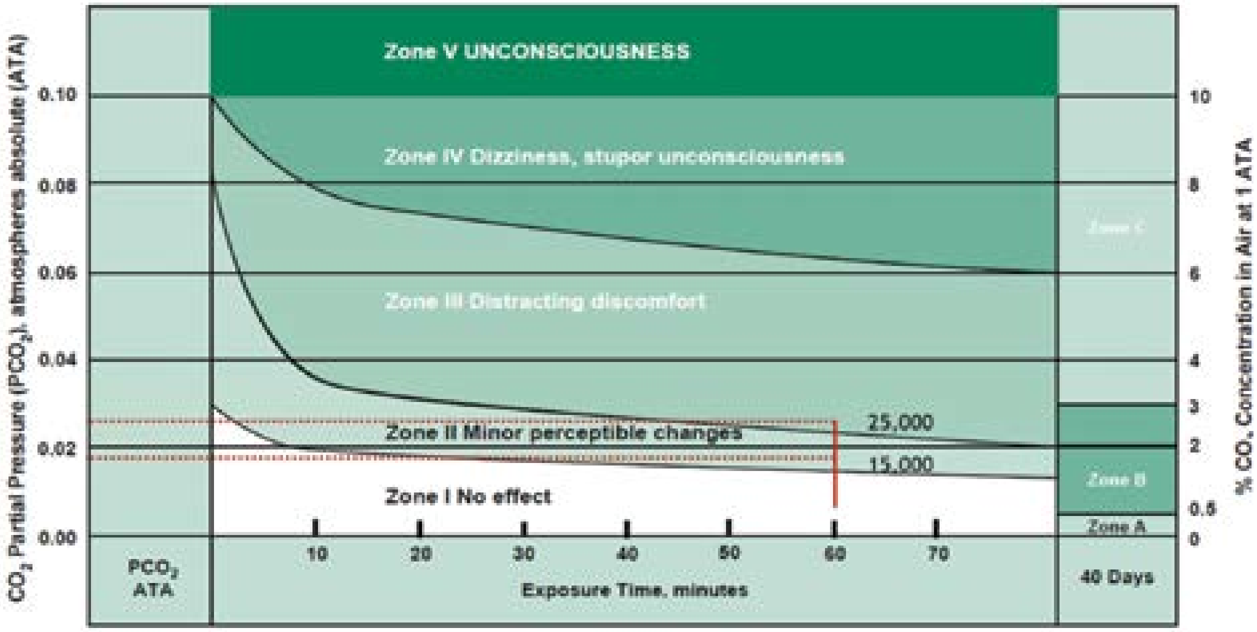
If we transpose these values to cylinder concentration for the deepest exposure (220 fsw), we know that to avoid exceeding Zone II, the CO_2 level in the cylinder should not exceed 2,600 ppm_V (which equates to SEV of 20,000 ppm_V); the maximum value to avoid exceeding Zone I would be 1,950 ppm_V (which equates to a SEV of 15,000 ppm_V).

Based on maximum expected depths (regardless of the gas being used), and bottom times determined by realistic recreational decompression obligations, these limits are extremely conservative.

Building on these considerations, we can conclude that for regular breathing air, conservative open water, and open circuit diving, a level of 2,000 ppm_V in a filled scuba cylinder would be regarded as safe and acceptable. This value encompasses both the levels of CO_2 currently in the air as well as local CO_2 production- such as from a restaurant or passing vehicles.

*The surface equivalent value at the surface when dives to 220 fsw (67 msw or 7.7ATA).

Figure A1: Relationship of physiological effects in CO_2 partial pressure.*



The purpose of this article is not to set a new limit, but to show that the current CGA limit of 1,000 ppm_V, even though the European limit is 50% less, will most likely not cause adverse effects at depth. This limit is conservative and certainly safe enough.

In the future, dive shops should continue to collect and analyze air samples regularly – preferably quarterly, but at least annually. CO_2 monitors are not cheap, which means that many dive centers and most recreational scuba divers would typically not own an analyzer.

Based on only periodic air sampling, a cautious compressed gas filling facility should trace where excess CO_2 is being produced. CO_2 levels above ambient levels will be recognized by a CO_2 value above 400 ppm_V.

It is also important to note that sources of CO and CO_2 are not significantly different. A previous Alert Diver article provides some degree of guidance in this regard.[17]

APPENDIX B: WHAT IS A SAFE LEVEL OF CARBON MONOXIDE IN OUR BREATHING AIR?[18]

A variety of articles on preventing breathing gas contamination have been published in Alert Diver.[18, 19, 20, 21, 17]

While these do discuss the sources, hazards, effects, and preventative measures, the issue of why we have specific limits and the impact of exceeding these is perhaps less clear to the scuba diver. In this article, we will discuss the effects of CO poisoning and how the limits are derived, and provide some guidelines to avoid inappropriate and inaccurate discussions where any amount of CO is suspected.

Numbers are just that, numbers. They are not absolute and always need a degree of interpretation as to which are important. As divers, we know that we have to factor in compressed gas, depth, gas uptake, and even our dive profiles to any discussion containing gas. Then, we have our fitness and health levels to consider. This means that numbers might not apply equally to all divers.

The effect of CO uptake at depth is neither linear nor do we know all the factors that may affect it. However, here is what we do know:

1. Depth has a direct impact on partial pressure; what this means is that the deeper we dive, Dalton's law tells us that the partial pressure of all the constituents of the breathing gas in our cylinders will increase. In more practical terms, this means that the actual number of molecules per breath increases. It is a linear effect measured against absolute pressure in exactly the same way as Boyle's law addresses volume.
2. This means that a level of say 10 ppm_V in our cylinder at the surface will translate to the same effect that 60 ppm_V has at 165 fsw or 6 atmospheres absolute ATA (10 ppm_V x 6 ATA = 60 ppm_V). This is known as the surface equivalent value, or SEV.
3. When producing nitrox, either by gas separation (using a permeable membrane) or gas generator

*This figure is a partial replica of Figure 3.11 in the 5th edition of the NOAA Diving Manual, originally extracted from the US Navy Diving-Gas Manual, 1971. The original data used to produce fig. 3.11 is attributed to Dr CJ Lambertsen at the University of Pennsylvania.[31]

Table A6: Expected diver physiological effects with increased CO_2.*

ppm_v (%) at 1 ATA	Effect	Resulting conditions
250–350 (0.025–0.035%)	None	Low CO_2 environment
351–1,000 (0.035–0.1%)	None	Typical well-ventilated indoors
1,001–2,000 (0.1-0.2%)	Complaints	Poor air, drowsiness after several hours
2,001–5,000 (0.2–0.5%)	Increased Respiration	Increased respiration rate, possible headache commencing after several hours.
5000 ppm_V (0.5%) is the maximum workplace 8-hour exposure.		
5,001–10,000 (0.5–1%)	Onset of symptoms	Potentially: fatigue, anxiety, loss of energy, jelly legs, poor concentration, drowsy.
10,001–20,000 (1–2%)	Commencement of hyperventilation	Lung ventilation up to 50% and headache for some people after 60 minutes. Elevated blood pressure.
20,001–40,000 (2–4%)	Serious	Dyspnea (from 30,000 ppmv), significant headaches after several minutes
25,000 ppmv is the NRC recommended maximum 1-hour exposure level†		
40,001–50,000 (4–5%)	Severe breathing	Violent panting, severe headache, dizziness: commencement of danger-to-life while submerged.
50,001-100,000 (5–10%)	Potentially irreversible or fatal	Serious disturbances, unconscious, or near unconsciousness commencing from 1 minute.
≥100,001 (≥10%)	Unconscious	Spasms from above 150,000 (15%), coma, possible death after 1 minute.

(using pressure swing absorption or PSA technologies), we further increase the actual number of CO molecules in the gas. For example, producing 40% nitrox, using either of the above technologies, we will increase the concentration of CO by a factor of up to 3* (meaning that we need 3 volumes of air to produce 1 volume of 40% nitrox). 10 ppm_V in the air could thus result in up to 30 ppm_V in the cylinder. When we consider the SEV at a maximum diving depth of 80 fsw (3.4 ATA), the SEV would be 30 times 3.4, or 102 ppm_V.†

4. However, this is where the complexities begin. The partial pressure of oxygen also increases, regardless of the breathing gas we are using. The deeper we dive, the greater the number of oxygen molecules. At 165 fsw we will have 6 times more oxygen molecules in each breath than at the surface breathing same gas mix.
5. The danger of CO in our breathing gas is the great affinity that this toxin has for our hemoglobin – the main carrier of oxygen in blood. CO binds at least 200 times more readily to hemoglobin and turns part of it into carboxyhemoglobin (COHb). The resulting effect is that less hemoglobin is available to carry oxygen to the tissues. With the rise of COHb, tissues rapidly become starved of oxygen This is where the harm begins. The greater the number of CO molecules, the higher the percentage of hemoglobin turns into COHb (%COHb) and the greater the harm; we in fact suffocate when the oxygen levels in our tissues drop too low.
6. There are other complex CO binding processes that take place, causing further harm and especially longer-term deficits in cellular respiration and energy production; however, CO poisoning is typically diagnosed by assessing the relevant symptoms, recent CO exposure and COHb levels.
7. There is one mitigating factor, however. When we increase the partial pressure of oxygen,

*The values in this table are a correlation by the author of data published by NOAA, NIOSH, OSHA, the EPA and the NRC (National Research Council). The effects and conditions vary significantly between divers.

†The NRC recommended Emergency Exposure Guidance Level (EEGL) for a 1-hour exposure is 25,000 ppm_v. This is published in National Research Council 2007. Emergency and Continuous Exposure Guidance Levels for Selected Submarine Contaminants: Volume 1 (Washington DC, National Academies Press). Chapter 3 contains a summary of relevant epidemiologic and toxicologic studies on CO_2. The wide range of studies reviewed shows significant variations in conditions based on specific exposure levels; the EEGL is a very conservative level, accounting for the level at which dangerous conditions may present.

it dissolves into our blood (the plasma) and despite the high percentage of COHb and decreased load of oxygen carried by remaining hemoglobin, this dissolved oxygen can still keep our tissues supplied. So far so good.

8. As we then ascend, the partial pressure of oxygen will reduce and hence the dissolved oxygen too. However, the amount of COHb does not reduce at the same rate, as it is a chemical bond and not a dissolved gas. It would typically take 4 – 6 hours to reduce the COHb level by half.
9. This is the reason why divers breathing excessive amounts of CO may well be asymptomatic at depth, but rapidly become affected when they ascend.
10. This is all pretty well understood; however, the numbers are not so easily understood and there is a degree of debate and uncertainty over their relevance. We would ideally like to be able to predict these effects so that we can determine a safe level of CO in our cylinders. Time, the amount of CO, the diver's breathing rate, and the diver's general health condition all have an effect.
11. While we do not have any significant research data on these effects in divers at depth, we do have the results of many occupational health and safety studies. Workers exposed to elevated levels of CO, which is quite possible in factories with power plants, furnaces, engine exhausts, and certain chemicals, and even in submarines, need to be able to complete their working day safely.
12. Table A7 contains some of the published data‡and safety levels found in a wide range of studies, regulatory documents, and workplace standards. The differences in the actual amounts stated appears to vary between sources§, but the effects are similar.

These COHb values are based on one-hour exposures with a respiratory minute volume (RMV) of 20 l/min. As exposure times lengthen to exceed 8 hours, the COHb values will eventually plateau. The higher the RMV, the higher the %COHb for given concentrations of CO and time – RMV values measured in divers can range from as low as 6 l/min to well above 35 l/min.

In Table A8 we can see the effect of depth on the potential toxicity of CO. You may recall that the deeper we dive, the greater the actual number of CO molecules, even though the concentration actually remains the same.

Table A7: Potential effects of elevated CO on the surface.

ppm_v	%COHb¶	Effects on the body
≤5	≤1	Normal
10	1.8	Normal
25	3.5	Maximum allowed in the workplace
30–60	5–10	Maximum safe level
60–150	10–20	Headache, breathless
150–300	20–30	Add dizziness, nausea, impaired dexterity
300–650	30–50	Add vomiting, confusion, and loss of consciousness
700–1000	50–65	Organ impairment, coma, fatal if not treated
>1000	>65	Fatal

Note: In smokers, %COHb may vary between 1.5% and 14%.

Once again, these are based on 1-hour exposures with a RMV of 20 l/min.

These two tables contain many numbers, which may indeed be confusing to some. However, one can quickly determine the dramatic effect depth has on COHb and the accompanying rapid negative impact on health.

We need to pay special attention to where the %COHb could rise above 30: the diver may lose consciousness at this level; the consequence could be drowning.

Most of the accepted or required breathing gas limits for CO are either 5 ppm_V[1, 4, 5, 8] or 10 ppm_V[2]. Both of these levels should be safe when considered for a dive time of around 60 minutes on air at the depths indicated in Table A8 above.

However, consider air with a CO concentration of 10 ppm_V that is used to produce 40% nitrox. The resulting SEV of up to 102 ppm_V at 80 fsw (3.43 ATA) is clearly in the danger zone with a COHb content of approximately 14% (interpolated from the values in Table A8).

*An efficiency factor of 50% has been assumed, which is typical for low-cost membrane separators.

† This assumes that the nitrox generator unit does not use a filtration system that includes an element to catalyze out the CO in the air. Catalytic converters are 99% effective at CO removal.

‡ Sources include NIOSH (National Institute for Occupational Safety and Health is the United States), the EPA (United States Environmental Protection Agency), the HSE (Health and Safety Executive in the UK), the HSWA (Health and Safety at Work New Zealand), and the WHO (World Health Organization). The information is all open access.

§ Despite the above sources illustrating potential effects of elevated %COHb, a peer-reviewed article [29] provided an even greater spread of the results of CO poisoning. There is thus no definitive correlation between %COHb in the blood and ill-effects as these effects vary between people. For the purposes of this article and based on the regulatory sources in footnote 2 above, this table still serves as a guide until modified by future studies.

¶ COHb values are interpolated linearly between known values although the correlation is only linear for the first few hours of exposure. Typical dive times thus allow for this. The values are rounded-off to the nearest integer for values in excess of 3.5 at the surface.

Table A8: Surface equivalent levels at depth.

At the surface (1 ATA)		At 66 fsw (3 ATA)		At 100 fsw (4 ATA)		At 130 fsw (5ATA)	
ppm_V	%COHb	ppm_V	%COHb	ppm_V	%COHb	ppm_V	%COHb
≤5	≤1.0	15	2.5	20	3.2	25	3.5
10	1.8	30	4.7	40	6.1	50	7.4
25	3.5	75	10.4	100	14.0	125	16.5
30–60	5–9	90–180	13–22	120–240	17–27	150–300	19–31
60–150	10–19	180–450	22–41	240–600	27–48	300–750	31–54
150–300	20–29	450–900	41–59	600–1200	48–66	750–1500	54.0–68
300–650	30–49	900–1950	59–70	1200–2600	66–70++	1500–3250	68–70+++
700–1000	50–65	2100–3000	Lethal	2800–4000	Lethal	3500–5000	Lethal
>1000	>65	**Fatal**					

Having said this, divers with existing health issues, including impaired respiratory function, may be at a higher risk. For instance, a 1-pack a day smoker may live with a basal COHb level of 3% to 6%*. Breathing a CO-contaminated nitrox mix could take COHb levels well into the danger zone.

We need an accepted and realistic standard which is safe, achievable, and practical for the greater majority of divers. This should thus be 5 ppm_V. Many inexpensive, portable CO analyzers measure in the range 0 – 25 ppm_V with a 1 ppm_V resolution making them suitable for detecting safe levels of CO in the diving environment.

Why 5 ppm_V when 10 ppm_V might also be safe you might ask? Generalizing here, a maximum background level of as high as 5 ppm_V is realistically possible. However, to achieve 10ppm_V means that there is likely a source nearby. So, while 'perhaps' safe at this level, the compressor filling station needs to investigate the likely source and assess the risk of drawing in CO well in excess of 10 ppm_V. Remember, most of them do the required quarterly, 6-monthly, or annual air quality tests – depending on the requirements where they are located. This is not going to provide much assurance as to the level in your cylinder on the day that you dive.

This is not a thorough scientific analysis of the effects of elevated CO on us as divers; neither is DAN the appropriate organization to state limits. However, in our opinion as a leading dive safety organization, we feel comfortable in advising that a maximum of 5 ppm_V represents a relatively safe level. While 10 ppm_V on the day may be safe to dive with, the value could feasibly change between filling sessions to levels that rapidly approach the danger zone.

This makes little difference whether you are diving on nitrox or air. Also, we have not touched on what happens in technical diving, where the gas volume at depth will contain greater and greater amounts of CO. Ideally, you should expect zero.

The following references provide additional discussion on the complexity of simplifying the issues of COHb levels[22], how poising takes place[23], and why smoking and diving make an unfortunate pair.[24, 25]

APPENDIX C: WHY ARE WE CONCERNED ABOUT OIL AND PARTICULATES IN OUR BREATHING AIR?[26]

While the effects of elevated partial pressures of CO and CO_2 on human health are described in the literature, solids (such as oil mist and particulate matter) only really appear in occupational health and safety studies, and only in terms of breathing at the surface.

Some scientific work has been published relating to the fire hazard introduced by the presence of any combustible product (such as oil and particulates), especially in the presence of elevated oxygen concentrations.

Whereas the difference in limits of CO and CO_2 between the US CGA and the European norm is limited to a factor of 2, when oil content is concerned, the discrepancy factor is 10.

*A 1-pack per day smoker may start the dive with a %COHb of 3–6.

CGA Grade E (scuba air) limits the amount of condensed oil to ≤ 5 mg/m³.[2] EN 12021 (breathing air) limits the amount of oil to ≤ 0.5 mg/m³.[1]

The limit for oil appears in almost every published compressed air specification, whether it be condensed oil, oil mist, mineral oil, or synthetic oil. Ref. Table A1: Maximum limits for contaminating substances in breathing air

However, some specifications combine both oil and particulate matter into one limit*; others do not specify any limit for particulates; and in some cases, limits of VOCs are provided to address flammability and toxicity arising from oil in vapor form.

The task is to carefully consider these discrepancies to ensure that, irrespective of any regulatory limits, scuba diving air is safe.

We will begin with an overview of basic concepts, to serve as a starting point for those with an interest in the topic.

1. Depth has a direct impact on partial pressure. According to Dalton's law, the deeper we dive, the higher the partial pressure of all the constituents (separate gases that make up the air we breathe) of the breathing gas at depth.
2. Technically, there is no such thing as a 'partial pressure' of oil mist or particulate matter, but the effect is the same. Instead of thinking of these as having a pressure, we need to think about the actual number of molecules of the substance in a unit volume. Let's say for example that a cylinder was filled at the dive shop with a gas mix containing a concentration of 1 mg/m3 of condensed oil. If this cylinder was used on a dive down to 130 fsw (40 msw or 5 ATA), the amount of oil in each breath would rise to 5 times the surface value, or 5 mg/m3. This is the surface equivalent value (SEV) discussed in the previous two appendices.
3. When producing nitrox using a membrane separator, both oil and particulates will be reduced, as the physical sizes of the molecules are much larger than those of all the gases. The effective diameter of all particulate matter is measured in microns (µm or 10-6 m), whereas the diameters of gas molecules (and membrane fibers) are measured in Angstroms (Å or 10-10 m).
4. In general, (assuming that appropriate compressor oil and filters are used), no toxic or flammable particulates should be contained in the gas in a filled cylinder.
5. In terms of oil and particulates, rather than being concerned about toxicity, the two risks of concern are effects on the respiratory system and risk of fire. It is these two concerns that will be discussed in this article.
6. The elevated partial pressure of oxygen at depth has no discernible effect (amelioration or compromising) on respiratory issues, with specific reference to particulates. However, the risk of fire increases if oxygen-enriched gases are used.
7. Analysis of these contaminants is an additional complication. In the past, field analysis was performed using gas detector tubes – an easy way to spot-check air quality.
   - With the introduction of human-safe (non-toxic) synthetic oils, gas detector tubes largely became ineffective. There is a mechanical device that is used in place of detector tubes, but an expert opinion*, as well as the author's empirical findings, are that these devices are ineffective and do not appear to detect particulates when laboratory instruments do.
   - Laboratory analysis is used to determine the levels of oil and particulates with a good degree of accuracy. However, this requires a sample to be taken and sent for analysis: this is therefore a delayed spot-check and takes both time and money to achieve.
   - There are several volatile organic compound (VOC) analyzers on the market which can offer real-time monitoring of contaminant levels. These analyzers have two weaknesses. The analysis assumes that the user knows the constituents of the type of oil they are using – something very few compressor oil producers appear to provide in their datasheets (perhaps due to their trade secret). A second assumption is that the oil content is determined as a combination of CO, VOC, and moisture, where a VOC is measured as a gas and not in a particulate (or liquid/condensate) form.
   - We have been using the term "ppm" in the context of volume (ppm_V being the ratio of the number of molecules of, for example, CO to the total number of molecules of gas in the cylinder). Unless we know the exact molecular weight of the oil, we cannot specify allowable limits in terms of ppm_V. Even where we do have the molecular weight of an oil, the equivalent concentration to the CGA

*Both of these contaminants represent fire and health hazards, both are considered as solids (non-compressible matter), and both are difficult to separate when it comes to some analytical techniques employed.

limit of 5 mg/m^3 would be is in fractions of a ppm_V – typically between 0.006 and 0.3 ppm_V.

- If we need to know the concentration in ppm_V, then we need to consider ppm by weight. In this case, mg/m^3 almost relates to the same value of ppm_{wt}.

8. While breathing air compressor oils are required to be human-safe (non-toxic), this assumes that the correct maintenance has been performed on the compressor and that it is in good running state. If the compressor overheats, it can easily burn the oil – regardless of the type. Combustion implies the production of CO – the silent killer. This has been confirmed through sufficient published cases of CO toxicity as a result of this compressor's overheating.

With the background information sufficiently covered, we will now move on to the issues of concern: fire and respiratory effects, starting with the essential basics of how oil and other particulates affect us.

HEALTH ISSUES:

Particulate matter such as dust, metal particles and oil particulates will cause respiratory issues for the diver – especially a diver with an existing respiratory weakness.

Many are aware of the hazards of hypoxia in smoke, but maybe not those hazards unrelated to CO, CO_2 or other combustion products. The environmental agencies who determine these hazards compute and publish these in terms of particulate limits.

For example, in the US, the EPA[†] publishes the health effects of particulate matter (PM) in terms of size (μm) and concentration (μg/m^3). Concentration values are divided into two sizes, 2.5 μm[‡] ($PM_{2.5}$) and 10 μm (PM_{10}), determined over a 24-hour period. This is then correlated with population health effects, ranging from good to hazardous.

However, when compared to breathing air quality standards that do regulate particles, the limits appear to be orders of magnitude higher than those allowed in compressed breathing air. Clearly, we do not have a good handle on this topic and more research is needed[§].

What is published in compressed breathing air standards, and generally adopted by the diving industry, is the concentration of combined oil and other particulates.

The essential issue here is based on the sizes of the particulates. Whereas the EPA categorizes them as $PM_{2.5}$ and PM_{10}, compressed breathing air standards categorize them as those approximately > 5 μm and those approximately < 5 μm. The actual size is less important than the observed affect around this size.

Smaller particles (those smaller than 5 μm) tend to lodge in the deep recesses of the lungs, hindering the passage (exchange) of gases and resulting in hypoxia. This is a cumulative effect: the longer the exposure during the dive, the greater the build-up at the end of the dive. The greater the number of dives around that time frame, the greater the build-up. The body can get rid of these, but this takes time.

The larger particles (greater than 5 μm) tend to cause upper respiratory tract issues (irritation and inflammation).

A properly maintained compressor and breathing air filtration system will remove the larger particles. The inlet filter to the first stage regulator will typically be fitted with a 5 μm sintered filter, hence it is unlikely that the diver will present with respiratory tract issues due to large particulates unless there is a mechanical and associated maintenance breakdown.

Where a sintered filter will remove larger particles, it is the particles smaller than 5μm that cause irritation and inflammation of the lungs. This is sometimes referred to as chemical pneumonia – although the particles, including oil, are not chemically toxic.

While these small particles are not individually visible, it is possible to see an accumulation over time – typically as a white, red, or black powder in the second stage housing. White powder generally indicates aluminum oxide; red or black powder usually ferrous oxide: both of these are related to the two different types of cylinder metals. In practical terms, this is our only visible clue other than through actual air quality analysis – it should be heeded, and the cause(s) determined and addressed.

Oil contamination is rarely visible except for obvious, gross contamination; the closest one gets to detecting oil is through taste and/or smell. The human nose is capable of detecting the aromatic compounds found in compressor lubricating oils at levels as low as 0.001 ppm_V (referred to as an odor threshold).

Symptoms of exposure to excessive amounts of any particulate include nausea, shortness of breath, fatigue, respiratory distress, and eye and skin irritation. Excessive,

[*] Dr Thorburn Burns produced an expert witness report in a legal case. [33]

[†] The United States Environmental Protection Agency publishes the effects on humans of elevated air quality indices or AQI. The AQI is determined as a combination of particulates, CO and CO_2 as far as we might be concerned.

[‡] A μm or micron is a unit of length equivalent to 1 thousandth of a meter (or 0.001 mm) and in imperial measures, one 25,400th of an inch.

[§] Ian Millar, who published a review article on compressed breathing air in 2008, expressed this recommendation too. [13]

longer-term exposure may even result in organ failure, although unlikely to occur in recreational diving.

FIRE RISKS:[9, 27]

When dust or any form of particulate matter travels at high velocity, this can collide with any form of flow obstruction. These collisions, or impactions, have the potential to cause ignition, referred to as particle impact ignition. The fine particulates also serve as a fuel. Oxygen is an oxidizer (it helps a fire to burn) and is present at elevated partial pressures in all types of recreational diving gases.

A second ignition source is called adiabatic heating. A significant increase in temperature is caused by breathing gases experiencing a rapid increase in pressure when flow is stopped suddenly. For example, this could occur if the cylinder valve is opened rapidly, but flow is stopped at the first stage regulator, or at a valve in the filling system, or even in a component not designed to prevent adiabatic heating. Exact temperatures for non-ideal gases in non-theoretical situations are hard to determine properly. For this reason, it is difficult to give a precise temperature that we would find in an adiabatic heating situation. Research has shown a range of temperatures versus pressure, but by way of an indication, air starting at 2901 psi (200 bar) and striking a stoppage could result in a temperature spike as high as 1,976°F (1,080°C)*.

Considering that the autoignition temperature (AIT)† of the average synthetic oil is 725°F (385°C), and that the adiabatic heating temperature potential in air at 2901 psi (200 bar) is 1,976°F (1080°C), one can clearly understand the risks of fire and explosion.

The requirements for oxygen cleaning where oxygen-enriched gases are being used is relatively common knowledge – this is based on preventing fire and explosion where any oil products are present in the gas flow path. The level at which air would be considered oxygen-enriched is heavily debated and plagued with incorrect interpretations from the many different standards and regulations. A very general range would be between 21 and 25 percent oxygen. There are recreational diving organizations that insist on 40%. However, consider that compressed air with 20.9 percent oxygen contains 200 times more oxygen molecules at 2,900 psi (200 bar); common sense suggests that this is more than sufficient to support a fire.

Once again, actual data providing safe contaminant levels is hard to come by, and certainly not within the domain of recreational diving. We must also consider that oil may not only exist in aerosol form, (measured in mg/m^3), but could also already be on the surfaces of all the wetted‡ parts (measured in mg/m^2).[28]

So, we have variations in oxygen partial pressures, flammability of particulates, location of contaminants, and ignition temperatures. The question now is: what is a safe limit?

SOUND ADVICE:

There are many variables to consider in terms of health and fire risks for oil and particulates. Still, we also hear about failures on a frequent enough basis to validate the dangers of the presence of these substances in compressed gas for scuba diving.

Conservative practice based on existing limits, even though these have been determined for other applications rather than those underwater should be:

1. Health: 5 mg/m^3 is the occupational health and safety limit for condensed oil particles for surface breathing. If we apply the effect of depth, say to the maximum depth on air of 230 FSW (67 MSW), then we should divide this limit of 5 mg/m^3 by 7.7. An appropriate limit would then be 0.65 mg/m^3. The European limit is 0.5 mg/m^3; the CGA Grade E limit is 5 mg/m^3. Prudence would dictate that we follow the lower limit – and almost all scuba air quality tests done pass this requirement.
2. Fire: There are too many variables here to know where to establish a safe limit. Oxygen-compatible gas is generally considered to be gas where the oil content is less than 0.1 mg/m^3. This is the lowest limit at which we can measure and detect particulates using field testing rather than costly laboratory instruments. There are manufacturers of field analyzers that claim the ability to measure to as low as 0.01 mg/m^3, but this is done based on combining moisture, CO, and the VOC content.
3. Safe practices and limits are intended to assure safety under normal circumstances. Since we never know what might be in the cylinder or in the gas flow components, we should always stand clear when filling any cylinder with an oxygen content of 25% or higher*.
4. Responsible practice would be to ensure proper maintenance of compressors:
   - piping, hoses, regulators and valves, and especially the compressor inter-stage and final stage liquid separators are regularly checked and cleaned;

*Research has shown a spread of temperatures at different pressures, combined with speed of gas, materials, flow paths, and so on; however, even with published data of actual tests demonstrating temperatures of 1,292 °F (700°C) in air, we are still well above the AIT of the compressor oil. [32]

†The AIT is the lowest temperature at which a substance will spontaneously ignite without an external source of ignition.

‡ By wetted parts we mean any surface that is in direct contact with the gas flow.

- breathing air filters are changed according to manufacturer's recommendations;
- all gas leaks are repaired, but never while the system is under pressure; and
- appropriate cleaning practices are followed, especially when dealing with oxygen enriched gases.

In conclusion, best practice would be to follow the European limit for particulates in air (0.5 mg/m^3) and to follow the limit for oil-free breathing gas (0.1 mg/m^3) where the oxygen partial pressure exceeds 0.25 atmospheres at any given depth. This is equal to 25% oxygen in the cylinder when measured at the surface.

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APPENDIX B. RESEARCH HIGHLIGHT

A REVIEW OF DAN EMERGENCY CALLS INVOLVING DIVING MINORS

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INTRODUCTION

Minors have been diving for decades, but the incidence of scuba diving injuries among them remains poorly studied.

As opposed to most other outdoor recreational activities, the main challenge while scuba diving is managing the inherent risks of using life-support equipment to survive in a hostile environment. Scuba diving requires a specific set of skills, and demonstration of those skills in a highly controlled environment such as a swimming pool may not readily transfer to the open-water environment.

Children are not small adults. Their body and organs are not just growing in size, they are also maturing in physiology and function. The prevalence of childhood asthma, for example, diminishes with age, demonstrating that the respiratory system is often still developing until teenagers become young adults.

During childhood, dramatic changes in the brain allow us to perfect decision-making processes, regulate emotions, detect threats, and activate appropriate fear-related behaviors in response to threatening or dangerous stimuli. Psychological immaturity can prevent minors from reacting to underwater emergencies with the same capacity as adults. Panic can lead to uncontrolled rapid ascents, increasing the risk of pulmonary barotrauma. Children can often lose focus and make mistakes, putting them at an increased risk for a number of threats.

Over the years, researchers have raised concerns about the effects of compressed-gas diving on minors, especially the potentially harmful effects of decompression stress on growth rates. But after decades of extensive diving by minors, including long-term follow-ups on cases of decompression sickness (DCS), there does not seem to be any evidence to support this theory.

The DAN Emergency Hotline is a remarkable resource. In response to a number of cases involving minors who dive, DAN created a retrospective study to examine the types of injuries they experience. We analyzed records between 2014 and 2016 and identified 149 cases involving minors.

As part of a 2019 DAN Research internship in the medical department, Elizabeth Helfrich analyzed the data under the mentorship of doctors Matias Nochetto, Camilo Saraiva, and Jim Chimiak, and published the study.[1] Figure B-1 is a flowchart of the number of cases that were included/excluded for the purpose of this study.

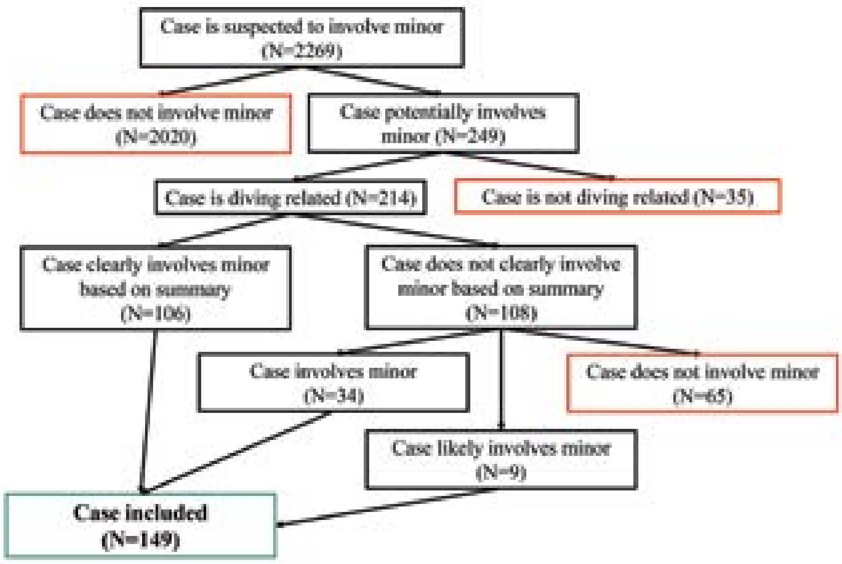
RESULTS AND DISCUSSION

We split the study data into catergories: the reason for call (initial concern), and the final differential diagnosis. DCS concerns were the most common reason for a call involving minors, accounting for 38%, followed by issues with ears and sinuses (ENT) at 26%. Pulmonary barotrauma (PBT) was suspected in 12 cases (8%) and arterial gas embolism (AGE) in six cases (4%). Table B-1 illustrates the distribution of the caller's chief complaint versus the final differential diagnosis after DAN review.

Despite its prevalence as the most common reason for the call, DCS accounted for only 6% of the final diagnoses. Based on manifestations, four cases were neurological DCS, four were mild DCS, and one case was inner-ear DCS. Only one minor diagnosed with DCS reported having decompression obligations during the dive. As with adults, ENT issues were minors' most common dive injury (32%).

Surprisingly, PBT accounted for 15% of the dive injuries. While no reliable data are available on the incidence of PBT in adult divers, the authors' impression based on personal experience suggests that the number of PBT cases in minors trends much higher than in the general dive population. Therefore, we looked at this issue in more detail.

Figure B-1. Flowchart of inclusion/exclusion for the Children and Diving study.



In seven cases of PBT there were confirmed reports of a rapid ascent; six of those involved confirmed or highly suspected anxiety. One child became anxious after practicing a controlled emergency swimming ascent during training; another reported an anxiety attack that led to breath-holding and a rapid ascent.

A child freediver planned a dive to 15 feet (4.6 meters) and then extended to 35 feet (10.7 meters) for unknown reasons. This child then had seizure-like activity underwater, right-leg weakness upon surfacing, and a final diagnosis of AGE. It is unreported if the child breathed from compressed air at depth, although that's likely given the symptomatology and the treating physician's diagnosis.

Three other minors likely became anxious at depth, leading to rapid uncontrolled ascents and consequent PBT. On four instances an event happened at depth that likely led to accidental breath-holding and PBT. Two of those cases resulted from issues with equipment: One child reported a free-flowing regulator, while another reported being overweighted. It is likely this last diver attempted to assist ascent by increasing lung volumes with deep inspiration and breath-holding.

One diver reported uncontrollable laughter underwater, another reported a "large belch," suggesting they swallowed air at depth, and four had no identifiable reasons for injury. Also of interest is that two young divers with PBT noticed chest pain after the first dive but continued to dive for the day. It is unclear whether that might have contributed to the severity of the initial injury.

The role of anxiety as an injury's trigger and the root cause is likely underrepresented. This could be due in part to the subjective nature of anxiety and possible behavioral bias from minors not always accepting and verbalizing their fears, among other possibilities. When considering the overall narratives, anxiety and consequent panic are woven throughout many cases.

REMARKS FOR THE INDUSTRY

When training individuals in vulnerable populations, no other group generates more polarization than young divers. Children often have a well-developed sense of adventure and a less-developed sense of mortality.

Chronological age is a poor predictor of maturity in minors. Albeit more cryptic and admittedly rather impractical, perhaps a reflection on the intersection between biological, psychological, and social age could more accurately predict the response of a person under adverse circumstances.

Just as dive professionals must be trained and hold certifications to teach wreck diving or to lead a group on a wreck, specialized training for teaching and guiding diving minors could be beneficial. This training should focus on children's individual needs and unique behavioral aspects that make them more prone to certain incidents and injuries.

Children should always be at arm's length from an able-bodied adult diver who can closely monitor them, especially regarding comfort. As the diver matures and their response to stress becomes more predictable, the distance could gradually increase.

Safety enhancements can be made for open-water dives. Diving minors may not be reliable dive buddies due to their maturity, lower strength, and often unpredictable responses

Table B-1. Number of calls for each sub-category with chief complaint and final differential diagnosis (Ddx) after DAN review.

Sub-Category	Chief Complaint	Final Ddx
Decompression Sickness (DCS)	56	9
Arterial Gas Embolism (AGE)	6	2
Pulmonary Barotrauma (PBT)	12	13
Anxiety	1	3
Ear, Nose, Throat Injuries	39	47
Hazardous Marine Life Injury	12	12
Immersion Pulmonary Edema (IPE)	1	0
Musculoskeletal	0	23
Other	5	14
Unrelated Gastroenteritis	0	18
Unrelated	0	8
Caller uncertain	17	0

to threats. These discrepancies could compromise both divers' safety, so a buddy system of two adults and a child would be more prudent, where one of the adults is someone who knows the youngster well and is sensitive to subtle cues of stress or discomfort, someone such as a parent or other close relative or guardian.

People who dive with children should understand and recognize the age group's unique behavioral aspects to help prevent situations that could lead to severe injuries. With proper training and supervision, we can reasonably mitigate the inherent risks of a minor joining their family in exploring the underwater world.

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APPENDIX C. PEER REVIEW RESEARCH PUBLICATIONS

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