Fatalities involving divers using surface-supplied breathing apparatus in Australia, 1965 to 2019

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Abstract
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Introduction: This study identified characteristics and diving practices of victims of fatal surface supplied breathing apparatus (SSBA) incidents in Australia from 1965–2019 to determine underlying factors and risks associated with these activities, better educate the diving community and prevent such deaths.
Methods: A hand search was made of 'Project Stickybeak' reports from 1965–2000 and SSBA fatality data were compared to the Australasian Diving Safety Foundation fatality database. The National Coronial Information System was searched to identify SSBA diving deaths for 2001–2019. Extracted data were collated and analysed using descriptive statistics and Poisson Regression. A chain of events analysis was used to determine the likely sequence of events.
Results: There were 84 identified SSBA-related deaths during the study period. Most victims were relatively young, healthy males (median age 33 years). At least 50% of victims were undertaking work-related diving, and 37% were recreational diving. Equipment issues, mainly compressor-related, were the main contributor, identified as a predisposing factor in 48% of incidents and as triggers in 24%.
Conclusions: Preventable surface-supplied diving deaths still occur in both occupational and recreational diving, often from poor equipment maintenance and oversight. Incorrect configuration of the SSBA and lack of training remain on-going problems in recreational users. These could be addressed by improved education, and, failing this, regulatory oversight. The increase in health-related incidents in older participants may be controlled to some extent by greater medical oversight, especially in recreational and non-certified occupational divers who should be encouraged to undergo regular diving medical assessments.

Introduction

Surface-supplied breathing apparatus (SSBA) diving involves breathing gas underwater, usually compressed air (unless in deeper commercial diving) supplied from the surface through a long hose to a demand valve. The term 'hookah' is frequently used in Australasia to describe a minimalist version of SSBA. This equipment supplies air from a simple, usually petrol-driven, compressor which feeds a small reservoir and in turn delivers the air along a hose to a demand valve regulator. If the demand valve is not of the 'upstream' type, the system should incorporate a non-return valve to prevent potential injury to the diver from a gas supply failure, such as a hose rupture. It is essential that such compressors are fit-for-purpose, well-maintained, appropriately configured to provide a steady and plentiful supply to the number of divers using it at the target depth. They also need to be positioned securely in a well-ventilated area to prevent overheating, while also ensuring that any exhaust fumes cannot contaminate the breathing gas. The diver wears a mask (or helmet in commercial diving), fins and thermal protection, weights, and ideally, a buoyancy compensator device (BCD). An emergency gas supply in the form of a bail-out cylinder is highly desirable to enable the diver to reach the surface in the event of an interruption to the breathing gas supply. Commercial divers may also have a communication system to liaise with the surface tender.

In Australia, SSBA is used for a variety of purposes. These may include generally well-trained and experienced commercial divers undertaking underwater work; commercial seafood harvesters such as abalone divers and fish farmers; pearl divers; research divers; recreational divers, often hunting or harvesting seafood; and rank novices participating in an underwater experience. Unlike in the past,[1] commercial diving operations have generally become better organised and are under the oversight of workplace regulators, and subject to relevant Codes of Practice. However, serious incidents involving systemic failures still occur.[2,3]

Unlike scuba, where a certification is supposed to be checked prior to the filling of a cylinder, there are currently no restrictions on who can obtain and use a SSBA for recreational use. In addition, some users convert compressors designed for non-diving purposes or fit their compressors out inappropriately, sometimes with dire consequences.[4]

An earlier summary of SSBA-related deaths in Australia indicated that many deaths were the result of equipment-related issues and lack of training or experience.[5] The aim of this current and more detailed study is to examine all Australian SSBA diving-related deaths recorded on the Australasian Diving Safety Foundation (ADSF) database[4] to determine the likely chain of events, examine trends, and to better educate the diving and medical communities and prevent such deaths.

Methods

Approval for the study was received from the human research ethics committees of the Victorian Department of Justice, the Royal Prince Alfred Hospital, Sydney; the Coroner's Court of Western Australia; and the Queensland Office of the State Coroner.

SEARCH

This was a complete case series of known SSBA diving-related fatalities that occurred in Australian waters from 1965 to 2019, inclusive. A hand search was made of the relevant 'Project Stickybeak' reports published in the diving medical literature.[5–7] The data obtained were compared to that recorded on the Australasian Diving Safety Foundation (ADSF) fatality database[4] and adjustments made where necessary. In addition, a comprehensive key word search was made of the National Coronial Information System (NCIS)[8] to identify SSBA diving deaths reported to various State Coronial Services for the years 2001–2019, inclusive. Key words included compressed air, compressed gas, or surface supply, or hookah and diving. Cases identified were matched with cases collected by the investigator via the media or the diving community to minimise the risk of over- or under-reporting.

The review procedure involved review of the published case reports and database entries for cases from 1965 to 2000, to investigate any discrepancies and enter relevant data in a specially designed Excel spreadsheet. The coronial data were also reviewed for cases from 2001 to 2019 and relevant data were also entered into the spreadsheet.

PREDICTORS

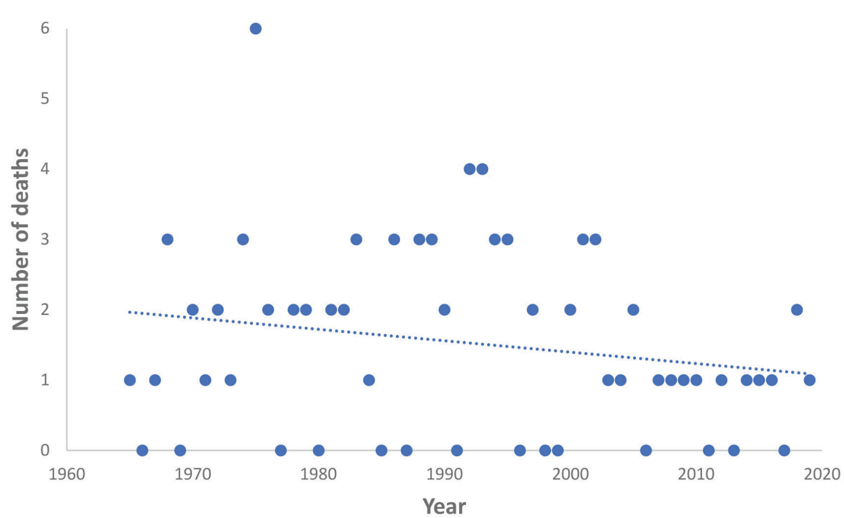
A range of potential predictors was extracted, including diver demographics, certifications and experience; dive location; buddy and supervision circumstances; dive purpose and depth; equipment used and any associated problems; incident description.

CHAIN OF EVENTS ANALYSIS

A chain of events analysis (CEA) was conducted to identify predisposing factors and outcome measures including trigger, disabling agent, disabling condition, and cause of death. The CEA was based on the criteria and templates for scuba fatalities previously published.[9] The investigator applied the published templates (with the term 'Disabling Condition' replacing 'Disabling Injury') to these data and obtained the results reported below. An example of the application of such a template is: A faulty compressor (predisposing factor) stalls and interrupts the diver's air supply (trigger), causing the diver to make an emergency

Figure 1

Australian surface-supplied breathing apparatus-related diving fatalities by year, 1965 to 2019 (n = 84)



ascent (disabling agent). He suffers a cerebral arterial gas embolism (disabling condition), becomes unconscious and subsequently drowns (cause of death).

STATISTICAL ANALYSIS

Descriptive analyses based on means and standard deviations or medians and ranges as appropriate was conducted using SPSS Version 25 (IBM® Armonk, NY; 2017). Poisson regression was used to analyse possible trends. All models were fitted using the Stata 16 software (StataCorp 2019).

Results

There were 84 recorded fatalities in divers using SSBA during the 54-year study period.

ANNUAL COUNTS

The median (IQR) number of annual deaths was 1 (0.5, 2) with a maximum of six. The annual deaths generally reduced until 2002 and then remained relatively steady, although the trend was not significant ($P = 0.064$) (Figure 1).

DEMOGRAPHICS

The median (IQR) age of the victims over the study period was 33 (26, 40) years; range 16–72 years). There was a small albeit statistically significant ($P < 0.001$) rise in the age of victims over the period of approximately 3.1 years per decade. The median (IQR) age of victims over the final 20 years was 36.0 (28, 47) years. All but one of the 84 victims were male. Non-occupational divers were older than occupational divers (with means 38 and 32 years, respectively), although this difference was not significant ($P = 0.053$).

LOCATION

The distribution of deaths between the various states and territories was: Victoria (16), Western Australia (17), Tasmania (15), Queensland (15), South Australia (12), New South Wales (8), and Northern Territory (2).

TRAINING AND EXPERIENCE

In 36 of the 84 cases the victims were reported to have undergone some form of training, although the level of training was unspecified in 26 of these. At least seven victims were scuba certified, and at least three had undergone commercial diver training. Twenty-one victims were untrained, and the level of training was unreported in 24 cases. Significantly more of the occupational divers had undergone some type of training ($P = 0.03$).

Although all but 11 of the reports included a description of the diver's experience, or lack thereof, there was no detailed quantification of this experience, so the following summary is somewhat arbitrary. Fifty-two of the victims were described as experienced, 11 had some experience (in some cases very little), and 10 had no experience at all.

Table 1
Diving activity during the fatal incident in 84 SSBA divers. *Construction, oil rig, maintenance, salvage

Activity	Deaths
Occupational	
Commercial*	16
Abalone collecting	10
Pearling	9
Aquarium fish collecting	3
Sea cucumber collecting	2
Crayfish collecting	1
Scallop collecting	1
Research	1
Recreational	
Crayfish collecting	14
Sightseeing	6
Scallop collecting	5
Spearfishing	4
Abalone collecting	1
Self-training	1
Miscellaneous	
Other	4
Unknown	6

ACTIVITY

Forty-three of the 84 victims were undertaking work-related diving, and 31 were diving for recreation, whether harvesting seafood or sightseeing. One untrained and inexperienced victim was trying out the second SSBA demand valve while his friend was underwater. One victim was involved in an underwater survey for his studies (Table 1).

BUDDY/SUPERVISION CIRCUMSTANCES

Solo diving was three times more prevalent in occupational divers than in others. In 64 of the 84 incidents, the victim had either set out alone, or had already separated from his buddy before the fatal incident had occurred. However, in at least 47 of these incidents there was an observer present. Overall, a surface observer was present in 58 cases, and there was no observer in 16 cases. The presence or absence of surface support was unknown in 10 cases.

DEPTH

The dive depth was not reported in eight cases. For the remaining 76 incidents, the median (IQR) dive depth was 11.25 (7.5, 6.75) metres' seawater (msw), range 3–74 msw. Only nine fatal dives were reported to have been deeper than 30 msw. Seven of the 42 occupational divers and only one of the others were known to have been diving deeper than 30 msw. The depth of the incidents shown in Table 2.

Table 2
Depth of fatal incident in 84 SSBA divers. NR = not reported.

Incident depth (msw)	*n* (%)
Surface	15 (18)
Ascent	17 (20)
0–10	22 (26)
11–20	12 (14)
21–30	4 (5)
> 30	4 (5)
NR	10 (12)

WEIGHTS

One victim was known not to have worn weights for his dive, and the weighting circumstances were unreported in 16 incidents. Of the 67 victims who were known to have been wearing weights, 61 were still wearing these weights when rescued or recovered.

BUOYANCY COMPENSATOR DEVICES (BCDS)

There was no indication whether a BCD was worn in 23 of the incidents. However, at least 56 of victims were not wearing a BCD. Five victims were reported to have been wearing a BCD and none of these were inflated when found. One was found to have been faulty.

Chain of events analysis

PREDISPOSING FACTORS

One hundred and seventeen predisposing factors (PFs) were identified as possible or likely contributors to the 84 deaths (Table 3). There were insufficient data to suggest any PFs in 18 cases, and no obvious PF in one incident, despite detailed information. Multiple factors were identified in 42 incidents: 22 incidents with one identified PF, 31 incidents with two, and 11 incidents with three PFs. The main PFs identified were related to equipment, planning, and health issues.

Absence of appropriate equipment or use of defective equipment

Defects, sometimes multiple, were found in a variety of equipment, mainly compressors which were poorly maintained and/or defective (19). Defects included poor hose connections, inappropriate hoses which were overly long, kinked and/or melted, and the absence of intake hoses. Defective demand valves (2), or full-face mask (1) were also implicated. At least two deaths resulted from the compressors' inability to supply sufficient air to multiple divers at their operating depth. Loss of unsecured demand valves (3), obvious overweighting (2) and a very tight wetsuit were also implicated. Of note, the reports rarely mentioned the carrying of a bail-out gas cylinder which would generally be considered as appropriate equipment for such diving.

Planning

Poor planning decisions were often made, usually immediately before the dive. The most common of these was inappropriate placement of the compressors, which was a factor in 13 deaths, mainly due to exhaust gas entering the air intake. Failure to properly assess and plan for environmental dangers contributed to six deaths. These dangers included strong water flows in water supply containment areas, toxic gas in an enclosed space, an active cleaner pump, an engaged boat propellor and the increased risk of local large shark activity. Three divers, who died from decompression sickness (DCS) had not followed any decompression guidance. Two divers were diving solo without surface oversight (one at night), and another two had failed to ensure their working platform was properly secured.

Health

Health-related factors contributed to at least 15 deaths, including eight of 61 deaths occurring before the year 2000, and at least seven of the 23 subsequent deaths. Half of these deaths were in occupational divers. The most common health condition was pre-existing, albeit apparently undiagnosed, ischaemic heart disease (IHD). Pulmonary blebs, pleural scarring after pleurisy, and asthma were implicated in three deaths (one also involving IHD), seizures in three (two associated with congenital brain abnormalities and one idiopathic) and severe obesity in one. Alcohol and heroin appeared contributory to two incidents. There were insufficient data in most cases to determine whether the victims had undergone a recent diving medical examination.

Training, skills, experience

There were at least 13 cases where lack of any or sufficient training, inexperience, and associated lack of skills likely contributed to the outcome. Although six of the victims had scuba certification, in four it was recent, and they had little experience. One very experienced scuba diver died on his first SSBA dive though lack of familiarity with the equipment. Two untrained but experienced SSBA divers were unable to read decompression tables and died from DCS after omitting large decompression obligations. One untrained and inexperienced victim drowned during his first use of SSBA while his friend hunted fish below.

Supervision

Poor supervision likely contributed to at least 14 incidents. Eight of these involved inadequate oversights of the compressor and resulted in contamination of the breathing gas by compressor or boat exhaust, a burning air intake hose, or overheating. In two cases, the surface tender failed

Table 3

Predisposing factors associated with 65 of 84 SSBA fatalities. Some deaths involved multiple predisposing factors, hence the number predisposing factors exceeds the number of cases

Predisposing factor	Subgroup	*n*
Absence of appropriate equipment or use of faulty equipment		27 (32%)
	Defects in equipment	19
	No demand valve security	3
	Insufficient supply capability	2
	Overweighting	2
	Tight wetsuit	1
Planning		28 (33%)
	Poor compressor setup	13
	Environmental danger	6
	Absent decompression planning	3
	Unsupervised solo diving	2
	Unsecured dive platform	2
	Other	2
Health		15 (18%)
	Significant medical history	13
	Alcohol and drug intake	2
Training/experience/skills		13 (15%)
	Scuba trained, novice SSBA	6
	Inexperience-related anxiety/panic	4
	Untrained – no understanding of decompression tables	2
	Untrained, no experience	1
Supervision		14 (17%)
	Compressor oversight failure	8
	Inexperienced working diver	3
	Hose endangerment	3
Activity		9 (11%)
	Seafood collection	6
	Deep commercial dives	3
Organisational		8 (9%)
	Lack of appropriate procedures or equipment	4
	Poor equipment maintenance	4
Poor communication/ co-ordination		3 (4%)
	Failure to communicate site dangers	3

to act promptly on compressor failure and consequent loss of air supply. Another two cases of loss of supply involved the diver's hose being cut by the propeller or entangled around the stern. Both problems were not noticed by the lookouts until too late. There were two incidents involving poor oversight of inexperienced divers in commercial operations, one where a surface tender failed to confirm that the propellor was disengaged when a diver entered the water nearby, and another where a commercial operator failed to have an effective rescue plan, which lead to a delayed, and ultimately unsuccessful, rescue.

Activity

Six of these incidents involved divers who were collecting or harvesting sea life in areas likely to be frequented by large sharks due to whale and seal activity. Two involved deep commercial dives on an oil rig, and one incident occurred during a deep commercial dive in a cold dam with zero visibility and snagging hazards.

Organisational

Poor or absent protocols or procedures for managing commercial diving activities contributed to four incidents. These included inadequate induction procedures and oversight of new divers in commercial operations (seafood/pearling). Poor organisational equipment maintenance protocols contributed to four deaths, and a lack of appropriate diver rescue procedures to another. A further death would have been prevented by the fitting of a propeller guard on a diving work barge.

Table 4
Triggers identified in 63 of 84 SSBA fatalities. Some deaths involved multiple triggers

Trigger	Subgroup	*n*
Equipment		20 (24%)
	Compressor problem	9
	Hose disconnection	4
	Air hose entanglement	3
	Separation of unsecured mouthpiece	3
	Loss of fin	1
Environmental		20 (24%)
	Marine creature	7
	Entrapment	4
	Immersion effects	3
	Conditions	3
	Boat	3
Gas		14 (17%)
	Contamination	10
	Interrupted/reduced supply	3
	Incorrect gas	1
Exertion associated with…		8 (10%)
	Pre-existing ischaemic heart disease	6
	Epilepsy	1
	Severe asthma and overweighting	1
Diver error		4 (5%)
Anxiety		1 (1%)

Communication

Failure to communicate to the divers the presence and potential site-associated dangers of fast-flowing dam or pipeline waters was instrumental in three deaths.

TRIGGERS

No triggers were identified in 21 incidents due to lack of sufficient information. Sixty-seven possible or likely triggers were identified in the 63 remaining incidents, the main ones related to equipment and environmental factors (Table 4).

Equipment

The main equipment-related triggers arose from problems with compressors, including overheating, valve failures, a blown gasket and the falling over of a poorly secured compressor. Other problems were hose separation due to poor connectors and hose entanglement with work equipment or platforms. Mouthpiece separation from the demand valve due to the absence of securing ties featured in three incidents. All of these affected the supply of breathing gas to the diver.

Environmental

Seven of the fatal incidents were triggered by the presence of dangerous marine creatures, six of these large sharks and the other a crocodile. Another two events were triggered by moving boats, one of which was the diver's working platform. The other diver was hit by a passing speedboat, despite the display of a 'Diver Below' flag. The incidents involving entrapment included three divers entangled in kelp, and one was trapped when his BCD strap was sucked into a hull scrubber. Three incidents involved adverse water conditions, including current and high water flows. Three deaths in divers with pre-existing IHD are thought to have been triggered by the circulatory effects of immersion.

Gas supply

Gas supply-related triggers were largely due to contamination of the air supply due to poorly maintained, functioning, or positioned compressors. One of the incidents triggered by interruption or reduction of the gas supply was due to a kinked hose. Another occurred when the (inexperienced) diver's air supply was interrupted while surface cylinders were changed, and he failed to transfer to his bail-out bottle. Another occurred when the surface team mistakenly changed the supply from an air cylinder to an oxygen cylinder.

Exertion

Exertion unrelated to sea conditions, was implicated as a trigger in nine incidents. Most of these involved performing heavy work underwater. Six of the victims had significant IHD, one a history of seizures, and a severe asthmatic was very over-weighted and working in adverse conditions.

Figure 2
Disabling agents associated with 72 of 84 SSBA fatalities. PBT/CAGE – pulmonary barotrauma/arterial gas embolism; IHD – ischaemic heart disease; DCS – decompression sickness; SAH – subarachnoid haemorrhage

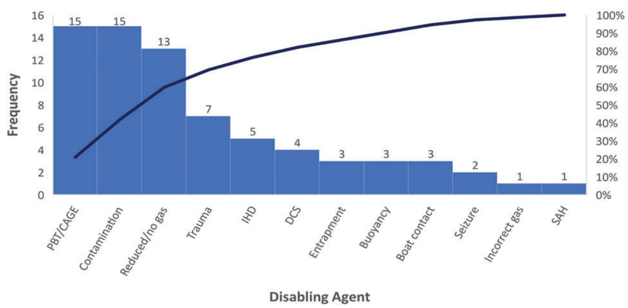
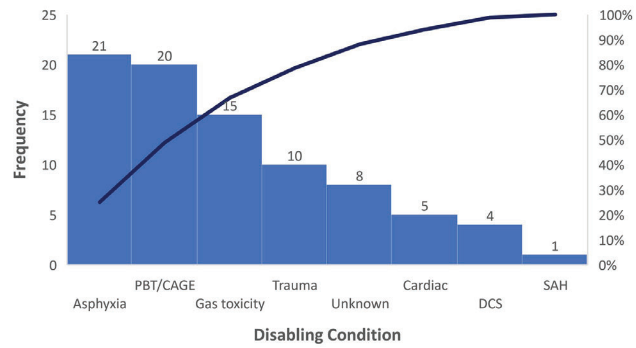


Figure 3
Disabling conditions associated with 84 SSBA fatalities. PBT/CAGE – pulmonary barotrauma/arterial gas embolism; DCS – decompression sickness; SAH – subarachnoid haemorrhage



Primary diver error

Three cases involved failure to adequately plan and follow any decompression guidance and all resulted in fatal DCS. The other involved the diver failing to disengage his boat's engine before entering the water.

Anxiety

Although anxiety and consequent panic are often associated with diving incidents, there was only one case where it was specifically mentioned in the reports. This very inexperienced diver aborted an earlier dive due to anxiety and, after calming down somewhat, attempted another dive where he was seen to suddenly ascend rapidly to the surface. When checked, the equipment was found to be working correctly.

DISABLING AGENTS

Likely disabling agents (DA) were identified in 72 of the incidents. These were related to the gas supply (28), ascent (19), medical conditions (9), environmental circumstances (13), and buoyancy (3). No DAs were identified in 12 cases due to insufficient information (Figure 2).

DISABLING CONDITION

The predominant disabling conditions were asphyxia, CAGE with or without evidence of PBT, and gas toxicities (Figure 3). Of note, the victims with cardiac disabling conditions were considerably older (median 43 y).

Discussion

SSBA diving-related fatalities have reduced over time with a current frequency of around one per year. The victims were predominantly relatively young, healthy males who were experienced SSBA divers. One half of the victims were diving for work and more than one third for recreation, often harvesting seafood. Equipment faults and poor planning predisposed to many of the fatal incidents.

DEMOGRAPHICS

Although the age of SSBA victims increased over the study period, with the median age increasing to 36 years beyond the year 2000, these victims were considerably younger than those of scuba (median 45 y) and snorkelling (median 51 y) victims post-2000.[10,11] Of interest, certification records from the Australian Diver Accreditation Scheme (ADAS), the certification agency for occupational divers in Australia since 2003, show a median age of 45 years for currently certified ('active') SSBA divers. (A Sordes, personal communication, 15 July 2020). This may indicate that the younger cohort of SSBA divers are more at risk of an accident. ADAS records also reveal that 99% percent of certificants are male, consistent with the proportion of male victims.

EQUIPMENT PROBLEMS

Equipment-related issues were the major contributor to these fatalities. Absence of, or faulty equipment predisposed to one third of the deaths. Equipment problems were also identified as the triggers in one-quarter of cases. The main source of problems were compressors which were often poorly maintained, poorly positioned, or inappropriately configured. This led to interruption of the breathing gas supply or breathing gas contamination by carbon monoxide (CO), among other contaminants. Adequate separation of the engine exhaust from the compressor air intake is important to reduce the risk of contamination.[12]

The compressor must be placed in a secure and well-ventilated position to prevent overheating or toppling. Although electric compressors are available, most of the SSBA compressors are driven by a petrol or diesel motor, so it is essential that exhaust fumes are prevented from entering the air intake, which should be positioned in an elevated position upwind of the compressor. The compressor and intake should be constantly observed throughout use for correct function and the effect of any wind changes. Appropriate filters to remove dust, water and odour must be fitted and replaced when needed. Additional sensors/converters to detect or remove contaminants such as CO can be fitted but are relatively uncommon. Correct lubricants must be used to ensure smooth operation and avoid gas contamination from lubricant breakdown. Regular checking and maintenance are essential to maximise the likelihood of smooth and safe operation. It is also important to ensure, in advance, that a compressor can provide a steady and plentiful supply of air to the number of divers who will use it, at the target depth, and their likely level of exertion.

It is also important to use and maintain appropriate non-kink hoses and secure fasteners for hoses and demand valve mouthpieces. The demand valve should be adequately secured so it is not inadvertently pulled from the diver's mouth. BCDs were seldom used but may have saved several lives had they been available and inflated, especially with victims who were over-weighted or had failed to ditch their weights when needed.

The number of victims who failed to ditch their weight belt is alarming and reflective of the high incidence in scuba diving victims.[10] However, with SSBA divers, it may also be associated with securing the belt and air hose together, a practice that should be discouraged. Some victims wore multiple weight belts, and several belts were not fitted with quick-release buckles. Both factors would have made it difficult to ditch weights when needed. The carrying of a bail-out bottle, rarely evident in this series, is a very important safety measure that needs to be strongly encouraged.

TRAINING, EXPERIENCE AND SKILLS

Inadequate training, experience and skills were identified as contributors to at least 16% of the deaths. Traditionally, if SSBA divers had any formal training, they were either trained as commercial divers to work in the offshore industry or trained to use scuba. Less than half of the victims were known to have undergone any formal related training and, in many cases, the training was not sufficient to address the particular equipment and skills required to safely perform SSBA diving.

Over more recent times, a variety of courses have been available through the Australian Nationally Recognised Training System and taught by registered training organisations. These range from introductory programs offered by recreational scuba diver training agencies, to comprehensive commercial diving courses certified by ADAS. However, despite the increased availability of pertinent training, some divers still take untrained friends or workmates on SSBA dives, occasionally with serious consequences.[13] In addition, some training programmes need ongoing monitoring and improvement to better equip divers for the tasks they need to perform and problems they might encounter.[2]

Experience is valuable in reducing diving risks, but it can sometimes cause complacency. Many of the more than 60 percent of victims who were described as experienced, were not heedful enough of the risks associated with poor planning, equipment maintenance and configuration.

ORGANISATIONAL, PLANNING AND ACTIVITY RISK MANAGEMENT

The fact that half of the victims were undertaking work-related diving is a cause for concern and reflection on the need for safe working practices to be adopted, adhered to, and continually monitored. Many of the victims were self-employed and dived solo, often with an observer on the boat or another nearby platform. Good planning and vigilant surface supervision are essential for safe SSBA diving in such circumstances. Some industries, such as the Tasmanian abalone industry, have created codes of practice to try to improve standards and practices, although this is far from universal.

Poor organisational procedures and practices predisposed to several preventable deaths. Improved induction procedures and oversight of new divers, more rigorous maintenance protocols, and careful planning would have reduced the likelihood of problems in these occupational settings. Relevant Australian standards and regulations pertaining to occupational diving exist and workplace regulators have an important role to play in monitoring compliance.[14,15]

The incidents in the recreational setting were mainly associated with seafood harvesting by relatively inexperienced divers. They often involved the victim becoming overwhelmed by the environment or circumstances while distracted by the 'thrill of the chase'.

Some of the activities undertaken involved increased risk, such as working at substantial depths, near very fast-flowing water, and harvesting seafood in areas and at times where large sharks are likely to be present. Such activities require heightened planning and vigilance, and back-up in the event of a problem.

BUDDY/SUPERVISION CIRCUMSTANCES

As with scuba fatalities,[10] a high proportion of SSBA victims, in this case three-quarters, had either set out alone or had already separated from their buddy before the incident. Unlike many recreational scuba situations where the diver was solo or separated, there was often a surface observer present, theoretically increasing the opportunity for rescue. However, in many of these cases, the observer missed opportunities to prevent or reduce the severity of the incident by inadequate supervision of the compressor, air hoses or environmental hazards and failing to identify and act on a problem. Although working without visual contact is common in some occupational settings, the combination of communications with an in-water or a surface stand-by diver is invaluable in preventing or managing life-threatening incidents.

PRE-EXISTING MEDICAL CONDITIONS

Over the entire study period, health-related factors, predominantly undiagnosed IHD, contributed to one fifth of the incidents and were identified as disabling agents in more than ten percent. However, the increased involvement of health factors in later years is consistent with more recent reports for scuba diving and snorkelling victims where health issues were contributory to over 40% of deaths.[10,11] This increasing incidence likely reflects an older cohort of participants with the associated higher prevalence of medical conditions. In the recreational setting, all divers and prospective divers aged 45 years or more are advised to have a diving medical examination, irrespective if they have any known health conditions.[16] Among other things, such an examination would assess cardiovascular health and might prevent some cardiac-related diving deaths. In addition to immersion *per se*, diving involves a variety of other cardiac stressors, such as the exertion often associated with underwater work and seafood harvesting, whether recreational or occupational.

In Australia, occupational divers are supposed to have an initial, and subsequent annual, fitness-to-dive examination by a doctor with relevant training.[15] ADAS requires evidence of this for certification and recertification. Such examinations are designed to determine potentially problematic health conditions so that they can be addressed to reduce perceived associated risk. However, recreational SSBA divers are not subject to this requirement, and not all occupational operators comply or monitor compliance, especially in small owner-operator businesses where certification may not be sought.

DISABLING CONDITIONS

When comparing the disabling conditions in these SSBA deaths to those in a cohort of scuba deaths in Australia[17], several differences become apparent. These include lower proportions of deaths from primary asphyxia (25% vs. 37%) and cardiac factors (6% vs. 25%), and higher proportions from PBT/CAGE (24% vs. 15%) and gas toxicity (18% vs. 0%).

The lower prevalence of cardiac-related deaths likely reflects the comparatively younger age of the SSBA cohort and, in some cases possibly a higher level of fitness and the requirement for regular dive medicals or monitoring in the occupational sector. The greater prevalence of PBT/CAGE is very likely a direct consequence of the higher incidence of problems with cessation or reduction in breathing gas, a relatively common occurrence in this series. Severe gas contamination is, fortunately, a relatively uncommon occurrence in the scuba arena due to more rigorous protocols around the filling of scuba cylinders, especially in a commercial recreational setting. However, as evidenced in this report, it remains a serious concern with SSBA. Finally, the lower proportion of deaths from primary asphyxia is likely a direct result of the other higher attributions. There were additional cases where drowning was determined to be the cause of death, but this was secondary to unconsciousness from CO toxicity or PBT/CAGE.

LIMITATIONS

As with any uncontrolled case series, the collection and analysis of fatality data are subject to inevitable limitations and uncertainties associated with the incident investigations. Many incidents were not directly witnessed, so assertions in the reports are sometimes speculative. Important information was not available in some cases, especially in the earlier reporting years, which rendered COE data incomplete, thus limiting the conclusions that can be drawn. Even with the use of a template, classification of cases into a sequence of five events in the COE is imperfect and remains vulnerable to some subjectivity. The chain of successive events is a simplified representation of incidents that may be the result of parallel events and more factors than fit into the five categories used. Therefore, misclassification of factors into such categories is possible. However, this should not prevent identification of modifiable factors in what were, ultimately fatal events.

Conclusions

SSBA diving-related fatalities have reduced over time. This is likely because of improvements in education, training, equipment, and regulation, predominantly in the occupational sector. However, the recreational sector remains problematic with little or no oversight of who can use such equipment, and generally poor education and training in its use.

Preventable fatalities still occur in both sectors, often because of poor equipment maintenance and oversight. Incorrect configuration of the SSBA unit and lack of training remain on-going problems in recreational users, and could be addressed by improved education, and, failing this, regulatory oversight.

The increase in health-related incidents in older participants may be controlled to some extent by greater medical oversight, especially in recreational and non-certified occupational divers who should be encouraged to undergo regular diving medical assessments. Commercial organisations should periodically assess their protocols and practices to identify and address potential shortcomings regarding safety.

References

1 Smart D, McCartney P. High risk diving – Tasmania's Aquaculture Industry. SPUMS Journal. 1990;20:159–65.
2 Lippmann J, Lawrence C, Fock A, Jamieson S. Provisional report on diving-related fatalities in Australian waters in 2012. Diving Hyperb Med. 2018;48:141–67. doi: 10.28920/dhm48.3.141-167. PMID:30199888. PMCID: PMC6205854.
3 Walker D, Lippmann J, Lawrence C, Fock A, Wodak T, Jamieson S. Provisional report on diving-related fatalities in Australian waters 2005. Diving Hyperb Med. 2010;40:131–49. PMID: 23111911.
4 Australasian Diving Safety Foundation. Diving-related fatality database and cumulative register. [cited 2020 July 15]. Available from: http://www.adsf.org.au (data available only to authorised internal researchers).
5 Walker D. Report on Australian diving deaths, 1972–1993. Melbourne: Submariner Publications; 1998.
6 Walker D. Report on Australian diving deaths, 1999–2002. Melbourne: Divers Alert Network Asia-Pacific; 2009.
7 Walker D. Report on Australian diving deaths, 1994–1998. Melbourne: Divers Alert Network S.E. Asia-Pacific; 2002.
8 National Coronial Information System (NCIS) [Internet]. Administered by the Victorian Department of Justice and Regulation. Available from: http://www.ncis.org.au. [cited 2020 June 02].
9 Lippmann J, Stevenson C, McD Taylor D, Williams J, Mohebbi M. Chain of events analysis for a scuba diving fatality. Diving Hyperb Med. 2017;47:144–54. doi: 10.28920/dhm47.3.144-154. PMID: 28868594. PMCID: PMC6159623.
10 Lippmann J, Stevenson C, McD Taylor D. Scuba diving fatalities in Australia, 2001 to 2013: Diver demographics and characteristics. Diving Hyperb Med. 2020;50:105–14. doi: 10.28920/dhm50.2.105–114. PMID: 32557411. PMCID: PMC7481108.
11 Lippmann J. Snorkelling and breath-hold diving fatalities in Australia, 2001 to 2013. Diving Hyperb Med. 2019;49:192–203. doi: 10.28920/dhm50.2.105-114. PMID: 31523794. PMCID: PMC6884103.
12 Chin W, Huchim O, Wegrzyn GH, Sprau SE, Salas S, Markovitz GH. CO and CO_2 analysis in the diving gas of the fishermen of the Yocatan Pensinsula. Undersea Hyperb Med. 2015;42:297–305. PMID: 26403015.
13 Walker D, Lippmann J. Provisional report on diving-related fatalities in Australian waters 2003. Diving Hyperb Med. 2009;39:4–19. PMID: 22753163.
14 Safe Work Australia. Model Work Health and Safety Regulations Dec 2019. Published by Parliamentary Counsel's Committee. [cited 2020 July 15]. Available from: https://www.safeworkaustralia.gov.au/system/files/documents/2003/model-whs-regulations-dec2020.pdf.
15 Standards Australia/Standards New Zealand. Occupational diving operations – Part 1. AS/NZS 2299.1: 2015. Sydney: SAI Global Limited; 2015.
16 Jepson N, Rienks R, Smart D, Bennett MH, Mitchell SJ, Turner M. South Pacific Underwater Medicine Society guidelines for cardiovascular risk assessment of divers. Diving Hyperb Med. 2020;50:273–7. doi: 10.28920/dhm50.3.273-277. PMID: 32957130. PMCID: PMC7819720.
17 Lippmann J, Taylor DMcD. Scuba diving fatalities in Australia, 2001 to 2013: Chain of events analysis. Diving Hyperb Med. 2020;50:220–9. doi: 10.28920/dhm50.3.220-229. PMID: 32957123. PMCID: PMC7819731.

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