The investigation of diving accidents and fatalities

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Abstract

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Diving accidents result from a variety of causes including human error, inadequate health and fitness, environmental hazards and equipment problems. They usually involve a cascade of events resulting in the diver being injured or deceased. The accuracy and usefulness of a diving accident investigation relies on well-targeted interviews, good field investigation, evidence collection and preservation, and appropriate equipment assessment. In the event of a fatality, a thorough and targeted autopsy is indicated. Investigators should have the appropriate knowledge, training, skills and support systems to perform the required tasks. Relevant investigations include the victim's medical and diving history, the dive circumstances and likely accident scenario, management of the accident including rescue and first aid, equipment inspection and testing and a thorough postmortem examination conducted by a forensic pathologist with an awareness of the special requirements of a diving autopsy and the knowledge to correctly interpret the findings. A chain of events analysis can determine the likely accident scenario, identify shortcomings and inform countermeasures.

Introduction

Diving is a popular recreation for many millions of people throughout the world who dive for recreation, exploration, seafood harvesting, photography and other reasons. The underwater world is also a workplace for a variety of occupational divers. No matter what the goal, diving is conducted in a potentially hostile environment and so involves various risks, although many of these may be mitigated in a healthy, experienced diver with an adequate and appropriate breathing gas supply and suitable, familiar, functional equipment.

Common contributors to a diving incident include human error, natural disease, underwater accidents, equipment problems or a combination of these. Safety can be influenced by a range of factors present before, during, and sometimes after the dive. Such factors may include health and fitness, organisation and planning, communication and supervision, equipment problems, decision making and various environmental factors.

In the earlier decades of recreational scuba diving, most participants were relatively young, training was less available, equipment generally less suitable and reliable and a higher proportion of deaths were due to primary drowning.[1] The age of recreational divers has increased[2,3] and with this there is a higher prevalence of co-existing disease.[4] Unsurprisingly, more recent fatality reports include an increased representation of older divers[5,6] with at least one quarter of the deaths being cardiac-related.[7,8]

Investigation of diving accidents

When an accident occurs, an investigation will commence and its effectiveness will be enhanced by good field investigation, including targeted witness interviews, evidence collection and preservation, appropriate equipment assessment, and, in the event of a fatality, a thorough and targeted autopsy.

It is advantageous to have a system in place to quickly activate various emergency services and expertise, such as diving medical advisors, diver evacuation specialists and dive search and rescue squads. This may be easier to establish in a locality where diving accidents are more common. With a fatality, such a system can ensure that the victim's body and equipment is secured with minimal inappropriate handling, witness interviews are timely, targeted and thorough, and that a postmortem computed tomography (CT) scan is performed with minimal delay. In a non-fatal accident, the system should facilitate more efficient and appropriate onsite management and transfer of the patient to suitable medical care.

DEPTH AND FOCUS

The depth and focus of an investigation may vary greatly depending on a variety of factors, including:

- The outcome of the accident – fatal or non-fatal;
- The nature of the accident – recreational or occupational;
- The location of the accident – in some countries or jurisdictions, dive accidents are investigated relatively thoroughly. In others, such as in many developing countries, only relatively scant investigations are usually done, if any.
- The interest and experience of the investigators – in some places, investigations are conducted by experienced police divers, dive equipment technicians and diving-savvy forensic pathologists/medical examiners. In others, it is only a rudimentary overview by local police with no understanding of diving or diving pathology.
- The reason for the investigations – in the event of a suspected homicide, police will take a special interest. If the accident occurred in an occupational setting, a workplace authority will often be involved. If the diver or dive company were insured, the insurer may be involved. In some cases, a private investigator may be commissioned by the family or insurer.

INVESTIGATION STAGES

The investigation itself will include a variety of stages. The inclusion and thoroughness of some of these may depend on the severity of the accident, the purpose of the investigation and the skill of the investigators. For example, if the desire is to allocate or negate culpability to a person or operation, there will likely be a greater focus on duty of care and responsibility of others involved, rather than simply an explanation of what occurred. If the aim is to understand and improve shortcomings in an operation, there will be a greater focus on organisational processes and procedures. The stages of the investigation may include:

Interviewing witnesses

Witnesses may include dive buddies, dive supervisor, dive operator, vessel crew, rescuers, first aiders and bystanders. Information may be sought about the roles and responsibilities, qualifications and experience of some of these parties and their relationship to the victim, as appropriate.

It is important to seek relevant information about the diver's training, certification and experience; health, fitness, state of mind and preparedness before the accident; as well as pertinent events leading up to the dive. Information should also be sought about the known or likely accident scenario, as well as details of the rescue or recovery and any first aid or resuscitation provided.

Rescuers or recovery divers should be questioned about where the diver was found, their posture, any entanglements, what equipment was in place or obviously missing, what equipment was inflated, deflated, or ditched by the rescuer during the process and the timings and complications. If there has been a considerable submersion time and survival is impossible, it is useful for the recovery divers to photograph or video the victim's body as found for later consideration. Information sought from first aiders should include the time frames involved, any equipment used, complications and outcomes. Such information can help to assess any shortcomings in preparation or procedures which need to be addressed and to inform improvement measures. The time from unconsciousness to rescue, commencement of resuscitation, attachment of a defibrillator and the potential oxygen concentration delivered is often not recorded, so the opportunity to assess the effectiveness of these measures is often lost.[9]

If the accident was non-fatal, the diver themselves may provide valuable information and insights into the sequence of events. In fatal accidents, witnesses may be able to provide information about the accident depth, what the victim was last seen doing, any apparent signs of distress and any obvious causes of the event. Gaining a thorough history of the victim and the accident will provide a solid basis for the entire investigation. However, many accidents are unwitnessed, especially fatalities, and the likely or possible scenario will need to be constructed based on any available information and varying degrees of speculation.

Site inspection

Site inspection should include a physical description of the site including the topography, hazards and other features, the forecast and prevailing weather and sea conditions (e.g., swell, chop, surge, current, visibility, water temperature, tide) at the time of the accident and their possible influence.

Equipment collection, inspection and testing

The victim's equipment should be collected, photographed and secured for inspection and testing by an appropriately qualified, independent technician. The 'Chain of Custody' of all equipment and other evidence must be fully and carefully documented to facilitate preservation of evidence and minimise the chance of loss or manipulation.

At the site, the contents of the breathing gas cylinder(s) should be recorded, and the pressure gauge photographed before the cylinder valve is turned off, with the number of turns, or part thereof, required recorded. The lines should not be purged so any leaks might be evident. The level of inflation of the buoyancy compensator device (BCD) should also be noted. All equipment needs to be clearly listed and a note made of any that is missing so that it is clear what the diver was wearing and what might have been ditched or become detached. The equipment then needs to be securely stored for thorough inspection and testing, which should be done as soon as possible as some components may deteriorate over time.

Inspection includes checking that the equipment had been assembled correctly, and carefully checking all components for faults, damage and wear and tear. The type, thickness and coverage of exposure suit should be recorded. Testing of regulators and demand valves involves assessing their function and breathing performance and comparing these to the manufacturers' specifications. Buoyancy control devices and drysuits should be checked for leaks and correct inflation and deflation performance. Pressure gauges and depth gauges should be checked for accuracy and dive data downloaded from the dive computer(s) for later analysis. Available weights should be recorded and whether it is likely that some are missing. If the technician is unfamiliar with a piece of the equipment (e.g., with a certain model of rebreather), they should enlist the help of an independent expert on that equipment.

If there is breathing gas remaining in the cylinder, it should be sent to an appropriate laboratory for testing and comparison to the relevant air purity standard. This will reveal the composition including the oxygen percentage and the presence of any contaminants.

Where practical, it can sometimes be informative to take the equipment on a re-enactment dive to check its in-water functioning under similar circumstances to those of the accident. This will sometimes flush out problems that had not been obvious during bench testing or confirm suspicions of problems.

Dive computer data download

The victim's dive computer can act as a 'silent witness' and may provide valuable information about the diver's profile and the nature and timings of certain events. It may show changes in depth, ascents and descents and the associated rates, decompression violations, cessation of movement. However, the profile needs to be interpreted carefully and knowledgably.

Although the depth and time elapsed measurements of various computers are generally accurate, this is not always the case so these should be checked, and deviations noted. Dates and times shown on the profiles depend on whether the computer was correctly set prior to the dive. Decompression data will be reliant on the computer decompression model and any prior personal adjustments made by the user. On some computers, ascent rate alarms can be particularly sensitive, and a violation recorded with a very small and insignificant depth change. Water temperature and air consumption estimations vary between computers, some being more accurate than others.[10]

Computers vary in how they display the depths during the sampling intervals on the downloaded profile. Some models display the average depth during the interval, others the maximum depth and both can introduce inaccuracies, especially with longer sampling intervals. The shorter this interval, the closer the profile will match reality. For example, if the profile displays the maximum depth reached during each sampling interval and, if the interval is wide, significant changes in depth between the surface and the maximum depth will not be shown. This can mean, for example, that an ascent to or near the surface within an interval may be missed. On occasions, such as a with a profile shown with a single descent and a single recovery ascent of a deceased diver, this can confuse the interpretation of the relationship between the downloaded profile and the presence of arterial gas embolism.

Medical history

Family members may provide some insights into the victim's medical history, but consultation with the victim's primary care physician and/or diving medical examiner may yield important information about their health, medications, medical investigations and treatment. If the deceased diver was diving with a buddy or in a group, other divers may be aware of any pre-dive health complaints and possible use of over-the counter medications for seasickness or acute respiratory illness. There also may be a history of alcohol or drug use the evening before the dive. This information should be shared with the forensic pathologist as it may supplement autopsy findings and help to understand the accident scenario.

Diving history

The victim's diving history, including qualifications, period of diving, range of diving experience and the number and nature of dives completed can provide important insights. The diver's logbook or dive computer downloads assist this, including whether there had been a significant period of inactivity prior to the accident. A regular buddy or dive operator may also be able to provide information. The dive computer may contain evidence of diving behavior such as habitual rapid ascents or the use or non-use of safety stops.

The postmortem examination

A complete forensic autopsy should be performed in all diving-related deaths, preferably by a forensic pathologist who possesses a knowledge of diving practices, diving physiology associated with breathing compressed gas underwater, and the correct interpretation of the autopsy findings in these challenging cases. The pathologist should be aware of some modifications in autopsy technique that can be employed to determine if a gas embolism may have occurred. If the pathologist is not familiar with diving procedures and pathophysiology, it is highly recommended that consultation be obtained, either from another pathologist or from a diving physician. There are some excellent resources which explain the requirements and techniques for a diving autopsy.[11–15]

As is the case for all medicolegal autopsies, the primary goal is to establish a cause of death. However, in diving-related deaths it is even more important to establish the sequence of events leading up to the fatal outcome. For the proper interpretation of the autopsy findings the pathologist performing the postmortem examination needs to be made aware of the dive profile, the results of the equipment evaluation, the deceased diver's medical history, and the circumstances surrounding the dive.

Depending on jurisdiction, the coroner, pathologist, or medicolegal death investigator may go to the scene. This is preferable, as it provides context for the autopsy and it allows for interaction between the coroner/medical examiner staff and law enforcement, coast guard personnel, and witnesses which may include other divers. If the diver had been transported to hospital, the investigation may include visits to both the primary and secondary scenes.

The postmortem interval, the time between death and the autopsy, should be minimised to the extent possible to limit artifacts. In some diving-related deaths, the body is not recovered for days or even weeks after the dive. Decomposition changes and postmortem animal predation present a challenge to the pathologist and the information provided by the postmortem examination may be limited.

Postmortem radiographic imaging should be obtained prior to the autopsy. If available, postmortem computer tomography (PMCT) is preferred (Figure 1). Full body PMCT is desirable, but imaging of at least the head and thorax should take place, at a minimum. The scan can indicate the possible signs of arterial gas embolism (AGE), as well as bullae, blebs, parenchymal hemorrhage, signs of drowning, immersion pulmonary edema, trauma, cardiac disease, and other natural disease processes.[16] Imaging should take place as soon as possible, even if the autopsy cannot be immediately performed. The longer the delay, the more likely the assessment of AGE will be complicated by gases from putrefaction and postmortem decompression artefact.

After postmortem imaging is completed, the autopsy should begin with a meticulous external examination. The body may be accompanied by the dive gear, and thermal protection, such as a wet suit or dry suit, may still be in place. All of this should be documented as should any evidence of trauma, including marine animal bites and stings. Findings such as subcutaneous emphysema, pedal oedema, or frothy fluid emanating from the nose and mouth are important to note. An examination of the tympanic membranes with an otoscope may reveal evidence of barotrauma. The goal of the external examination in forensic autopsies is to document how the body and environment interacted.

The internal examination should include not only documentation of any diving-related pathology such as intravascular and intracardiac gas, but also the presence of natural disease processes such as coronary artery atherosclerosis, cardiomegaly, and left ventricular hypertrophy. Potential intracardiac shunts, such as a patent foramen ovale or a ventricular septal defect, should be noted if present. Evidence of pulmonary issues that can result is air trapping, such as bullous emphysema or asthma, are also important to note.

A few modifications in autopsy technique are recommended, particularly if high-quality postmortem imaging is unavailable. One method for checking if a pneumothorax is present involves dissecting through the intercostal muscles on each side of the chest wall to see if the visceral and parietal pleurae are still adjacent (Figure 2). If the visceral pleura does not fall away from the parietal pleura as the chest cavity is breached, a pneumothorax is present.

A recommended technique for demonstrating the presence or absence of intracardiac gas involves opening the pericardial sac and filling it with water. The right and left ventricles of the heart can then be sequentially incised to determine if intracardiac gas is present (Figures 3, 4). Prior to opening the cranial cavity and removing the brain, tying off the carotid arteries may minimise the introduction of gas into the cerebral vasculature (Figure 5). More extensive techniques

Figure 1

Post-mortem computed tomography scan of a diver who died due to a gas embolism. Note the large amount of intravascular and intracardiac gas. (Courtesy of Michael Pickup, M.D., Provincial Forensic Pathology Unit, Toronto, Ontario)

Figure 2
The intercostal muscles can be dissected in layers to expose the lungs as a test for the presence of a pneumothorax

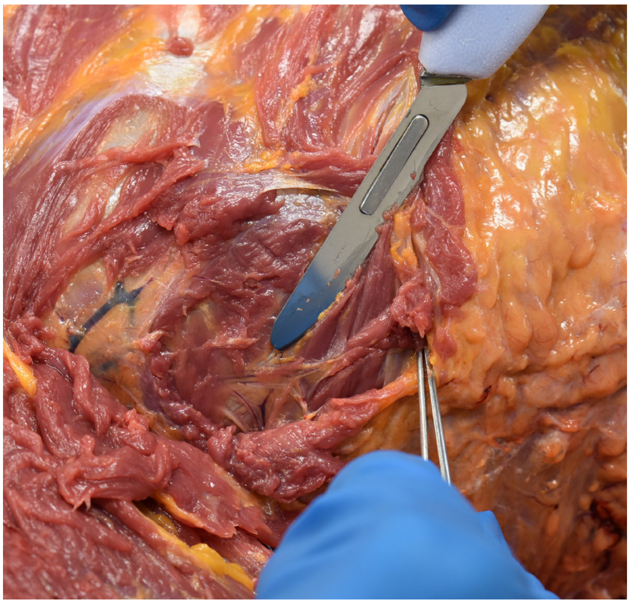


Figure 3
Filling the pericardial sac with water is one method that can be used to check for intracardiac gas in air embolism

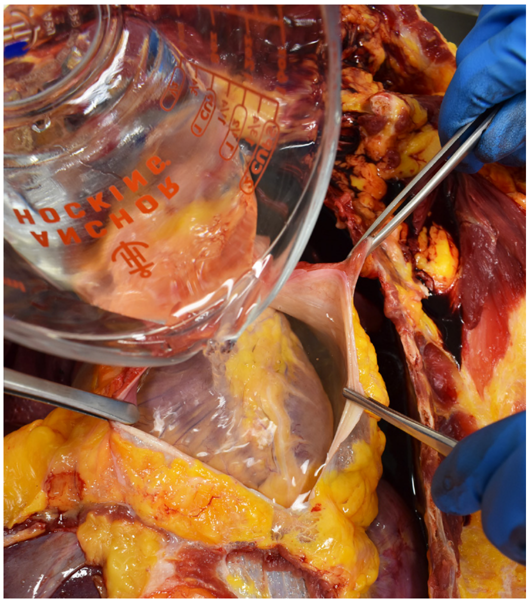


Figure 4
After the pericardial sac has been filled with water the right and left ventricles can be incised to see if any gas escapes

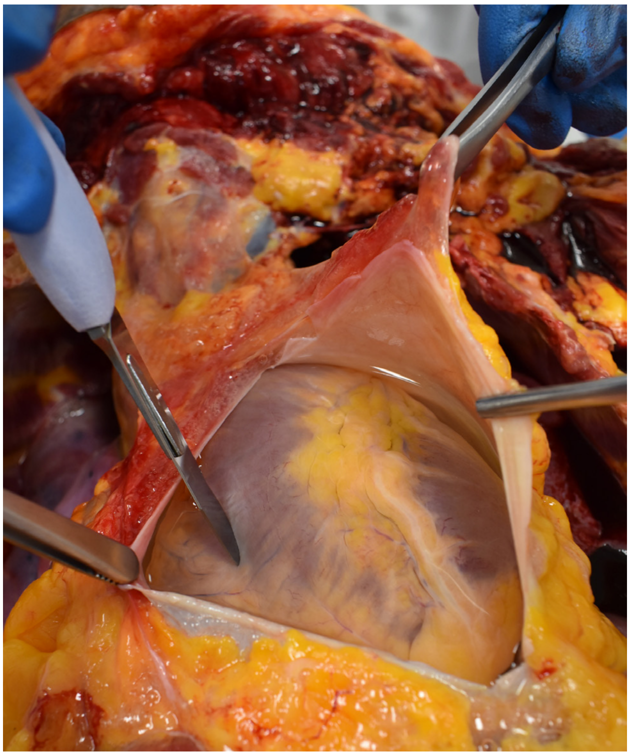
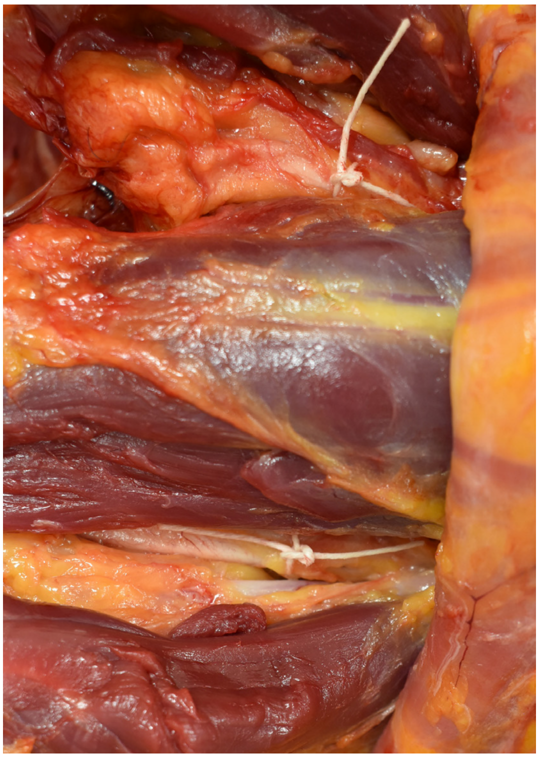


Figure 5
Tying off the carotid arteries prior to opening the head and checking cerebral arteries for intravascular gas can minimise artifact



to minimise postmortem artifact have been suggested.[17] Ancillary studies should include obtaining comprehensive postmortem toxicology looking for ethanol, typical drugs of abuse, and select prescription and over-the-counter medications that may have affected the diver's performance in the water. Testing for exposure to carbon monoxide to exclude a contaminated gas supply is also necessary. At the pathologist's discretion, histologic examination of the major organs, particularly the heart and lungs, may reveal evidence of significant natural disease processes.

Autopsy interpretation

The presence of pulmonary barotrauma in the form of pneumothorax or subpleural haemorrhage corroborates the occurrence of a gas embolism. Intravascular gas noted at autopsy is commonly misinterpreted by pathologists who are unfamiliar with diving pathophysiology. This diagnosis has been made even in the absence of an ascent, e.g., when a diver has been entrapped in a cave or shipwreck. Anyone who has breathed compressed gas at depth and then surfaces, either on their own or is brought up from depth during body recovery, may have intravascular bubbles at autopsy. Postmortem off-gassing is the process by which dissolved gas that accumulates in tissues during the dive comes out of solution after death. Some of this gas will be intravascular and can mislead the pathologist to conclude that a gas embolism has occurred. Postmortem bubbles and gas accumulation in the left side of the heart and within the arteries at the base of the brain and on the epicardial surfaces are more indicative of a gas embolism having occurred. Bubbles in the inferior vena cava and right side of the heart may simply represent postmortem off-gassing.

If a patent foramen ovale or other potential intracardiac shunt is present, the possibility of paradoxical embolism may be considered. Venous bubbles can arterialise if right heart pressures transiently exceed left heart pressures, which may occur with strenuous lifting or performing the Valsalva manoeuvre. Deaths due to a paradoxical embolism are rare, but this would be a situation where gas embolism may be diagnosed without a rapid ascent or associated barotrauma.

The presence of middle ear, sinus or facial barotrauma may indicate an unconscious descent. The same is true for the presence of haemorrhage into the petrous portions of the temporal bones. In many cases the pathologist will correctly conclude that the cause of death is drowning. There is no definitive autopsy finding that allows the pathologist to make the determination that the diver drowned. However, the presence of congested and hyper-expanded lungs, dilation of the right ventricle of the heart and engorgement of the large central veins, frothy fluid in the large airways, fluid in the sphenoid sinus, watery fluid in the gastric contents are all consistent with drowning.[18]

The potential contribution of natural disease processes to a diving-related death cannot be overstated. Cardiovascular disease appears to be increasing in the diving population and therefore sudden cardiac death while diving or incapacitation from a cardiac dysrhythmia that results in drowning are increasingly common scenarios. In the absence of any definitive postmortem test to confirm whether an arrhythmia or dysrhythmia has occurred, a determination must be based on surrogate markers such as evidence of cardiac disease or abnormality at autopsy. A critical luminal narrowing is generally regarded as being greater than 70%. However, a cardiac event may be triggered simply by cardiomegaly and left ventricular hypertrophy, which are often present in divers who have hypertension. Atherosclerotic cardiovascular disease and hypertensive cardiovascular disease are often seen together at autopsy.

Rarely, the dive history and symptom presentation will indicate that a diagnosis of fatal decompression sickness should be considered. These deaths will typically involve very deep dives with omitted decompression or simply uncontrolled rapid ascents to the surface from excessive depth. Cardiopulmonary decompression sickness, also known as 'the chokes', has a characteristic clinical presentation and may rapidly progress to death. This presentation is more common in cases of altitude decompression sickness but also occurs in divers. Frothy blood in the pulmonary vasculature may be present at autopsy. Severe neurological symptoms from decompression sickness are generally more insidious in presentation and, when fatal, the diver has often received multiple treatments with hyperbaric oxygen during hospitalisation. On rare occasions, death will occur prior to recompression. There may be nothing specific in the autopsy findings and death is often due to a complication such as sepsis, pulmonary embolism or multiple organ failure. The pathologist should be provided all related treatment records and antemortem imaging studies. As with all diving-related deaths, proper interpretation of the dive profile is essential. For these cases, it is highly recommended to have the brain and spinal cord examined by a neuropathologist after fixation in formalin.

By utilising postmortem imaging and employing a few modifications in autopsy technique, the pathologist can correctly interpret the autopsy findings. However, it should also be appreciated that a diver may sustain a gas embolism and not have obvious evidence of intravascular gas or pulmonary barotrauma at autopsy. It follows that the circumstances surrounding the death, particularly the dive profile, are even more important than the results of a postmortem examination. That is why it is imperative that the forensic pathologist has at least a functional understanding of diving medicine and that they also be made fully aware of the diver's medical history and the circumstances surrounding the dive, particularly the dive profile.

Analysis of a diving fatality

Identification of various contributory factors is hampered by the reality that most diving fatality reports are relatively sparse on detail. However, a diving fatality usually involves a series of related events culminating in death. A triggering event leads to a cascade of related events, some precipitated by the diver and some circumstantial. Preceding the trigger may be factors which predisposed to such an event.

An increasing number of studies of diver fatalities have utilised a chain of events analysis (CEA) to depict the suspected sequence of events within the accident. The concept was first applied to USA diving accidents[8] and later, with various modifications, to Australian fatalities,[19,20] and elsewhere[21] and recently to non-fatal diving incidents.[22] The earlier CEAs divided the accident sequence into four components: a trigger, disabling agent, disabling injury and cause of death.[8] Later, a category of predisposing factors was added to the CEA to account for various factors present before the dive that might influence events.[23]

The major categories for the chain of events analysis are:

- Predisposing factors – A relevant factor(s) that was present prior to the dive, and/or prior to the trigger occurring and which is believed to have predisposed to the accident and/or to key components in the accident chain.
- Trigger – The earliest identifiable event that appeared to transform what would have been an unremarkable dive into an emergency.
- Disabling agent – Actions or circumstances associated with the trigger that caused injury or illness.
- Disabling condition (previously called disabling injury) – The condition that was directly responsible for death or for incapacitation followed by death from drowning.
- Cause of death (COD) – As reported by the medical examiner.
- The COD is no longer included in some CEA reports as it is often not as informative as the disabling condition. The COD of many divers is recorded as drowning. However, the drowning is often secondary to a disabling condition such as cardiac arrhythmia or CAGE, and, from the analysis and preventative perspective it is more valuable to determine the likely disabling condition. Additionally, the disabling agent often adds little to an analysis so is sometimes omitted.

In the absence of definitive criteria, there is a potential for subjectivity in the categorisation of events, and classifications can vary substantively from case to case and between investigators. To minimise subjectivity and increase consistency between investigators, a set of templates with various subcategories was created to provide some guidance when analysing a diving fatality. These are explained in detail elsewhere[23] and summarised in Figure 6.

Figure 6
Flowchart of the chain of events analysis for a diving accident

Predisposing factors

health; organisational; training/experience/skills; planning; communication; equipment; activity; supervision; other; unknown

↓

Triggers

environmental; equipment; gas supply; buoyancy; exertion; anxiety/stress; diver error; other; unknown

↓

Disabling agents

gas supply; ascent; medical; buoyancy; environmental; equipment; other; unknown

↓

Disabling conditions

asphyxia; cerebral arterial gas embolism; cardiac; trauma; other medical; other; unknown

↓

Cause of death

as determined by a medical examiner

An example of a fatality scenario and CEA is as follows. A diver with a faulty pressure gauge runs out of air, makes a rapid ascent to the surface, sustains a CAGE, loses consciousness in the water and drowns. In this incident, a predisposing factor was the faulty gauge, the trigger was exhaustion of air supply, the disabling agent was the rapid ascent, the disabling condition CAGE and the COD drowning.

Conclusions

The investigation of dive accidents and fatalities requires a systematic approach based on sound principles and guidelines. The stages include witness interviews, field investigation, evidence collection and preservation, equipment assessment and a thorough and targeted autopsy in the event of a fatality. It is best done by investigators with a thorough familiarity with diving and the investigation processes. Specific expert assistance should be utilised where necessary.

Dive fatality research and reporting is valuable for learning from the misfortunes of the victims. More consistent reporting will help to better identify contributors to diving accidents and so enable the creation or reinforcement of appropriate countermeasures to help mitigate future deaths.

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