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Risk Management: A Diver's Perspective

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Abstract

Any activity one wishes to pursue will have a certain degree of risk. It is up to the person performing the activity to correctly identify and quantify the extent of such risk, and to define if possible, a mitigation strategy aiding in the decision of whether or not one is willing to accept the residual risk. Diving is a potentially dangerous activity. Proper risk assessment and management is therefore mandatory, especially for the more complex operations such as those required for scientific diving. Risk Assessment Matrixes (RAM) are based on the identification of hazards, the probability of their occurrence, the gravity of their consequences and the level of the resulting risk. Such procedures have been developed in a variety of operational situations including aerospace, industry, military and commercial diving. Human and Organizational Factors (HOF) are involved in the vast majority of diving accidents. Maintaining good Situational Awareness (SA) is a key factor for the safety and proficiency of divers. The use of checklists should be enforced as they will greatly reduce the occurrence of human errors. The risk of diving equipment failure can be reduced by proper maintenance and correct use. A diving-related accident is seldom the result of a single mistake. More often accidents result from a chain of events that may begin with a relatively minor problem that escalates to an uncontrollable situation. Defining consistent diving and contingency plans is the cornerstone of risk management.

Keywords: checklist, contingency procedures, diving plan, human error

Introduction

Any activity one wishes to pursue will have a certain degree of risk; it is up to the person performing the activity to correctly identify and quantify the extent of such risk, to define a mitigation strategy, to determine if it is safe, and to decide if one is willing to accept the residual risk or not. "Safe" is not the equivalent of "risk-free" as ruled by the US Supreme Court in 1972 (Craig, 2001) and this should be clearly understood before attempting any operation. With good planning and assessment, it is possible to reach a high degree of risk control but it will never be possible to completely eliminate risk in complex procedures performed within challenging environments (Gernhardt, 2004; Reason, 2006). Diving is a potentially dangerous activity that exposes participants to the risk of serious injuries or death. Proper training, adequate experience, knowledge of methods and procedures, and both psychological and physiological fitness are mandatory before attempting any diving operations. The complexity of the diving activity should be within the participants' physical, psychological and technical limits. The following is an outline of risk management for scientific diving activities and it is aimed at identifying the most common areas of potential hazards, the degree of their impact on the divers and possible mitigation strategies.

Risk assessment

Risk is defined as the product of the probability of an unwanted event (hazard) and the severity of the consequences of such an event (HSA, 2006).

Risk = P_h* C

P_h= probability of the hazard
C = Severity of the consequences

The severity of a given hazard depends on the gravity of the resulting accident in terms of injuries and damage to people and materials. The probability level of a given hazard indicates how likely it is for such an event to occur during the considered timeframe. Assessing risk requires a decision-making process to identify and quantify significant risks and to develop a mitigation strategy or a rationale of accepting such risks (Philipson and Buchbinder, 1997).

This process will follow a series of logical and consequential steps (Harrison, 1997):

- Identify significant hazards that can affect the operation
- Define what can be affected (e.g. diver injury, equipment damage, data loss)
- Assess probability of each hazard occurring within the operational timeframe
- Assess the resulting risk by providing a score (e.g. high, medium, low)
- Control the risk (elimination, mitigation or acceptance)
- Define contingency plans and ensure emergency procedures
- Identify management responsibility (dive leader, DSO, chief scientist, etc.)
- Monitor and review (maintain an updated risk assessment plan)

Once these points have been correctly assessed, it will be possible to develop a consistent and reliable risk-management procedure.

Risk Assessment Matrix (RAM)
From the combination of risk severity and probability, it is possible to build a Risk Assessment Matrix (RAM; Table1). Once the risk level has been assessed, adequate mitigation strategies should be applied to eliminate, reduce or control the risk. If no adequate mitigation procedure is possible, such as for events falling within the high risk zone of the RAM, it could be necessary to decide not to proceed further with the project in order to not expose the participants to unacceptable dangers (ECU, 2016).

Table 1. Risk Assessment Matrix

Probability	**Severity**			
	Catastrophic	**Critical**	**Marginal**	**Negligible**
Frequent	High	High	Serious	Medium
Probable	High	High	Serious	Medium
Occasional	High	Serious	Medium	Low
Remote	Serious	Medium	Medium	Low
Improbable	Medium	Medium	Medium	Low

Accident vs. Incident
Incidents and accidents are both unexpected negative events but they have clearly different outcomes as defined by the US Navy Diving Manual, 2008.

Accident: an unexpected event, which culminates in loss of, or serious damage to equipment or injury to personnel.

Incident: an unexpected event that degrades safety and increases the probability of an accident.

It is possible to identify three components in the events leading to an accident/incident:

- Direct cause: faulty actions or lack of appropriate actions immediately preceding the error.
- Contributing cause: the root of the direct cause.
- Compounding events: positive ones can help to mitigate the error; negative ones can exacerbate it.

In many diving accidents the contributing cause is multiple errors and/or negative attitudes, which start well before the diver enters the water (Blumenberg, 1996).

Qualitative hazard analysis
A qualitative hazard analysis aims to identify all the significant hazards and that the level of risk for each is "As Low as Reasonably Practicable" (ALARP) as defined in Lamb and Rudgley, 1997. The US Navy defined a Risk Assessment Code – RAC (Table 2) as a matrix of the severity of hazards and their probability to occur based on the RAM model (Liberatore, 1998).

Table 2. Risk Assessment Code matrix

<table>
<tr><td colspan="2" rowspan="2">A: likely to occur
B: probably will occur or expected to occur several times
C: may occur or can be reasonably expected to occur
D: unlikely to occur</td><td colspan="4">Probability</td></tr>
<tr><td>A</td><td>B</td><td>C</td><td>D</td></tr>
<tr><td rowspan="4">Hazard severity

1: Critical
2: Serious
3: Moderate
4: Minor
5: Negligible</td><td>Diver fatality</td><td>1</td><td>1</td><td>2</td><td>3</td></tr>
<tr><td>Severe injury</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td>Minor injury</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>Very minor injury</td><td>3</td><td>4</td><td>5</td><td>5</td></tr>
</table>

Of the sixteen combinations of severity and probability, only three are considered negligible; this highlights that mishaps can very likely lead to serious injury to the divers during diving operations.

Comply with standards
In this approach, the risk level is determined by providing a numerical value that considers if the procedure being analyzed meets a defined standard. There are 7 levels of risk with level 1 being the lowest. Any procedure falling within levels 6 and 7 indicates a failure in meeting the standards and should therefore be reviewed and modified (Bea, 1996). In scientific diving, respecting standards is a key factor for the divers' safety and for the reliability of collected data. Any new procedures should be evaluated on its compatibility with the accepted standards before being adopted. Such standards should also be periodically reviewed and updated so to be consistent with the best practice available.

Human and Organizational Factors (HOF)

Many studies show that failures in Human and Organizational Factors (HOF) are the cause of about 80% of offshore and marine accidents including diving activities (Liberatore, 1998). The probability of human error is linked to several factors including low familiarity with the task to be performed, its complexity, time-pressure, and distractions (Swain and Guttman, 1983). Unfamiliarity with the task and time-pressure are the most important factors (Dougherty and Frangola, 1986). These factors can be managed through appropriate training and good planning to ensure that the divers have appropriate experience and skills for the procedures to be performed and that they are not overloaded with too many goals to achieve.

HOF failure

HOF failure can be reduced by quality control and quality assurance provided by the dive buddy, standby diver and surface control team. Evaluating HOF in a complex diving environment can be challenging due to the wide range of variables involved including visibility, current, temperature, marine hazards and the physical and physiological condition of the divers. HOF checklists have been developed to assess the performance of the different aspects of diving operations using a score system from 1.0 (poor) to 4.0 (outstanding). For example, the US Navy uses a safety and planning checklist that addresses the following points (Liberatore, 1998).

- Identify mission objective and associated tasks
- General planning
- Collect, organize and analyze information related to the mission
- Identify environmental hazards
- Identify operational hazards
- Risk assessment and management
- Select diving technique
- Identify appropriate equipment
- Select and assemble the diving team
- Organize and schedule operations
- Dive team briefing

Skills acquisition

Skills acquisition follows a five-stage model:

- Novice: the student will merely follow rules without a proper understanding of the background concepts. This is the case of a diver at the very first stage of training.
- Advanced beginner: with an increase in experience, the diver will develop an understanding of relevant concepts such as air management and dive planning.
- Competence: the number of potentially relevant procedures recognized by the student becomes overwhelming and the diver will need to develop a plan to identify the relevant elements from the secondary ones. Pressure for potential failure is felt but emotional involvement and acknowledgement of both mistakes and achievements is the only way to learn beyond the mere application of rules.
- Proficiency: the theory of the skills is progressively replaced by situational discrimination. The diver is able to clearly identify the main points and the important aspects of the situation but does not yet have enough experience to react automatically.
- Expertise: this is the last stage of skills acquisition; the experience gained in a variety of situations allows the diver to have an immediate intuitive situational response.

In this model, divers develop their skills growing from novices to experts, with the decision-making process shifting from analytic to intuitive (Dreyfus, 2004). An intuitive response is what is needed to quickly address problems that can develop in complex diving environments when a diver is engaged in performing multiple tasks such as those required in scientific diving. Good skills are composed of a series of consecutive steps in its execution that need to be properly acquired during the training sessions. More complex procedures can be mentally divided into simpler component parts. Since skills acquisition is "state dependent", the knowledge gained under specific environmental conditions can be impaired in more challenging situations and this should be considered during the training phase. Skills not routinely used, such as emergency procedures, should be periodically reviewed and reinforced. Under stress and when a quick response is mandatory, over-learning allows the divers to react automatically to the situation. The rapidity of the events is the most challenging factor, and through over-learning, reacting in an efficient and timely manner is more likely to happen. A well-skilled diver will be a more confident diver who is able to cope with unexpected situations if an emergency arises (Bachrach and Egstrom, 1987). A gap between the feeling of overconfidence on the proper skills and the actual mastering of such techniques can be dangerous; this is demonstrated by an analysis of flying accidents where pilots with 100 to 299 hours of experience are those most involved in mishaps, likely due to it representing a transition phase from being a flying student, controlled by experienced instructors, to becoming an experienced pilot (Craig, 2001).

Decision-making

As in skills acquisition, the procedures involved in decision-making can be divided into categories:

- Analytical: this is the most complete approach to decision-making. All of the different options are logically and critically analyzed until the best one is identified. It is time-consuming and it is not realistically feasible under high stress and time pressure.
- Rule-based: the problems are solved following a series of rules and procedures that do not require much critical effort. The limit of this approach is that if the chosen rules/procedures are not the correct ones for the problem being analyzed, the entire decision-making process is faulty.
- Recognition-primed: this is a typical expert reaction built on the experience in similar situations. Confirmation bias can affect the process with the operator focusing on evidence supporting the chosen model only.

Clearly a correct decision-making strategy is crucial in diving-related operations where incorrect decisions could lead to potentially fatal consequences. Due to the time pressure and likely stressful condition of a diving emergency, recognition-primed is the only reaction that can guarantee a good level of survival (O'Connor, 2005). When confronted with a problem, an individual will likely rely first on rule-based procedures before attempting more complex analytical approaches (Reason, 1990); it is therefore mandatory that rules and standardized procedures are well understood and consistently applied.

The decision-making process is based on four phases:

- Scanning: acquisition of relevant information.
- Evaluation: analysis of the present situation compared with similar memories.
- Action: proper decision based on evaluation.
- Evaluation of consequences: the consequences of the action are stored in memory for future use.

This process can be interrupted in anxious divers who become stuck in a loop of the first two phases and become incapable of proceeding to further action (Bachrach and Egstrom, 1987). Having successfully avoided accidents, even when applying erroneous rules and procedures, they may develop a false sense of self-confidence that will lead to further application of the same bad decision-making behavior with a high probability of future errors (Reason, 1990). This is the case of divers who managed to escape accidents without realizing that the root cause was their own fault. These divers will not learn from the errors, failing in the correct evaluation of the consequence phase of the decision-making process.

Situational awareness (SA)
Situational awareness (SA) can be described as the ability of an individual to identify the relevant elements of the operative situation, understand their meaning and project the likely evolution of the current status. A decision will follow based on the processing of the acquired information, long-term memory of similar experiences and variable degree of automatic response. The process will then be reiterated following the dynamic evolution of the situation. Even if SA is focused mainly on the most relevant elements in function of the goals to be achieved, a certain degree of SA should be maintained on secondary aspects that could develop into new unexpected threats. Mental models are useful to enhance SA, providing knowledge of relevant elements and dynamics of the system, their integration within a meaningful framework and a consistent projection of the system evolution. In complex and fast-evolving environments, SA can be compromised by the stimuli and/or workload overwhelming the operator's attention capacity. Errors in SA can follow due to the incapacity of recognizing the relevant information, failing to understand the meaning of such information and incapacity to correctly project the evolution of the system (Endsley, 1995).

Diving accidents and fatalities are often linked to loss of SA resulting from a series of consequential small variances from assured safe procedures which are unnoticed by the divers or that are misunderstood therefore failing to trigger an appropriate response (Sadler, 2011). Divers are exposed to a high volume of information, and SA can be degraded by "attention tunneling" when a diver under high-stress becomes fixated on limited information losing contact with the wider figure of the evolving situation (Bachrach and Egstrom, 1987; Heywood. 2012). Failing to quickly recognize the first signs of a developing crisis will likely result in an accident; planning and preparation are needed to be able to manage unanticipated situations before they degenerate into problems (Blumenberg, 1996).

Human errors
There are three main factors in the generation of an error:

- Nature of the task and its environment: complex tasks in challenging environments are more likely to generate errors.
- Mechanics of the performance: elaborate operations can be affected by multiple errors.
- Nature of the performer: the individual attitude plays a major role in human errors.

Of those errors, slips and lapses occur when the action does not go as planned, and they are generally associated with monitoring failure when operating in familiar environments and/or performing routine tasks. Mistakes are due to faulty planning and are more difficult to be discovered and fixed before evolving into an accident (Reason, 1990).
Human errors can also be caused by prejudice when evaluating unexpected situations (Nevo and Breitstein, 1999):

- Availability bias: an individual confronted with multiple danger signals may focus on the most prominent only, ignoring other more latent, but not less dangerous, signals. For example, a diver who is too focused on navigational issues in bad visibility may lose awareness of breathing gas consumption.
- Suppression bias: new information not fitting conclusions already reached tends to be ignored. A diver who is confused and is swimming in the wrong direction may ignore the compass readings.
- Overconfidence bias: overconfidence in having identified the only correct solution thus disregarding any other option. This can typically affect more experienced divers.

In complex, dynamic environments such as diving, there is a tendency to follow the more general rules already successfully applied even if new circumstances suggest that different rules should be applied (Reason, 1990). This can lead to incidents and accidents. Another cause of error is when the operator is confronted with contrasting signals and it is not possible to easily discern the correct from the misleading ones. This was the case in some aviation disasters in which pilots received opposing indications about the aircraft speed from faulty systems; unable to identify the correct speed, they failed to apply the required procedures and this led the aircraft to crash (Thomson, 2013). In a diving environment, contrasting signals could be generated from faulty pressure gauges and diving computers or spatial disorientation in low visibility waters. Disorientation is one of the biggest hazards because it will create a high level of physical and psychological uneasiness likely leading to gross mistakes including loss of attitudinal control, similar to what happens to pilots flying in zero visibility without the support of adequate instrumentations (Craig, 2001). An accurate and comprehensive diving plan helps reduce the incidence of unexpected situations and subsequent confusion.

Risk assessment in diving operations

In order to apply risk assessment procedures to a diving environment, a thorough knowledge of its characteristics is needed including the most common divers' attitudes that lead to a diving accident, physical and mental conditions of the divers, equipment and configuration potential issues, accepted protocols and diving standards, and an analysis of diving fatality causes.

Factors affecting diving safety

Four factors have been identified as having the main impact on dive safety (Blumenberg, 1996):

- Environment: it is generally to be considered “hostile”. Environmental variables that are likely to affect divers safety should be carefully addressed.
- Equipment: should be treated as a “life-support system” and should be simple and robust. The divers should be fully proficient in its use.
- Diver performance: the diver should have proper training, knowledge and experience. Procedures that are too complex and/or ambiguous should be avoided.
- Team performance: the team should be able to proficiency perform as a whole. Redundancy and overlapping of skills and experience within the team is a key strategy for enhancing the team’s potential.

Attitude in diving incidents and accidents

A diver’s attitude is often the main cause of misjudgment that leads to an accident. A series of attitudinal errors leading to diving mishaps have been identified (Lewis, 2011; 2014):

- Ignorance of the risk: the diver may not have enough knowledge and awareness of the situation, so the risks will not be recognized as such, and therefore no mitigation procedures will be put in place.
- Peer pressure: the diver feels psychological pressure from other divers to dive even if he/she knows the conditions are unsafe and/or does not have enough skills or experience for that specific dive.
- Professional pressure: professional divers may feel the pressure of diving to fulfil their duties.
- Deviance from standards and procedures: divers may decide to deviate from assured standards and safe procedures, considering them an unnecessary burden.
- Complacency: overconfidence leads experienced divers to disregard good practice methods.
- Conflicts within the diving team: conflicts and confusion of roles may develop within a diving team when a clear status ranking is not determined. This will lead to leadership failure (no one is in charge) with potential bad decisions.

Another consideration about divers' attitude is when a group dynamic is present. In 1965, Zajonc developed a model showing that a group influences individual performance in two opposite ways:

- The group will improve performance of skills already learned with a positive feedback.
- The group will hamper performance of skills that are not yet completely acquired.

The latter situation can negatively influence the attitude of groups of beginner divers leading to potential incidents and accidents.

The chain of events

A diving accident is seldom originated by a single defined mistake; more often, it is the result of a consequential series of subsequent errors and problems that create a fatal chain of events. This chain of events may begin with a relatively minor issue, which if not recognized and corrected in time, will develop into more serious problems. Good situational awareness, excellent diving skills and consistent dive and contingency plans are therefore mandatory to quickly identify and solve potential problems before the situation escalates to an accident (Bachrach and Egstrom, 1987; Blumenberg, 1996; Lewis, 2011; 2014; Reason, 2006).

Human errors in diving incidents

Acott (2005) analyzed 1,000 diving incidents and accidents and classified the related human errors into five categories:

1. Knowledge-based: lack or inadequate knowledge of procedures and standards.
2. Rule-based: failure to apply the correct protocol.
3. Skill-based: failure to respond with the correct skill to a particular situation.
4. Technical: a combination of knowledge-based and rule-based errors.
5. Latent: deriving from adverse interactions with the environment.

Overall BC control and breathing-gas management were the dominant issues. A series of violations (standards, rules, procedures) were observed as being related to diving incidents of which 40% involved divers with basic open-water qualification and about 25% involved dive-leadership level divers. This latter figure is quite unexpected but can be explained by complacency and/or by dive leaders behaving in a different way when diving outside their professional framework taking risks that they would generally avoid.

Fatigue in diving accidents
A status of fatigue has several negative effects on the physical and mental conditions of the divers:

- Cognitive skills: loss of flexible decision-making and reduced ability to react to changes.
- Motor skills: loss of coordination.
- Communication skills: difficulty in finding the correct words, loss of articulate speech.
- Social skills: irritability and tendency to be isolated.
- Physiological: increased susceptibility to decompression issues.

Acute fatigue, due to a single physical exertion and/or sleep loss, can be alleviated by a single period of sleep. Operational fatigue, on the other hand, is induced by a series (3-4 days) of heavy tasking and/or sleep deprivation that is not relieved by just a single period of sleep but requires a longer resting time (O'Connor, 2005). In planning the operational schedule, the impact of fatigue should be considered and appropriate rest periods should be included. Extreme strenuous activity may cause the divers to over-breathe the regulator, which would not be able to supply the needed breathing volume; as consequence, breathing would become even more strenuous leading to further over-breathing in a vicious circle (Bacharach and Egstrom, 1987).

Stress and panic in underwater incidents
An individual's feeling (not necessarily justified) that there is a gap between his/her ability and knowledge and the requirements of the situation in which he/she is involved may cause stress and anxiety. A positive stress response is a cognitive process in which the actual situation is logically evaluated and potential solutions are considered. Too much stress can hamper the logical process leading to faulty responses. Education and training allow the individual to better manage stressful situations, mostly when immediate and intuitive action is required. A total absence of stressors, or failing to perceive any of them, is also negative because it can induce careless errors and poor performance (Blumenberg, 1996).

Environmental stressors can generate a high level of anxiety, which in turn will affect the subjects' performance. Several tests and experiments in dry chambers vs. open sea and in shallow waters vs. deep waters highlighted a drop in performance with narrowing in SA when the divers felt they were exposed to potential dangers. More experienced individuals repeatedly exposed to high level of stress can learn to inhibit their anxiety displacing it away from the point of perceived maximum danger so as to be able to cope better with stressors. In any case, performance in action is much worse that during training, and motivated individuals react better to high levels of stress (Baddeley, 2000).
Response to stress varies largely between individuals; the Dodson-Yerkes curve is a Gaussian-type curve (bell-shaped) where the level of performance (y axis) is related to that of anxiety (x axis). The curve shows that performance increases following the increase in anxiety until a peak is reached after which further increase in anxiety reduces the ability to react (Bougherara et al. 2011). Complex tasks requiring elaborate processing of information are better performed under low-stress levels; more basic tasks such as endurance and gross physical response benefit from higher arousal levels (Bacharach and Egstrom, 1987). Under high stress the attention field is reduced with the individual able to focus only on some aspects that are considered to be the most relevant but which are not necessarily those representing the real danger (Endsley, 1995).

Higher stress can also cause a "flight or fight" response which is an instinctive reaction triggered by stressful situations (Cannon, 1932). Escape reaction is not necessarily wrong; a direct and controlled action, for example when divers manage emergency ascent, is a positive behavior. If the reaction is instead out of control it may lead to panic and accidents (Bacharach and Egstrom, 1987).

Four phases have been identified during the response to high-level stress and are defined as “Seyle's General Adaptation Syndrome” (Seyle, 1946):

- Phase 1: alarm and shock cause the level of reaction to drop and the individual is “frozen” becoming unable to act.
- Phase 2: the body responds increasing the level of functioning and the individual reacts to the situation.
- Phase 3: physical and psychological reserves of energy begin to be depleted.
- Phase 4: exhaustion sets in. During this phase, mistakes and errors can easily occur.

In an underwater situation, these steps follow each other within a few minutes and the level of exhaustion is reached quickly due to the associated higher probability of committing errors (Lewis, 2014).

Reaction to stress is very individualistic depending on the personal learning and conditioning history; vulnerability to stress results from the anticipation of a potential threat. When exposed to stress the body will react with a rapid psychoendocrine adaptation to the stressor; in an anxious individual, a feeling of being unable to cope with the anticipated stressor may cause a sense of helplessness thereby making further controlled reaction impossible (Bachrach and Egstrom, 1987).
If the stress is not controlled, panic may develop causing an interruption of the logical and rationale stress-response with lack of action and/or continuation of inappropriate actions (Blumenberg, 1996).
Panic can easily lead to drowning/death mostly in one of the following two ways Nevo and Breitstein, 1999):

- Panic causes accelerated and shallow breathing leading to hypoxia and hypercapnia. The diver feels the need for more air and can bolt to the surface or expel the regulator, which, paradoxically, is felt as an “obstruction” for breathing.
- Over-activity of the sympathetic nervous system increases the pulse rate and blood sugar levels which, in extreme cases, may lead to heart attack.

To improve the divers' reaction to stress, good physical fitness is necessary to be able to resist cold, fatigue and physical exertion. Solid knowledge of diving techniques and equipment is helpful in giving the diver full confidence in his/her ability and in reducing the psychological effects stress. Procedures for emergency situations should be over-learned so that the reaction is fast and consistent, even under stressful conditions (Gilliam, 1999).

Under stressful conditions, the diver should adopt a procedure composed of the following steps:

- Stop: momentarily interrupt the action.
- Breathe: slow the breathing rate to help calm down and save air.
- Think: analyze the problem and decide upon the best action to perform.
- Act: select a solution and take action.

Managing stress is the only way to preserve the clearness of mind needed to assess problems and to maintain self-control in emergencies (O’Connor, 2005). For divers in high level of arousal and on the verge of panic, concentrating only on stress-reduction techniques may not be the best approach; instead the main focus should be on practical responses aimed at coping with the stressful situation (Bachrach and Egstrom, 1987).

Scuba diving incidents analysis

The majority of diving incidents are related to loss/incapacity of managing the breathing gas supply which is often followed by failure in emergency ascent procedures leading to AGE and/or drowning (Denoble et al., 2008).

An analysis of the causes of 128 fatal diving accidents shows the following distribution (Nevo and Breitstein, 1999):

- Medical factors (mostly panic) 50%
- Environmental factors (including entrapment in cave diving) 20%
- Equipment failure 5%
- Other 25%

The human factor is overwhelmingly the main cause of diving accidents; diving gear failure plays a very minor role in diving fatalities and many of those failures are likely due to bad maintenance and/or omitted checks. Since SCUBA is the main system used by both recreational and scientific divers, the DAN Annual Diving Report 2015 database about diving incidents in the recreational diving community for the period 2010-2013 gives relevant information (Buzzacot, 2015). The fatality statistics show that the bottom phase of the dive is where the chain of events leading to a diving fatality most commonly started and that faulty breathing gas management was the primary factor. The bottom phase of the dive, rather than other phases, is likely to cause more stress to the divers who in turn may commit errors more easily. Failure in the breathing-gas supply is clearly the most dangerous event and it is almost invariably fatal unless an external aiding event occurs, such as if a diving buddy provides an emergency breathing gas supply. It should be noted that in the majority of events the cause triggering the problems remains unknown highlighting the inherent difficulty in fully investigate diving accidents (Tables 3, 4).

Table 3. Phases of the dive where the chain of events leading to a fatality starts

Bottom	48%
Post-dive/surface	24%
Ascent	9%
Descent	8%
Other	11%

Table 4. Triggers of the chain of events leading to diving fatalities

Unknown	61%
Breathing gas management	6.8%
Entrapment/entanglement	6.5%
Health problems	6%
Equipment	5%
Environmental factors	3.4%
Rapid ascent	3%
Panic	1.55%

In an analysis of 346 diving-related deaths (Denoble et al., 2008; Orr, 2016), different triggers that started the fatal chain of events were identified with out-of gas being the most common (Table 5).

Table 5. Triggers of the chain of events leading to diving deaths

Out-of-gas	41%
Entrapment	20%
Equipment	15%
Environmental factors	10%
Unknown	16%

For 332 of such fatalities, a disabling agent was identified in terms of the hazardous behavior or circumstance temporally or logically associated with the accident trigger and possibly causing the disabling injury:

- Emergency ascent 55%
- Out-of-gas 27%
- Buoyancy issues 13%
- Other 5%

The events directly responsible for death were:

- Asphyxia 33%
- Age-related health issues 29%
- Cardiac arrest 26%
- DCS 2.5%
- Wrong gas 2%
- Other 7.5%

Victims were separated from their diving buddy/group 57% of the time, before the fatal accident. These data show that incorrect gas management is a key factor, and the main direct or indirect cause of accidents. A low-gas or an out-of-gas situation is the most dangerous because of its direct impact. If divers run out of breathing gas underwater, they will die, and an indirect gas shortage will reduce time availability and the diver will be under higher time-pressure stress likely leading to mistakes and frantic actions.

Failure in situational awareness was involved in 40% of events, with complacency and fatigue playing dominant roles followed by inexperience and lack of training. These data are based on analysis of 264 diving accidents (5 diving fatalities), as well as 272 US Navy diver questionnaires and 15 interviews. The diving supervisor was often overloaded by an excess of non-relevant information which deteriorated the SA, leading to leadership failure in all of the five fatal incidents. As a source of injury, DCS and AGE were the first and second causes, respectively (O'Connor, 2005, 2005a).

In single or multiple fatalities, the victims were often certified for the dive level that they were attempting but had limited experience and/or the experience was gained in a "rushed" way with several dives logged in a relatively short time thus not allowing for a consistent building up of skills and practice. Long-term diving inactivity was also a contributing factor in the deterioration of skills and ability. In a few cases the deliberate disregard of standards and rules was the cause of deadly events as shown by a detailed analysis of twenty diving accidents (Ange, 2006). Certification alone is not enough to ensure safe dives; experience under the diving conditions is mandatory (Orr, 2016). This highlights the importance for divers of continuous training, education, knowledge and respect of procedures in order to reduce risk.

More complex diving equipment, such as CCRs, has a different epidemiology of diving-related accidents and fatalities. An analysis of CCR-related accidents between 1998 and 2010 showed 181 deaths were related to about 14,000 active CCR divers in 2010, who each performed an average of 30 dives/year. The resulting death rate is of 5:100,000 dives, which is about ten times the rate of non-technical open-circuit SCUBA (OC). In general, 44% of the accidents were related to equipment issues and 30% of the deaths using CCR were caused by equipment failure compared with 9% when using OC. Hypoxia (17%) was the main cause of fatality. More than 50% of CCR failure was caused by poor training, incorrect procedures and omitted pre-dive checklists. Bad behavior such as diving without bailout, disregarding alarms, omitting checklists and even entering the water with a closed valve or electronics shutdown is often associated with accidents. A bias in comparing the CCR to OC accident rate is that CCRs are frequently used for deep mixed-gas dives thereby exposing the divers to dangerous environments, which can be the real cause of accidents independent from the diving apparatus used (Fock, 2013).

SCUBA equipment risk assessment

Self Contained Underwater Breathing Apparatus (SCUBA) is the most used diving system for scientific divers. It has several advantages, but also has some areas of safety concern when compared to other diving systems such as surface supply, saturation diving and atmospheric pressure suits (Table 6).

Table 6. Pros and cons of SCUBA

Advantages	Safety limits
Cost-effective	Time constraint based on tank capacity
Relatively easy training	Decompression management
High degree of freedom for the diver	Limited redundancy
Reduced logistic/surface support needs	No direct link with surface
Consistent and well proven diving protocol	Higher task load for the diver

The different components of the open circuit SCUBA system are associated with variable degree of risk. Generally the probability of failure in any of the components is low since SCUBA is a well-proven, relatively simple, solid and consistent system with several decades of utilization in a variety of applications and situations. On the other hand, the severity of any adverse event is by and large high since SCUBA is a life support system whose failure can easily lead to fatal consequences (Lewis, 2011). Table 7 presents some of the main hazards connected to SCUBA equipment and the related mitigation strategies.

Risk management in diving operations

Once the risk has been clearly identified, it is necessary to develop a series of procedures and strategies for its management with the aim of eliminating as many risks as possible and reducing the potential consequence of unavoidable ones.

Table 7. Risk analysis of SCUBA equipment

Component	Hazard	Consequences	Risk level	Mitigation
Gas reserve	Running out of breathing gas	Deco violation Drowning	High	Gas management
Gas composition	Contamination Oxygen toxicity	Potentially fatal intoxication	Serious to high	Gas supply analysis Respect of MOD
Valves	Leaks	Loss of gas supply	Medium to high	Maintenance Use of isolator
Regulators	Freezing	Free-flow	Serious to High	Anti-freeze systems Redundancy
Regulators	Mechanical failure	Loss of gas supply	Serious to High	Maintenance Redundancy
Pressure gauge	Leak	Small loss of gas supply	Medium	Maintenance
Pressure gauge	Mechanical failure	Loss of pressure readings	Medium	Maintenance Redundancy
BCD/dry suit	Power inflator blocked closed	Loss of buoyancy	Serious	Oral inflation Ballast jettison
BCD/dry suit	Power inflator blocked open	Uncontrolled ascent	Serious	Able to quickly disconnect the LP hose
BCD/dry suit	Exhaust valves leak	Slow loss of buoyancy	Medium	Maintenance Add extra air
BCD/dry suit	Inflator leak	Slow gain of buoyancy	Medium	Maintenance Dump air

Team management

Without a good team, no good results can be achieved despite any technological support that may be available. It is important to assess the proficiency of the team whose components must be able to work together as a unit, in a professional and effective way. Developing good teamwork requires time, and newly formed groups should not be rushed into challenging operations without having had enough time to train together.

A group test requiring coordination among its members, such as the assembly of an underwater structure, can be a good system to assess the proficiency of a team and to increase familiarity between the team members. Crew Resource Management (CRM) is a training procedure aimed at enhancing team reliability; it has been successfully used in the airline industry and in high-technological high-risk environments. Team members should be supported in admitting their fallibility and the impact of stress on their performance and trained to operate within their limits. Performance under stress can be implemented by simulated high-stress situations even if a degree of inconsistency in team behavior between the simulations and the real operative environment is unavoidable. The final aim of CRM is to improve team coordination and reward safety culture above productivity or costs (Blumenberg, 1996).

A SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis is another useful tool to assess the overall quality of the team. SWOT is based on a grid where each member of the team indicates the strengths and weaknesses they feel they will bring to the team; in a well-balanced team, the weaknesses should be offset by the strengths (Jackson et al., 2003; Lewis, 2011).

Complex diving operations, such as those needed for some types of scientific diving, require an extended team including surface personnel, support/standby divers and a diving supervisor who will be in charge of managing safety protocols and procedures and emergency response.
Ideally, the support divers should follow a dive profile with minimal inert gas intake so to be able to surface anytime if needs arise such as to communicate with the surface personnel and/or retrieve extra pieces of equipment from the surface (Lewis, 2001). An analysis of 300 US Navy teams highlighted a series of common elements for an effective team and a series of typical issues.

Positive attitudes that support teamwork are:

- Individual proficiency
- Clear communication and understanding of team tasks
- Motivation and shared common goals
- Flexibility
- Global awareness of the team's members

Negative attitudes that can damage teamwork are:

- Refusal of rules, procedures and regulations
- Rushed actions not critically evaluated
- Complacency
- Resignation
- Lack of role definition
- Lack of explicit coordination
- Miscommunication issues
- Poor leadership

More than 25% of the failures in nontechnical skills involved in Navy Diving fatalities were linked to some degree of teamwork and supervision breakdown (O'Connor, 2005).

Breathing gas management
The first step in gas management is to calculate how much gas one needs to complete a dive with a reasonably safe margin of reserve. There are several methods to estimate gas consumption at depth, and generally they are based to the surface air consumption (SAC) value. This value is obtained under ideal conditions and does not consider the increase in breathing rate that will likely follow a stressful situation; it is therefore necessary to consider a multiplier factor. For high workloads and/or extreme conditions, this factor could be high as 3 and up to 4 for gas sharing between two divers under controlled circumstances. For deco-gas reserve calculation the multiplier should be set to 2 (Lewis, 2014). In case of failure of the primary source of breathing gas, another independent source should be available as bailout. The minimum amount of bailout gas is that which allows the diver to safely reach the surface following a normal ascent or to reach the first decompression station where a gas source is available.

Relying on the dive buddy for an out-of gas situation should be carefully assessed considering the following points:

- Because two divers are following the same dive profile, unless there are huge differences in SAC between them and/or a different cylinder configuration is being used, if one of the two is running out of gas it is reasonable to suppose that even the buddy will not have as much gas left and that sharing this gas between the two divers will further deplete the reserve even quicker.

- In a catastrophic out-of gas situation, such as in a free-flow regulator, the gas supply will be depleted very quickly, and if for any reason the two diving buddies are not swimming relatively close to each other, there may not be enough time for the diver in need to reach the buddy's alternate source.
- Sharing gas with an alternate source, and even more, if the same regulator is to be used between the divers, requires extremely good coordination among the divers; they should periodically review the procedures.

Special tasks management

Specific underwater operations, such as those required during scientific diving activity, may have a degree of risk that has to be managed. For example, the use of lift bags can expose the divers to tangling and uncontrolled ascent, or the use of glass samplers may cause cuts if they break or are mishandled. Potential loss of collected data and information is also a serious issue for a scientific diver, which is why redundant recording systems should be used. The specific tasks should be carefully planned and analyzed in order to adopt a consistent and safe management.

Some scientific research may require diving in overhead environments such as below an ice canopy, in caves and in artificial structures and wrecks. In these situations, extra training and equipment is needed and divers with no specific certification or experience in diving in such environments should not be used in any circumstances.

In extremely complex environments and operations, it could be safer to add a safety team to the working team with the sole aim of supervising the safety of the working divers who will therefore be free to focus on the job to be done.

The diving plan

A dive plan can be considered as the backbone for any successful diving operation where all the necessary information is included and made available to personnel involved in the procedure. Even if a well-defined framework is necessary, the diving plan structure should allow for flexibility in case of unforeseen issues and be adaptable to changes in conditions (NOAA, 2013; Orr, 2016). In its basic form, a diving plan should assess: the team, breathing gas, diving and technical gear, operative goals and dive parameters (Lewis, 2011).

Diving and support team

Identifying the best team is the first step for a successful operation. The ability of the less experienced divers will set the limits of the diving activity. A team leader should be appointed and he/she should be in charge of managing the divers. It is important to assure a good degree of communication and understanding between the dive leader and any other manager who might be involved in the operation including senior scientist, safety officer, boat captain or representatives of the contractor. The team should be thoroughly briefed on all necessary aspects of the operation including contingency and emergency procedures.

Breathing gas

Breathing gas planning should be included, considering both its MOD and the necessary volumes for the operation plus a reasonable reserve. As stated before, poor breathing gas management is very often the main cause of diving accidents, which is why it is so important for divers' safety. The availability of enough breathing gas should be assured for each single diver and for the entire team so that even if some catastrophic gas loss were to affect a diver there would still be sufficient gas within the team to ensure a controlled and slow ascent to the surface. Working in overhead environments, such as in caves, requires additional specific knowledge, skills and training for breathing gas planning and management. The team should be well trained in gas sharing procedures and, if multiple gases are used, in the correct use of each gas in function of its operative depth.

Diving schedules and objectives
The diving operation goals should be clearly stated and a schedule of activities should be planned considering time, special equipment needed (if any), assignment of different jobs to the team members, and sequence of the underwater procedures. This section of the dive plan should also address the diving limits (e.g. time and depth) which, when reached, will terminate the dive. A series of appropriate waypoints "go-no-go" should be identified where divers will assess the diving conditions and will decide whether to proceed with or abort the dive or starting contingency/emergency procedures (Lewis, 2014).

Communication protocol
Procedures for communication between the divers and with the surface should be assessed considering the diving environment, the complexity of the information to be shared, the available communication equipment and the divers' experience in its use. The surface team should also be instructed on how to establish communication with other entities such as contractor's representatives, scientific supervisors, local authorities and emergency personnel. Diver recall and emergency signals should also be agreed upon between the diving and surface teams.

Diving and scientific equipment selection
Appropriate diving gear configuration should be identified in accordance with the needs of the planned dive. Differences in the diving gear configuration between members of the diving team should be kept to a minimum and the divers should be aware of the specifications and operative procedures of the other team members' gear to be able to manage it in the event of an emergency. The diving gear should be checked to make sure it is in working order, that it is serviced accordingly to the standards and/or legal requirements (e.g. hydro-test for cylinders), and assigned to the divers who will be responsible for its use and normal maintenance at the end of the dive. If scientific/technical equipment is used, it should also be checked to ensure it is in working order and that it does not present any hazard for the divers. The divers should be fully aware of the procedures for using such equipment. The complexity of the carried equipment, including the equipment needed for scientific tasks, should be limited to what can be safely managed by the diving team. More complex operations requiring larger equipment should be divided into smaller assignments among several dives. A list of all equipment used should be made to assure that all necessary items are carried to the diving site and back.

Contingency and emergency procedures
A contingency plan should address the procedures to be applied if unforeseen events were to affect the planned diving schedule. This plan may include alternate diving sites, alternate scientific tasks, and shortened/simplified diving schedule and operational procedures.

The emergency plan aims to define clear and consistent procedures to be applied in case of medical-related crisis. A copy of the plan including the estimated time of return to the base should be left with someone at the base and a deadline should be agreed, after which an emergency SAR team is to be activated. In case of voluntary delay, this person should be informed so as to avoid false alarms.

Checklists
Checklists are a well-proven system to ensure consistency in task management of complex operations and to reduce human error; they are a standard in aviation, space operations, medical assessment, commercial and technical diving procedures, and a variety of industrial activities (Lewis, 2011; Orr, 2016; Tetlow and Jenkins, 2005). A diving checklist should be composed of logical and consecutive steps to ensure that all key points of the diving method, equipment efficiency, safety procedures, etc. are verified before the actual dive begins. The best way to ensure consistency is to have the checklist read by one of the team members while another confirms each step.

Briefing and debriefing
A briefing should involve members of both the surface and diving teams, and it should review the main points of the diving plan.

Once the diving operations are concluded and all post-dive procedures have been completed, a debriefing should follow. This is an important moment to review the dive, point out problems that may have occurred, and to identify solutions and improvements. It is a team effort and everyone should be encouraged to actively participate by sharing ideas, comments and constructive criticism.

Conclusions

Scientific diving activities can be complex requiring multiple levels of technical expertise and well-trained and experienced divers. This complexity is also reflected in the variety of potential hazards that can affect diving operations. A comprehensive risk management plan, even if it cannot eliminate all potential risks, can greatly reduce the probability of their occurrence and the severity of their impact. Breathing gas management and buoyancy control are the most important technical factors involved in diving mishaps; therefore, education, skills and practice should focus on those aspects. Diving equipment is a life-support system and should be treated with care; divers should be well aware of how to properly assemble, use and maintain their diving sets.

Human factors are the main direct or indirect causes of diving accidents. Therefore, training, experience, standardized procedures and the use of checklists should be enforced by divers in order to reduce the incidence of human errors. The mental attitude of divers is not less important than their physical fitness and technical proficiency; the ability to maintain good situational awareness is mandatory for diving safety.

A degree of stress is unavoidable in diving, and up to a certain point it can also be positive, acting as mental stimulation. The divers should be able to correctly identify the onset of stress providing adequate response before it escalates into panic.

Scientific diving is a team effort involving divers and support personnel alike. Good communication and coordination within the team should be promoted and a safety approach should be rewarded. Becoming an expert diver requires time to progressively gain consistent skills and experience. No one should be rushed in diving operations above his/her ability to cope with the related hazards and tasks. A dive plan should be prepared well in advance and should always consider the safety of the divers as the primary goal.

The pre-dive briefing should be an important moment in the risk management process; it allows a review of key information about the dive plan with the divers.The debriefing should focus on how to further improve the proficiency of the team building on the acquired experience.

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