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Title page

Medical Care in Submarine Accidents

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Abstract

Submarine emergencies represent one of the most extreme and logistically challenging scenarios in disaster and military medicine, where isolated, high-pressure environments create a perfect storm of medical, psychological, and operational challenges. This perspective examines the unique challenges of providing medical care in submarine accidents, drawing on historical cases such as the Russian Kursk (2000), the Canadian Chicoutimi (2004), the USS San Francisco (2005), and the Argentine Navy's San Juan (2017) or the Indonesian KRI Nanggala (2021) which illustrate operational constraints and rescue feasibility issues inherent to these types of incidents.

The onboard survival phase is marked by rapidly deteriorating conditions, especially on non-nuclear submarines, including hypoxia, hypercapnia, hypo- or hyperthermia, toxic fumes, possible ionizing radiation and psychological stress, as life support systems fail and emergency resources, such as oxygen candles and carbon dioxide scrubbers are finite. Distress signaling is severely limited by the lack of reliable underwater communication, forcing crews to rely on surface beacons without confirmation of receipt, thereby inducing additional mental stress, prolonging isolation and self-sustainment efforts. Rescue operations, for instance coordinated through networks like International Submarine Escape and Rescue Liaison Office (ISMERLO), originally founded by NATO but now a worldwide collaboration, face significant logistical hurdles, including delays in localization, limited Deep Submarine Rescue Vehicle (DSRV) availability, and the complexities of mass-casualty triage, particularly when decompression illness (DCI) complicates trauma management.

The dual threat of trauma and DCI necessitates a modified triage approach, where traditional trauma classifications must be integrated with decompression risk assessments to prioritize treatment effectively. Ethical dilemmas further arise in conflict zones, where resource scarcity, security risks, and adherence to humanitarian law introduce profound moral distress for decision-makers and rescue personnel.

Keywords: triage, decompression sickness, hyperbaric oxygen treatment, submarine escape and rescue, arterial gas embolism, environmental conditions

Background

The provision of medical care in conflict and disaster settings is inherently complex, characterized by resource scarcity, logistical constraints, and unpredictable patient volumes. Whether in refugee camps overwhelmed by displaced populations, regions devastated by natural disasters, or the chaotic aftermath of armed conflicts, healthcare systems are frequently pushed beyond their operational limits. Among these high-stakes environments, naval warfare, and submarine accidents in particular, present some of the most extreme and logistically demanding scenarios for medical response. The isolated, potentially high-pressure, and resource-limited conditions in a deteriorating atmosphere aboard a disabled submarine create a perfect storm of medical, psychological, and operational challenges.[1,2]

A stark example of these challenges was the 2017 disappearance of the Argentine Navy submarine *ARA San Juan*.[3] Despite a multinational search and rescue operation, the vessel was only located a year later, 460 kilometers offshore at a depth of 907 meters, with the tragic confirmation that all 44 crew members had perished. Similarly, in 2021, the Indonesian Navy submarine *KRI Nanggala-402* was lost during a routine torpedo drill, with its debris subsequently located at a depth of 850 meters, significantly exceeding the vessel's estimated crush depth. The incident resulted in the tragic loss of all 53 crew members onboard.[4] These incidents underscore the severe difficulties associated with submarine rescue operations, where time, depth, and environmental conditions conspire to limit survival prospects. While comprehensive data on submarine accidents remain scarce, largely due to the classified nature of military operations, open-source reports suggest that approximately eight severe incidents that left the submarine disabled have occurred over the past 25 years, indicating that submarine accidents are more common than often believed.[5] If 'near misses', i.e., accidents with submarines that do not incapacitate the vessel, are included, this number increases to approximately three incidents per year worldwide. This overview examines the unique medical and operational challenges posed by submarine emergencies and their relevance to broader emergency and disaster medicine. Although the submarine escape and rescue community is built on international collaboration and sharing of knowledge, the military context in which submarine operations are usually conducted is far from that. Given the sensitive nature of military operations, this analysis intentionally excludes classified material and relies instead on open-access sources, which may occasionally lack rigorous scientific validation. For this manuscript, we build upon the historical insights gained from large scale submarine warfare, and associated incidents, during World War II and subsequent conflicts. Lessons that continue to inform contemporary maritime safety protocols. However, our primary focus lies in analyzing major submarine incidents from recent decades to ensure the relevance and practical applicability of our findings for current operational practices.

Operational environment aboard submarines

A submarine is a self-contained, highly engineered vessel designed for prolonged submergence in some of the most hostile environments on Earth. Military submarines are primarily tasked with reconnaissance, intelligence gathering, and offensive operations, including missile deployment and insertion or extraction of special forces. While operational depths and submergence durations are often classified, the internal environment is meticulously controlled to maintain sea-level atmospheric pressure, regulated circadian lighting, and air purification systems, all of which are essential for sustaining habitable conditions during extended missions.

However, while long-term health effects from submarine service appear to be minimal, life aboard a submarine presents extraordinary challenges.[6,7] The confinement, shift-based work schedules, and limited privacy impose significant psychological and physiological stressors on submariners.[8] Although this paper does not delve into the long-term health effects of submarine deployment, it is important to acknowledge that chronic stress, fatigue, and the mental strain of operating in such an environment may compromise crew resilience in the event of an emergency.[9] These factors can exacerbate injuries, impair decision-making, and reduce the effectiveness of medical interventions when crises arise.[10]

Submarine accidents

Prior to examining major submarine accidents, it is important to highlight that the most frequent causes of non-catastrophic submarine incidents, commonly referred to as "near misses", are collisions with other vessels while operating near the surface, followed by onboard fires and grounding events (i.e., unintended contact with the seabed). The majority of these incidents can typically be managed effectively, thereby preventing catastrophic failure or the sinking of the submarine.[5]

Catastrophic submarine accidents share key similarities with other high-risk incidents, such as industrial explosions, aviation disasters, or maritime collisions. Personnel undergo rigorous training to mitigate hazards, including fires, toxic gas exposure, and structural failures, and are prepared to respond under extreme time pressure. Yet, the consequences of such accidents can escalate with alarming speed, often leading to catastrophic outcomes within minutes. Several historical examples illustrate the diverse and unpredictable nature of these events.

Collisions with underwater terrain or objects can compromise hull integrity, leading to rapid flooding. The 2005 incident of the *USS San Francisco* serves as a case in point: the submarine struck an underwater seamount, resulting in one fatality and 97 injuries.[11] However, the crew’s immediate response, including the sealing of watertight compartments, prevented the vessel from sinking entirely.[12] Such incidents highlight the critical importance of damage control protocols in averting total disaster.

Fires aboard submarines are particularly perilous due to the risk of oxygen depletion and the release of toxic fumes. The 2004 fire aboard the Canadian submarine *Chicoutimi*, was caused by a short circuit after seawater entered the submarine during heavy seas. Smoke inhalation injured nine crew members, claimed one life and required the hospitalization of two others.[13] The crew's rapid intervention, extinguishing the flames and activating emergency air systems, was instrumental in preventing a larger catastrophe. However, the closed environment of a submarine means that even a small fire can quickly endanger the entire crew.

Submarines carry inherently dangerous materials, including torpedoes, missiles, and other munitions. The 2000 explosion aboard the Russian submarine *K-141 Kursk*, triggered by the inadvertent detonation of torpedoes, resulted in immediate flooding and the deaths of 95 sailors.[14] The 23 surviving crew members endured several days in the sunken vessel before rescue attempts ultimately failed, partly due to delays in international assistance reaching the site. This tragedy underscores the lethal combination of explosive hazards, rapid flooding, and the logistical challenges of deep-sea rescue operations.

These examples demonstrate that submarine accidents are highly variable in terms of injury patterns, operational constraints, and rescue feasibility. Submariners must be self-reliant, capable of autonomously responding to incidents to prevent further damage or casualties. While some submarines carry medical personnel, ranging from nurses to physicians with limited surgical capabilities, the loss of propulsion or buoyancy control can quickly render even the most prepared crew vulnerable to sinking, with devastating consequences. In the case of the *Chicoutimi*, while sailing operations remained unimpaired, the medical management of injuries, readily treatable in a shore-based setting, posed significant challenges in the austere maritime environment.

Distress signaling

In the event of a damaged or sunk submarine scenario, the immediate transmission of a distress signal is paramount. However, underwater communication presents a formidable challenge: most long-range systems are ineffective beneath the surface, leaving submariners reliant on emergency beacons that float to the surface to transmit signals via satellite or radio. A critical limitation of these beacons is their lack of two-way communication, meaning that crews cannot confirm whether their distress call has been received. This uncertainty forces submariners to self-sustain for prolonged periods, often without knowing whether help is on the way.

The psychological toll of this isolation cannot be overstated. Even in trainings scenarios, where the favorable outcome is guaranteed, psychological considerations have to be taken into account.[15] Crew members must conserve resources, manage injuries, and maintain morale in an environment where every decision carries critical stakes. The absence of real-time communication with rescue teams further complicates medical triage and survival strategies, as submariners are left to navigate the crisis with limited external guidance.

Onboard survival

Once a submarine is disabled, the failure of life support systems becomes an immediate threat, especially on non-nuclear submarines. Human respiration depletes oxygen and increases carbon dioxide levels, creating a rapidly deteriorating atmosphere. To counteract this, submarines are equipped with chemical oxygen generators, commonly referred to as "oxygen candles", which release breathable oxygen through a controlled chemical reaction. However, these devices must be monitored continuously to prevent oxygen toxicity or fire hazards.

Nuclear submarines may be less susceptible to these issues, as sea water can be electrolyzed to produce oxygen and the climate can be controlled as long as energy can be generated.

In diesel-electric submarines, carbon dioxide is managed using lithium hydroxide scrubbers, similar to ventilation devices in other fields of medicine, which are distributed in "curtains" to maximize surface area for chemical reactions. The effectiveness of these systems depends on ambient conditions, including humidity, temperature, and the number of surviving crew members. To extend their operational lifespan, submariners must minimize physical activity.

Nutritional challenges also arise in prolonged entrapment scenarios. Emergency rations provide approximately 2,500 kcal per day, but their limited variety and palatability often result in hypocaloric intake, alongside possible preexisting micronutrient deficiencies over the course of a submarine deployment.[16] Moreover, elevated ambient environmental conditions may exacerbate caloric requirements due to an increased work of breathing, potentially amplifying the existing caloric deficit.[17] Additionally, the loss of climate control of a damage submarine can result in ambient temperatures rising or falling, depending on the sea temperature around the submarine, the number of crew members and the part of the submarine they are in.[18] The cumulative effects of hypoxia, hypercapnia, malnutrition, and hypo- or hyperthermia create a hostile physiological environment, which is further aggravated by injuries, burns, or toxic exposures (e.g., fumes from fires or chemical leaks, ionizing radiation in nuclear submarines) and psychological injury or stress.

Rescue operations

In the event of a submarine distress signal, or the failure to receive a scheduled check-in, large-scale search and rescue operations can prompt activation of an international rescue network, such as the International Submarine Escape and Rescue Liaison Office (ISMERLO). Established by NATO in 2003, ISMERLO serves as a centralized coordination hub, facilitating multinational rescue efforts. However, the host nation retains ultimate authority over which assistance to accept, introducing potential delays in decision-making.

The first priority in any rescue operation is to locate the submarine and establish communication. Yet, as demonstrated by the *ARA San Juan* and *KRI Nanggala* incidents, this is not always achievable, particularly in scenarios where the submarine's whereabouts are unknown, for instance due to navigational errors or environmental factors that may obscure the vessel's location.

Upon successful localization of the distressed submarine, targeted intervention measures are initiated. The operational response typically aligns with one of three established methodologies. The first approach involves the salvage of the entire submarine, wherein the vessel is raised to the surface using specialized equipment and engineering techniques. Alternatively, a Deep Submarine Rescue Vehicle (DSRV) may be deployed to dock with the submerged submarine, facilitating the controlled evacuation of crew members through successive sorties to the surface. As a final option, crew members may undertake an independent ascent to the surface, either by free swimming or with the assistance of buoyancy-enhancing devices.

Salvaging of the entire submarine

The Russian *AS-28* deep submersible rescue vehicle became entangled in hydrophone lines at a depth of 190 meters in 2005.[19] Through international collaboration, particularly the fast deployment of a British remotely operated vehicle, the submarine was successfully disentangled, and all seven crew members were safely recovered. This operation highlights the success of international cooperation and advanced technology in submarine rescue missions.

Deep Submarine Rescue Vehicle

In 1939, the American submarine *USS Squalus* experienced a technical failure during a test dive, resulting in its descent to a depth of 74 meters.[20] While 26 crew members perished, the remaining 33 were successfully rescued using a pressurized "McCann" rescue chamber, an early iteration of modern Deep Submarine Rescue Vehicles (DSRV). This incident is widely regarded as the first documented successful rescue operation utilizing a crew transport system.

For submarines at rescuable depths, up to 600 meters of sea water, DSRV are deployed to dock with the disabled submarine, delivering medical supplies and extracting crew members.[21] However, the limited capacity of DSRV means that evacuation occurs in multiple trips which can take several hours per sortie, with medical triage determining the order of extraction. The global scarcity of DSRV, coupled with the 72–96 hours typically required for deployment, means that survivors’ conditions may deteriorate before rescue teams arrive. These types of operations are significantly influenced by prevailing environmental conditions. Adverse sea states, characterized by high waves or substantial swell, can impede the deployment of DSRV and complicate the execution of pressurized coupling procedures. Additionally, if the distressed submarine is in an unfavorable angle, docking to a DSRV may be difficult to impossible.

Ascent to the surface

If DSRV rescue is not feasible, crew members may attempt compartment escape (flooding a section and reaching the surface, either swimming or with the usage of a flotation device) or free escape using specialized suits, such as a submarine escape and immersion suit (SEIE). While these suits provide a limited air supply that prevents drowning, the rapid pressurization and subsequent ascent to the surface poses a risk of decompression sickness (DCS) and ENT or pulmonary barotrauma. The latter can lead to arterial gas embolism (AGE), a potentially life-threatening complication, which also occurs in training scenarios.[22] The incidence of DCS and barotrauma in real-world submarine escape scenarios remains difficult to quantify accurately. In controlled training environments, where escape depths are limited and participants are uninjured and medically screened prior to the escape, the reported incidence of non-severe but clinically relevant barotrauma, particularly affecting the ENT-regions, may be as low as 4%.[23,24] Aggregated data from eleven nations suggest that the rate of severe injuries during training and real life submarine escapes ranges from 0.1 to 0.6 per 1,000 escapes, with a fatality rate approximately fifty times lower than the severe injury rate.[25]

However, these estimates are derived from escapes conducted at relatively shallow depths. Available evidence indicates a steep increase in risk as depth increases from 10 to 30 meters of seawater, though extrapolating these findings to deeper, more "realistic" escape depths remains uncertain. Therefore, medical personnel responsible for the care of escapees may encounter a wide spectrum of clinical presentations, ranging from minimal injuries to a high volume of patients with complex injuries. Especially pneumothorax, AGE and severe DCS require immediate treatment to ensure a favorable outcome.[26]

Additionally, survivors face hypothermia and seasickness while awaiting extraction in inflatable rafts. Survival at sea is beyond the scope of this manuscript, but presents another complexity in the rescue endeavors. For readers interested in this topic, we would like to refer to the excellent ‘in-water mass casualty triage tool’ by Barton *et al*.[27]

The incident of the Peruvian Navy submarine *BAP Pacocha* SS-48 in 1988 serves as an illustration of this procedure.[28] The collision with a fishing vessel resulted in the deaths of four crew members, while 23 others abandoned the vessel and were located four hours later in the water. Tragically, three of these survivors succumbed to hypothermia, as the water temperature was 14°C. The submarine sank to a depth of 43 meters in less than five minutes, with 22 survivors remaining aboard. Due to the accumulation of toxic gases within the submarine, the crew was compelled to undertake an emergency ascent to the surface. Of note, at the time of the escape of the 22 survivors from the sunken submarine, it was not immediately apparent that the internal pressure within the vessel had increased. Consequently, the neurological symptoms presented by the survivors were initially attributed to AGE rather than DCS. Following the treatment protocols at the time, the survivors were recompressed in a hyperbaric chamber to an equivalent depth of 50 meters of seawater (msw) breathing air (referred to as a ‘treatment table 6A’), a depth that would not have been the optimal therapeutic approach for DCS. The standard treatment for DCS at the time would have involved recompression to 18 msw with

100% oxygen (‘treatment table 6’).[29] This diagnostic uncertainty introduced significant logistical challenges, compounded by the limited availability of treatment facilities capable of accommodating such a large number of patients simultaneously. Furthermore, the high demand for hyperbaric therapy created substantial operational difficulties in tracking patient entry and exit from the chambers, as well as maintaining adherence to the required treatment timelines. To our knowledge, this is the only recorded endeavor post-WWII where submariners successfully escaped a disabled submarine.

Decompression sickness and hyperbaric oxygen therapy

When the human body is exposed to elevated ambient pressures, such as those possibly encountered in damaged submarines, a net uptake of inert gases, primarily nitrogen, occurs in bodily tissues. Under normal circumstances, this process is asymptomatic and reversible. However, when ambient pressure rapidly decreases, such as during an uncontrolled ascent, the body’s capacity to carry dissolved nitrogen is exceeded, leading to gas supersaturation and the formation of bubbles in tissues and blood vessels. This pathophysiological process underpins DCS, a multisystem disorder characterized by a broad spectrum of clinical manifestations, ranging from mild joint pain and cutaneous rash to severe neurological impairment, and death.[30] For completeness, both DCS and barotrauma are frequently grouped under the umbrella term decompression illness (DCI) in literature, this terminology can obscure distinctions between the two conditions. Therefore, we use DCS and barotrauma separately in this paper.

Unlike saturation divers, who are prepared and equipped for prolonged exposure to high-pressure environments, submariners operating in a pressurized, damaged submarine face an unplanned and uncontrolled saturation scenario. The internal pressure of a compromised submarine can increase significantly, effectively transforming submariners into unintentional saturation divers. Consequently, any free escape attempt to ascend to the surface without controlled decompression carries a substantial risk of DCS, rendering immediate escape potentially life-threatening.[31,32] Even escapes from relative shallow depths may still result in DCS or barotrauma, necessitating immediate hyperbaric oxygen therapy (HBOT) upon surfacing. Also, possible AGE as a result from pulmonary barotrauma also necessitates immediate medical care.

In scenarios where ambient pressure within the submarine reaches critical thresholds, submariners may be compelled to initiate free escape procedures, even when DSRV operations may be underway. As described above, these procedures are not without risk. Additionally, if the submarine is sunk below 200 meters, the protective escape suits, such as the aforementioned SEIE, are not designed to withstand the physiological stresses of such depths. At these extremes, the risk of life-threatening DCS from the rapid ascent alone may preclude escape entirely, leaving submariners trapped without viable options.[33]

Even when ambient pressure permits the docking of a DSRV the transfer of survivors introduces additional complexities. If submariners are transferred under pressure to hyperbaric treatment facilities, they can receive HBOT, the standard of care for DCS. However, pressurization during the transfer procedure itself can induce complaints, such as joint pain, chest tightness and pulmonary oxygen toxicity.[33,34]

The NATO Submarine Rescue System (NSRS) represents a critical asset in managing mass-casualty submarine incidents, with the capacity to treat up to 72 submariners simultaneously using HBOT. However, the scale and complexity of treating such a large patient cohort introduce challenges in emergency and hyperbaric medicine. The necessity for HBOT may delay or complicate the management of non-DCS or non-barotrauma injuries, such as burns or fractures. Ideally, stable or non-life-threatening conditions (e.g., mild lacerations or closed fractures) are deferred until after HBOT. However, logistical constraints, such as equipment malfunction under pressure and altered effects of medications, can further limit treatment options.[36] For instance, an intubated and ventilated patient in an hyperbaric environment requires specific material and expertise in managing the cuff of an endotracheal tube, monitoring ventilation (both volume and pressure control may need to be adjusted to the hyperbaric environment) and prevention of oxygen toxicity, both of the pulmonary and central nervous system.[37,38] Additionally, medical personnel operating within the DSRV or hyperbaric chamber are themselves at risk of DCS if they exit too rapidly, potentially reducing the number of available treatment slots due to their own need for decompression.[39,40]

Given that submariners may arrive at different times, either due to phased rescue operations or free escape, the HBOT protocol must accommodate patients at varying stages of treatment. While some individuals may complete their HBOT sessions and be locked out of the chamber to make room for new arrivals, others may still require ongoing therapy. A significant challenge arises when new patients necessitate different treatment pressures than those already undergoing HBOT. Adjusting the chamber pressure to accommodate optimal therapy for new arrivals can disrupt the therapeutic progress of patients already inside, potentially compromising or delaying their outcomes.

An final remark on HBOT; the hyperbaric environment presents an inherent risk, e.g., fire hazard due to elevated oxygen levels or damaging or malfunctioning equipment as a result of increased ambient pressure. Consequently, all medical equipment utilized within the chamber must adhere to stringent safety standards to mitigate these hazards.[37] As a result, the management of certain patients, especially those who are intubated or mechanically ventilated, may face significant challenges in a hyperbaric setting compared to standard clinical conditions.[38] These limitations can affect the feasibility or outcome of medical treatment of non-hyperbaric injuries. Furthermore, the geographical or logistic constraints of the platforms on which these recompression systems operate may limit the availability of comprehensive post-recompression therapy. This includes critical care interventions, such as the management of ventilated and sedated patients in an intensive care unit setting, potentially compromising patient outcomes.

Triage

The capacity of the NSRS, while substantial, may still be insufficient for the simultaneous treatment of an entire crew of a large submarine. In such cases, triage becomes inevitable. Unlike conventional trauma triage, submarine accidents complicate prioritization due to the dual presence of trauma and DCS. For example: low-urgency trauma patients (typically classified as T3) may develop severe DCS (C1), elevating their priority to immediate HBOT. Conversely, high-urgency trauma patients (T1) with concurrent DCS may become untreatable (T4 in military triage) if

HBOT cannot be administered in a timely manner due to limited chamber availability. This overlap of conditions demands a modified triage approach, integrating both trauma severity and decompression risk to optimize survival outcomes. This is displayed in table 1, which is adapted from publicly available NATO doctrine.[2,41] It is important to note that AGE is primarily attributed to barotrauma rather than decompression stress. However, the clinical differentiation between AGE and severe DCS can be challenging, as their presentations may be indistinguishable as illustrated in the accident with the *BAP Pacocha* SS-48. Given that both AGE and severe DCS necessitate urgent HBOT, AGE may be classified as C1 for triage purposes to ensure timely and appropriate intervention.

[Table 1 could be placed here]

In NATO doctrine, all T1 patients are considered top priority, needing immediate care, often in the 'primary' treatment facility. All T2/C1 and T3/C1 patients may receive urgently required, non-life saving, medical treatment (e.g., wound care) as long as it does not delay recompression therapy more than 20 minutes. Patients labeled as T2, T3/C2 are to receive care in a 'secondary' treatment unit. All remaining submariners, aside from those marked as T4, are placed into a holding area for observation, while the latter receive palliative care. For treatment of DCS, the therapy ranges from immediate HBOT, delayed recompression or (only) supplemental oxygen under normobaric conditions.

Military and operational considerations

Submarine operations, by their covert nature, may occur in contested or enemy-controlled waters, where the risk of hostile engagement is a persistent concern. In conflict zones, rescue operations face substantial security challenges that extend beyond the technical and logistical complexities of submarine recovery. While the Geneva Conventions explicitly protect medical personnel, wounded combatants, and shipwrecked personnel, recent armed conflicts have demonstrated that adherence to international humanitarian law cannot be assumed.[42] Rescue vessels, hyperbaric treatment facilities, and supporting logistic assets may themselves become targets of attack, introducing an additional layer of risk for both rescuers and survivors. This heightened threat environment not only complicates the execution of rescue missions but also raises profound ethical dilemmas regarding the safety of personnel and the feasibility of operations in active war zones. And at an extreme: search and rescue operations may not be achievable in wartime conditions.

Additionally, survivors of submarine incidents often require specialized medical care that may exceed the capabilities available within the operational theater, such as the rescue vessel or nearby naval ships. If advanced treatment cannot be provided on-site, patients must be evacuated, typically by helicopter, to shore-based medical facilities. Aeromedical evacuation is a highly specialized field, demanding precise coordination and expertise. However, if geographical, meteorological, or operational conditions prevent safe transport, survivors must receive prolonged field care aboard the rescue vessel or nearby ships. This scenario introduces significant challenges, as medical personnel must manage critical conditions with limited resources, equipment, and personnel, further complicating the rescue operation and potentially impacting patient outcomes.

Ethical dilemmas

Submarine incidents of the last 25 years have predominantly occurred outside the context of large-scale armed conflict. However, in open warfare, the availability of medical resources, both personnel and equipment, may be severely constrained. Military command structures may deprioritize or delay submarine rescue operations if they are deemed to divert critical assets from other strategic or humanitarian priorities. The decision to allocate substantial resources, such as DSRV, hyperbaric chambers, and specialized medical teams, to a single rescue mission could compromise care in other sectors of the conflict, particularly if escalating threats necessitate the premature termination of rescue efforts.

Such operational trade-offs pose significant ethical conflicts for military leaders and healthcare providers. The failure to launch a rescue operation, even when justified by strategic necessity, can inflict profound moral distress on personnel, particularly those with a duty to protect and preserve life. Recent conflicts have highlighted the psychological toll of these decisions, with military and medical personnel experiencing lasting emotional and mental health consequences, including post-traumatic stress disorder, depression, and moral injury. The inability to intervene, whether due to resource limitations, security risks, or command directives, can leave deep and enduring scars on those involved. Survivors may struggle with "survivor’s guilt," while rescuers may grapple with the emotional weight of their decisions, particularly if not all crew members could be saved. Additionally, as psychological sequelae may manifest years after the incident, this underscores the need for proactive mental health support for all individuals involved in submarine rescue missions.

Conclusions

Submarine accidents represent an extreme and logistically demanding scenario in disaster and emergency medicine. The combination of the austere location, high-pressure environment, and physiological deterioration creates a perfect storm of medical, operational, and ethical challenges. The cases in this manuscript illustrate the tension between technological capability and environmental constraints, and underscore the critical importance of rapid distress signaling, effective damage control, and international cooperation in mitigating catastrophic outcomes. However, despite advancements in technology, the inherent risks of deep-sea operations, including DCS, barotrauma, toxic exposures, and the psychological toll of entrapment, remain considerable challenges. Medical treatment of survivors may require HBOT, which present additional challenges in the management of critically ill patients and introduces risks for the medical personnel themselves if not managed accordingly. The scarcity of specialized rescue assets, such as DSRV and HBOT in an austere environment further complicate the feasibility of these operations, especially in armed conflicts.

Beyond the immediate technical and medical responses, submarine accidents pose broader questions for emergency medicine, critical care, and disaster preparedness. The need for adaptive triage systems, considering both trauma severity and decompression risk, demonstrates the necessity of integrating specialized knowledge into mainstream emergency protocols and regular training. Clinicians and rescue personnel must be prepared to navigate not only the physiological complexities of DCS and barotrauma, but also the ethical dilemmas that arise in resource-limited or hostile environments.

List of abbreviations

AGE	Arterial Gas Embolism
DCI	Decompression Illness
DCS	Decompression Sickness
DSRV	Deep Sea Rescue Vehicles
HBOT	Hyperbaric Oxygen Therapy
ISMERLO	International Submarine Escape and Rescue Liaison Office
NATO	North Atlantic Treaty Organization
NSRS	NATO Submarine Rescue System

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Table 1 - System for mass triage of submarine casualties

	C1	C2	C3	C4
T1	Require immediate medical treatment Require immediate recompression	Require lifesaving immediate medical treatment Require non-urgent recompression	Require immediate lifesaving medical treatment Require surface oxygen and non-urgent recompression	Require immediate lifesaving medical treatment No indication that recompression is required
T2	Require non-lifesaving major medical treatment Require immediate recompression	Require non-lifesaving major medical treatment Require non-urgent recompression	Require non-lifesaving major medical treatment Require surface oxygen and non-urgent recompression	Require non-lifesaving major medical treatment No indication that recompression is required
T3	Require minor general medical	Require minor general medical	Require minor general medical	Require minor general medical

	care / observation Require immediate recompression	care / observation Require non-urgent recompression	care / observation Require surface oxygen and non-urgent recompression	care / observation No indication that recompression is required
T4	Unsurvivable with available treatment resources – palliative treatment only			