

Undersea and Hyperbaric Medicine

Case Studies and Review

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ABSTRACT

There is a dearth of studies in undersea and hyperbaric medicine (UHM), likely due to the limited number of clinicians currently specializing in UHM. Due to the high-consequence nature of diving and the effects of pressure on the human body, medical clearance is of the utmost importance. Despite all efforts to mitigate the possibilities of dive maladies, divers occasionally succumb to the effects of prolonged submersion. This article provides an in-depth look at three individuals who suffered from separate dive-related medical events. In each example, UHM was applied and successfully mitigated short and long-term medical consequences. The manuscript then reviews common and life-threatening dive maladies, with an in-depth examination of decompression strategies and diving clearance.

KEYWORDS: *undersea and hyperbaric medicine; hyperbaric medicine; diving medicine; dive; recompression chamber; emergency evacuation hyperbaric stretchers; pulmonary overinflation syndrome; decompression sickness; decompression illness; barotrauma*

Introduction

This article provides an in-depth look at three individuals who suffered from separate dive-related medical events. In each example, undersea and hyperbaric medicine (UHM) was applied and successfully mitigated short and long-term medical consequences. Following these case studies, the manuscript reviews common and life-threatening dive maladies, with an in-depth examination of decompression strategies and diving clearance.

Case 1

In September 2023, an Army engineer diver conducted a dive in Kauai, Hawaii. There was a diving medical technician (DMT) and hyperbaric chamber at the job site, and definitive care was located on the island of Oahu, approximately 120 miles away. The dive in question had a maximum depth of 72 feet of seawater (FSW) and a bottom time of 37 minutes. The diver was operating solo, per operational requirements, with a standby diver ready. The diver's ascent took 1:07min, more than doubling the allowable travel rate. The diver reported issues with his buoyancy compensator not deflating properly. Upon surfacing, the diver had no complaints, was examined, and placed under direct supervision; 13 minutes after surfacing, he reported a numb region on his chest. The diver was immediately placed on 100% O₂ and transported to the hyperbaric

chamber by the unit's DMT. Upon reaching the chamber, the area of numbness had spread, and he was recompressed to a treatment depth of 60FSW. A Navy Undersea Medical Officer (UMO) was consulted, and the patient completed a Treatment Table Six (described below) with no extensions, and symptoms were completely relieved. The patient was diagnosed with an arterial gas embolism (AGE) caused, in part, by a rapid ascent. The diver has since fully recovered and returned to diving duty after being cleared by an Army Diving Medical Officer (DMO) and Navy UMO.

Case 2

An Army engineer diver was conducting a dive off the coast of Hawaii with a maximum depth of 85 feet and a bottom time of 20 minutes. She experienced some facial pain during the descent but continued the dive. Upon surfacing, she had severe light sensitivity and diffuse subconjunctival hemorrhage. The patient was seen in the emergency department and released with the direction to apply cold compresses. Twelve days later she was seen by her DMO, who diagnosed her with facial barotrauma due to mask squeeze. This was caused by the failure to equalize the mask properly during descent. Her symptoms had continued to improve, but she still had light sensitivity and conjunctival erythema at this point. She denied blurry vision or hyphema at any time. The patient was referred to ophthalmology, who conducted an assessment 5 days later. The ophthalmologist confirmed the diagnosis of subconjunctival hemorrhage and cleared her to return to dive duty.

Case 3

In May 2023, the National Oceanic Atmospheric Administration (NOAA) Ship Rainier conducted scientific diving operations in the South Pacific Ocean. On board were approximately 35 crew, including eight scientific divers, two DMTs, and an Army DMO. Throughout the first 2 weeks of this leg of the journey, the divers sustained no major medical issues other than motion sickness and a mild case of middle ear barotrauma, colloquially referred to as "the squeeze." At this time, the Rainier was still days away from definitive medical care, operating solely under the supervision of the DMO, DMTs, and dive supervisor with a hyperbaric chamber on board.

The divers were conducting their fourth consecutive day of diving operations off the coast of Howland Island when one of the divers fell ill. They conducted approximately five to six dives daily, ranging between 20 and 45 feet in depth for

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approximately 40–60 minutes per dive. They remained well within no-decompression limits.¹ Approximately 30 minutes after the day's second dive, one of the divers operating on a small boat approximately 2 miles from the ship began to feel ill. The diver reported headaches, dizziness, nausea, and confusion, which was radioed back to the ship. Surface temperatures were approximately 100°F (37.8°C).

The DMO and dive supervisor immediately started gathering information, the boat was recalled, and the hyperbaric chamber was prepped. The immediate concern was type II (neurogenic) decompression sickness. The patient denied any paresthesia, vomiting, chest pain, or dyspnea. The diver reported a history of migraines with similar features to what she was currently experiencing.

Upon returning to the boat, a complete neurological examination was completed. A 0.9% normal saline (NS) intravenous (IV) line was started, oral rehydration and passive cooling were begun, and the patient took sumatriptan, ibuprofen, and Tylenol. The neurological exam was unchanged from the patient's baseline, and symptoms improved rapidly with the above interventions. It was determined that the patient was experiencing migraine headaches likely related to heat exhaustion and dehydration, so there was no need for recompression treatment. The patient was closely monitored for the rest of the day with continued improvement and returned to diving operations 48 hours later after being cleared by the DMO.

Case Study Summary

These conditions outlined above are a sample of what medical personnel supporting military or government diving operations must be prepared to manage. Through military diving operations, there is also a concern for type I (musculoskeletal) decompression sickness (DCS), musculoskeletal injuries, oxygen toxicity, toxic gas exposure, hypercapnia, aquatic wildlife-related injuries, and many others. These operations often occur in remote or austere environments, days from definitive care. Military DMOs must be prepared to manage these conditions with minimal to no support, delayed evacuation capabilities, and limited supplies.

Discussion

Injuries or maladies relating to underwater diving range from mild to life-threatening.

Middle Ear Barotrauma

The most common barotrauma injury is middle ear barotrauma, which can cause a range from mild hyperemia to ruptured tympanic membrane (TM).² Occurring primarily during descent, this phenomenon occurs when the ambient pressure exceeds that of the middle ear. This increasing pressure forces the TM inward, initially equalizing the pressure by compressing the middle ear gas out via the eustachian tube. This is commonly referred to as a middle ear squeeze. The best way to eliminate a squeeze is to stop descending, squeeze the nose, and Valsalva; this forces the eustachian tube open, allowing pressure to equalize.

In those with middle ear dysfunction or in those who descend too fast without equalizing often, the stretching capability of the TM is limited. At a certain point, the middle ear pressure exceeds the ambient pressure, which creates a vacuum in the middle ear. This negative pressure results in the vasculature of

the TM and lining of the middle ear to first expand, then leak, and ultimately rupture.¹ In these cases, pain is the primary presenting symptom of a middle-ear squeeze. A more ominous sign in this case is when the pain becomes so severe and suddenly stops. In this situation, pressure has likely equalized due to a TM rupture.

The most common finding and best diagnostic assessment is a notable history of the symptoms previously mentioned, along with the presence of a hemorrhagic TM upon surfacing.³ A thorough history in these cases will likely reveal a history of congestion, allergies, or cold symptoms before diving, resulting in eustachian tube dysfunction and the inability to “clear” the squeeze. The most effective management of middle ear barotrauma is education and prevention. Frequent clearing during descent is a necessity for a safe dive. Although it is wise to avoid diving operations when congested, decongestants are often used as a “quick fix” to facilitate clearing, especially if the mission is time sensitive. Following injury, however, treatment is centered around pain management and decongestants as necessary. A small-diameter ruptured TM routinely heals without surgical intervention; otolaryngology referral should be reserved for large-diameter ruptures and prolonged duration at depth with rupture or delays in the initial evaluation. Antibiotic drops such as non-ototoxic fluoroquinolones may be indicated when a TM rupture is combined with suspected middle ear contamination OR evidence of infection.⁴

Sinus Squeeze and Facial Barotrauma

Sinus squeeze is another common injury among those who dive and can be described as increasing pain and pressure over the maxillary or frontal sinuses. While middle ear barotrauma occurs in approximately 10% of divers, sinus barotrauma occurs in less than 1%.⁵ Diving should be avoided when an individual has any signs and symptoms of sinus congestion to avoid this malady.¹ Management of these symptoms involves immediately halting descent and ascending to the depth where symptoms resolve. Another common condition is facial barotrauma caused by mask squeeze (as seen in case 2) when a vacuum effect is caused within the mask during descent due to the increasing pressure and decreasing air volume within the mask. According to the *U.S. Navy Diving Manual*, looking up, putting two fingers on the top of the goggles, and exhaling forcefully through the nose can generally equalize the pressure in a face mask.¹ Goggles that do not cover the nose remove the ability to clear mask squeeze and should, therefore, only be used for surface swimming. Mask squeeze often leads to ecchymosis of the face along with subconjunctival hemorrhage. This generally resolves without treatment; however, severe cases may necessitate an ophthalmology consult.

Pulmonary Overinflation Syndrome

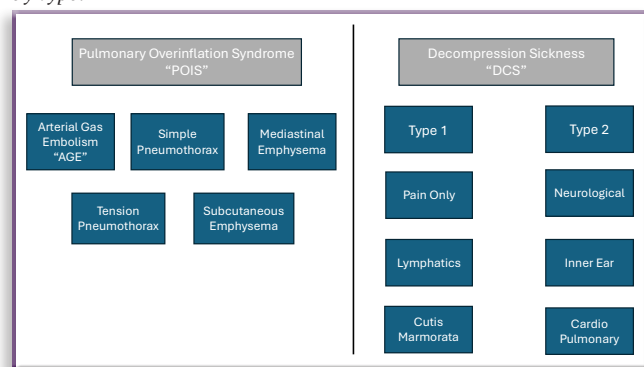
Less common but more severe injuries fall under the umbrella of decompression illness (DCI). DCI is further subclassified into pulmonary overinflation syndrome (POIS) and DCS. POIS is best understood during diving by applying Boyle's law, as this describes how water pressure affects the lungs. As a diver descends, water pressure increases, causing the air within the lungs to be compressed and occupy a smaller volume. As a diver ascends, water pressure decreases, causing the air within the lungs to expand and occupy a larger volume. Based on this phenomenon, if a diver holds their breath during ascent, the lungs will continue to over-expand until they burst. As a result, POIS almost always occurs during the ascent portion of a

dive.¹ As a safety precaution, divers must continuously breathe out as they ascend from depth.

POIS includes AGE, pneumothorax, and mediastinal or subcutaneous emphysema. In addition to not exhaling during the ascent, these injuries can also occur in individuals with asthma or chronic obstructive pulmonary disease, which causes air trapping and local pulmonary obstructions. This overinflation can lead to AGE, which may include apnea, unconsciousness, seizure, vertigo, sensory changes, confusion, loss of coordination, visual changes, weakness, numbness, and/or convulsions, which can manifest within minutes of surfacing.³ This was evident in case 1, where the patient began developing symptoms 13 minutes after surfacing.

Treatment for POIS includes 100% oxygen, basic first aid, and immediate recompression as necessary.⁶ Application of Advanced Cardiac Life Support protocols, needle chest decompression, and tube or open thoracostomy may also be required to treat POIS.¹ The best strategy is POIS prevention, which highlights the importance of well-trained and calm divers who do not panic and continually exhale during ascent. Equally important is the diver's need to report any current illness or medical conditions to a dive supervisor before diving (Figure 1).

FIGURE 1 Decompression illness (DCI) diving maladies separated by type.



Decompression Sickness: Types and Symptoms

DCS is the other subset of DCI. DCS is caused by the buildup of inert gasses, primarily nitrogen, which creates bubbles within a diver's tissue or vasculature.³ This phenomenon can best be understood by an application of Henry's law, whereby the amount of dissolved gas in a liquid is directly proportional to the partial pressure of that gas. Thus, gasses are absorbed into body tissue more quickly at an increased depth due to increased pressure. DCS is a byproduct of the dive depth and duration of time spent at depth. As a diver ascends, pressure decreases, which results in the release of inert gas from the blood, causing DCS.

DCS is further subclassified as type I and type II. Type I DCS is generally less severe and involves the skin, lymphatic system, muscles, and joints. Type II DCS can be life-threatening and affects the nervous system, respiratory system, or cardiovascular system¹. The signs and symptoms of DCS depend on the type. Type I DCS symptoms may include burning of the skin or rash, swollen lymph nodes, and/or joint pain (usually unilateral and only one joint). Type II DCS symptoms vary based on the body system affected, which may include blindness, dyspnea, hypoxia, paralysis, chest pain, and ear pain, among others.¹ Type II DCS symptoms may be delayed and occur from minutes after surfacing to a few days after the dive.¹

Decompression Sickness: Treatment

Treatment for type I DCS varies by severity. According to the U.S. Navy treatment tables, type II DCS is treated with 100% oxygen and immediate recompression.¹ Recompression involves taking a diver back to "depth" under pressure (hyperbaric) to increase the partial pressure of oxygen (PO₂) at treatment depth, thus increasing the oxygen gradient and pulling nitrogen (N₂) out of the system, followed by slow ascension with safety stops to prevent bubble formation in the bloodstream and tissues. This can be done at depth or out of water in a hyperbaric chamber,⁷ although chamber recompression is preferred. Recompression should be done as quickly as possible, as delays of over 24 hours are associated with a far higher rate of residual symptoms after recompression therapy.⁸ As seen in Figure 2, the *U.S. Navy Diving Manual* has a series of treatment tables that describe indications and treatment strategies for injured divers using hyperbaric chambers to achieve recompression.¹

The preferred method for out-of-water recompression is the dual-lock/multi-place recompression chamber (Figure 4). This chamber allows inside tenders to be changed out if needed and allows supplies larger than the med-lock to be locked into the treatment lock. Unfortunately, these are located at fixed facilities across the country and are not transportable. There are many occasions where dive operations occur in austere environments or remote locations. In these cases, time to a certified recompression chamber may exceed 12 hours, so the Transportable Recompression Chamber System (TRCS) or Standard Navy Double Lock (SNDL) containerized recompression chambers are forward deployed to afloat staging bases and shore installations. In instances where it is not possible to secure a TRCS or SNDL due to the urgency/security of the mission or lack of regional sites, the portable and deployable emergency evacuation hyperbaric stretchers (EEHS, Figure 3) may be used as a single-person emergency transport tool for a diver who requires immediate emergency recompression.

Military divers use the *U.S. Navy Diving Manual* to determine how deep and long their dives can be. The dive tables within this text prescribe how long a diver may stay at a certain depth before needing to surface and if they need to conduct a decompression stop along the way (Figure 5). A recompression stop would be a prescribed period of time stopped at a specific depth to off-gas inert gasses before continuing the ascent to the surface.¹ There are no-decompression tables for many depths, decompression tables at various depths, repetitive dive tables, and tables for different air mixes such as air, 100% O₂, or nitrox. These tables were first developed by the U.S. Navy in 1915 and have been regularly updated and expanded upon based on new evidence and advances in diving.⁹

Medical Dive Clearance

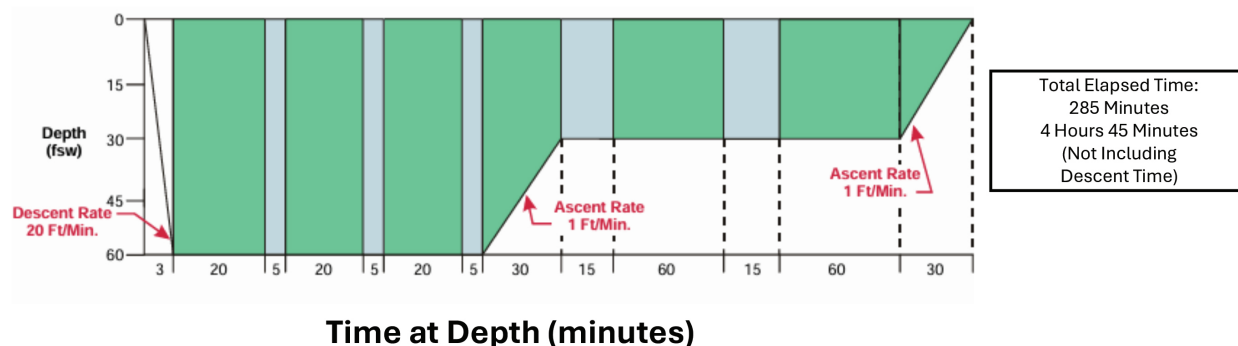
Underwater diving is not without significant risks. For these reasons, medical dive clearance is warranted in civilian and military environments. Diving, even at shallow depths, puts severe stress on the respiratory system, cardiovascular system, and middle ear, so medical providers who are certifying divers should have a modicum of knowledge on the topic.¹⁰

For civilian recreational diving, clearance can be completed by any medical provider. In 2020, the World Recreational Scuba Training Council endorsed a new medical screening system for recreational scuba diving and freediving.¹¹ This system has three tiers, the first of which is a participant questionnaire.

FIGURE 2 U.S. Navy Diving Manual Treatment Table 6 – Depth/Time Profile used to treat arterial gas embolism (AGE), Type II decompression illness (DCS), moderate-severe Type I DCS, cutis marmorata, among others.¹

1. Descent rate – 20 ft/min.
2. Ascent rate – Not to exceed 1 ft/min. Do not compensate for slower ascent rates. Compensate for faster rates by halting the ascent.
3. Time on oxygen begins on arrival at 60 feet.
4. If oxygen breathing must be interrupted because of CNS Oxygen Toxicity, allow 15 minutes after the reaction has entirely subsided and resume schedule at point of interruption (see paragraph 17-8.10.1.1).
5. Table 6 can be lengthened up to 2 additional 25-minute periods at 60 feet (20 minutes on oxygen and 5 minutes on air), or up to 2 additional 75-minute periods at 30 feet (15 minutes on air and 60 minutes on oxygen), or both.
6. Tender breathes 100% O₂ during the last 30 minutes at 30 Feet of Seawater (FSW) and during ascent to the surface for an unmodified table or where there has been only a single extension at 30 or 60 feet. If there has been more than one extension, the O₂ breathing at 30 feet is increased to 60 minutes. If the tender had a hyperbaric exposure within the past 18 hours, an additional 60-minute O₂ period is taken at 30 feet.

Treatment Table 6 Depth/Time Profile



Adapted from U.S. Navy Diving Manual – Revision 7a.
CNS = central nervous system.



FIGURE 3 Emergency evacuation hyperbaric stretchers (EEHS) “Hyperlite” portable recompression chamber, assembled.

FIGURE 4 Dual-lock/multi-place recompression chamber at the National Oceanic Atmospheric Administration (NOAA) in Seattle, WA.



If the participant answers yes to any of the screening questions, the second tier of the system requires clearance by a medical provider. The final tier requires a provider to use the UHM Guidance on the Undersea & Hyperbaric Medical Society website if the provider is unsure if the participant should be cleared for diving.¹² The most popular diver certification organizations include the Professional Association of Diving Instructors (PADI), the National Association of Underwater Instructors (NAUI), Scuba Diving International (SDI), and Scuba Schools International (SSI), all of which follow this medical screening system. Surprisingly, recreational divers are only required to obtain an initial medical dive clearance and can continue throughout their lives without any routine follow-up clearance.

Diving medical clearance in the military is more involved and includes more thorough evaluations. All prospective divers must undergo a physical examination, including a patient questionnaire, chest x-ray, laboratory tests, optometry clearance, hearing evaluation, and a complete physical examination. These items are documented on medical forms specific to each Service. The credentialed medical provider who completes the examination and where the results are sent depends on the branch of service and where the dive training occurs.

Conclusion

The types and presentations of dive injuries are vast. It is important for medical providers, particularly those in the Special Operations community, to have a general awareness of the causes, symptoms, and treatments for the most common and most severe dive injuries. Dive injuries can vary from minor (e.g., the facial barotrauma seen in case 2) to life-threatening (e.g., the AGE in case 1). It is also important to cast a wide differential during diving and not only focus on dive injuries. This is incredibly important to providers as awareness of the patient's history and understanding of the patient's presentation in case 3 prevented unnecessary recompression and evacuation in a remote environment.

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Author Contributions

MD and JR studied the topic in tandem. They both studied the topic in tandem. They jointly developed the format for

FIGURE 5 180 feet of seawater (FSW) dive table with decompression stops from the U.S. Navy Diving Manual.¹

Table 9-9. Air Decompression Table (Continued). (DESCENT RATE 75 FPM—ASCENT RATE 30 FPM)															
Bottom Time (min)	Time to First Stop (M:S)	Gas Mix	DECOMPRESSION STOPS (FSW) Stop times (min) include travel time, except first air and first O ₂ stop										Total Ascent Time (M:S)	Chamber O ₂ Periods	Repet Group
			100	90	80	70	60	50	40	30	20				
180 FSW															
6	6:00	AIR										0	6:00	0	E
		AIR/O ₂										0	6:00		
10	5:20	AIR										8	14:00	0.5	G
		AIR/O ₂										4	10:00		
In-Water Air/O ₂ Decompression or SurDO ₂ Recommended -----															
15	4:40	AIR								2	3	14	24:20	0.5	K
		AIR/O ₂								2	2	7	16:40		
20	4:20	AIR							1	5	7	29	47:00	1	M
		AIR/O ₂							1	5	3	15	29:20		
25	4:20	AIR							5	6	7	57	80:00	1.5	O
		AIR/O ₂							5	6	4	24	44:20		
Exceptional Exposure: In-Water Air Decompression ----- In-Water Air/O ₂ Decompression or SurDO ₂ Required -----															
30	4:00	AIR						3	6	6	7	95	121:40	1.5	Z
		AIR/O ₂						3	6	6	4	34	63:00		
35	3:40	AIR				1	5	6	6	6	22	144	188:20	2	Z
		AIR/O ₂				1	5	6	6	11	41	79:40			
Exceptional Exposure: In-Water Air/O ₂ Decompression ----- SurDO ₂ Required-----															
40	3:40	AIR				2	6	5	13	28	178	236:20	2.5		
		AIR/O ₂				2	6	5	13	14	48	97:40			
45	3:40	AIR				4	5	10	20	28	235	306:20	3		
		AIR/O ₂				4	5	10	20	14	63	130:40			
50	3:40	AIR				4	8	13	25	29	277	360:20	3.5		
		AIR/O ₂				4	8	13	25	15	75	154:40			
55	3:40	AIR				5	11	19	26	28	336	429:20	4		
		AIR/O ₂				5	11	19	26	14	87	181:40			
Exceptional Exposure: SurDO ₂ -----															
60	3:20	AIR			1	8	13	23	25	31	406	511:00	4.5		
		AIR/O ₂			1	8	13	23	25	16	100	205:20			
70	3:20	AIR			4	12	21	24	25	48	499	637:00	5.5		
		AIR/O ₂			4	12	21	24	25	24	119	253:20			
9-82															
U.S. Navy Diving Manual — Volume 2															

presenting this information to the reader. MD recorded the cases from personal experience. MD and JR conducted research and wrote the review. Both authors reviewed and approved the final manuscript.

Disclosures

The authors have nothing to disclose.

Disclaimer

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