Aerospace Medicine Clinic

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You are a military flight surgeon assigned to a flight medicine clinic. This is your week to man the on-call phone and, as luck would have it, you receive a call from a Dive Medical Officer (DMO) from a sister military service. The DMO states that one of your unit's rotary wing crew chiefs was involved in a recreational diving accident earlier today while on leave. The DMO assures you that the crew chief does not appear to be seriously injured but is being treated in a hyperbaric chamber. You appreciate that the DMO has reached out in a timely fashion and is going to update you periodically throughout the day to make sure that you are informed about the details of the event and the service member's treatment course.

The DMO states that on the second scuba recreational dive of the day, the service member experienced what appeared to be an arterial gas embolism (AGE) after exceeding the travel rate on ascent from his dive. The crew chief is a novice diver who was using compressed air and was in the company of experienced military divers who initiated an emergency action plan. This plan included diving first aid and immediate ground evacuation to a nearby military recompression chamber for recompression treatment under the supervision of the DMO who was on call.

The divers were attempting to dive a shipwreck with a maximum bottom depth of 72 ft of seawater (fsw). The service member left the bottom after 37 min of bottom time. He reached the surface 1.0 min and 7.0 s after leaving the bottom, more than doubling the allowable travel rate. According to the DMO, the prescribed dive table and schedule stated that the service member's ascent was to have taken no less than 2 min and 24 s from 72 fsw. You are not a diver. However, training in aerospace medicine has given you a background in the subject and you ask about how the first dive could have contributed to the problem. The DMO is happy that you asked the question, as repetitive diving can increase the odds of decompression sickness (DCS) due to a series of additive exposures and the possible cumulative retention of nitrogen gas (i.e., "residual nitrogen"). In this case, the first dive was a short test of the equipment and an orientation to the dive environment. It was at a depth of approximately 15 ft (5 m) at a bottom time of 10 min and would not require safety stops or other extensive surface time. With a lot to think about, you turn your attention to ascent rates and what rates the U.S. Navy recommends.

1. What is the generally recommended ascent rate for scuba dives put forth by the U.S. Navy?
   A. 60 ft · min^{-1} (18 m · min^{-1}).
   B. 30 ft · min^{-1} (9 m · min^{-1}).
   C. Ascend slower than the bubbles coming from your respirator.
   D. 75 ft · min^{-1} (22.5 m · min^{-1}).

ANSWER/DISCUSSION

1. B. The U.S. Navy Diving Manual section 9-6.3 states, "The ascent rate from the bottom to the first decompression stop, between decompression stops, and from the last decompression stop to the surface is 30 fsw/min".[1] The National Oceanic and Atmospheric Administration also uses this rate. The Professional Association of Diving Instructors and other civilian diving organizations use 60 fsw/min when ascending from more than 60 fsw. Ascending slower than the bubbles coming from your respirator is a poor rule of thumb that has been used unofficially for years. In addition, it was used by the U.S. Navy from 1957–1991 for hard-hat divers using surface-supplied air. Ascending at 75 ft · min^{-1} (22.5 m · min^{-1}) is too rapid and it is not generally endorsed as a safe procedure.

Your crew chief was ascending at a rate of approximately 65.5 ft · s^{-1} (19.3 m · s^{-1}), not the 30 ft · min^{-1} (9 m · min^{-1}) that would have taken him 2 min and 24 s to surface. Shooting to the surface so quickly greatly increased his risk of developing decompression illness (DCI), and this did not account for the possible decompression stops he may have missed. The service member may have needed to break up his ascent with stops at

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intermediate depths for appropriate wait times before continuing the ascent to more safely manage the DCI risk.

2. What are some common reasons for ascending too quickly on a dive?
   A. Diver does not monitor air supply, resulting in an out-of-air situation.
   B. Inadequate buoyancy control.
   C. Failure to properly monitor ascent rate.
   D. Buoyancy compensator or other equipment failure.
   E. All of the above.

ANSWER/DISCUSSION

2. E. All of the above answers are correct. However, there are additional reasons that may lead to a rapid or uncontrolled ascent to the surface, such as seeing a shark, following another diver who is ascending too rapidly, or suffering an injury.[2] Fatigue, physical fitness, and lack of experience or training on the part of the diver also contribute to the increased incidence of diving injuries.[3] Obtaining a history where the patient or witness attests to a rapid ascent can help narrow the differential diagnosis to AGE. This can help differentiate between the presentations of more common concerns, such as hypoglycemia or acute hemorrhagic stroke.[2]

The DMO describes that the patient stated he knew he exceeded the travel rate; however, he suggested his buoyancy compensator was not deflating properly, contributing to the cause of his fast ascent. The service member exited the water under his own power. The more experienced divers, following their military training, stripped the crew chief of his equipment and performed a rapid neurological exam after surfacing and placed him under direct observation. The service member reported no concerns at the surface and the rapid neuro exam was normal. However, after 13 min of observation, the diver notified his friends that he felt tingling that turned to numbness of his right flank. Initially, a 4.5-in diameter numb spot was mapped approximately 6.0″ under his right nipple. He was placed on 100% oxygen, delivered by a venturi mask, at a rate of $15\ L \cdot min^{-1}$ while being transferred to shore and to the dive treatment facility. A more robust neurological exam was in progress under transit conditions. The numb spot was observed to be growing laterally from the sternum toward the patient's right side.

The patient is now in a recompression chamber under the supervision of the DMO. After 20 min of treatment using the "standard of care" (i.e., Navy Dive Table VI), his vitals are within normal limits and the numb patch is less than a quarter of its original size. You thank the DMO for the call and you are standing by for updates as the treatment continues.

3. Which one of the following is NOT part of a Navy Dive Table VI?
   A. 5-min compression phases to a depth of 18 m of seawater (msw).
   B. A decompression phase to 9.0 msw.
   C. 2 air cycles lasting 60 min each.
   D. 285 min of total elapsed time.

ANSWER/DISCUSSION

3. C. The cycles use 100% oxygen, not air. The bubbles causing the problem are most likely nitrogen. As air contains approximately 71% nitrogen, breathing 100% oxygen is best to flush out the nitrogen, rather than breathing in more nitrogen. Navy Dive Table VI consists of a compression phase approximately 5 min long to a depth of 18 msw under 100% oxygen, and four oxygen cycles lasting 20 min each with short air intervals. Afterward, the patient is decompressed to approximately 9 msw and exposed to two oxygen cycles lasting 60 min each and slowly returned to surface pressure. The total elapsed time is approximately 285 min (4 h 45 min). Navy Dive Table V is similar to Dive Table VI, but with shorter and fewer oxygen cycles; the total elapsed time is approximately 135 min, excluding descent.[2]

The DMO mentioned that the hyperbaric chamber should help the patient, no matter what type of DCI he has. He reminds you that "decompression illness" refers to DCS Type 1 (cutaneous and musculoskeletal) and Type 2 (neurological), as well as AGE. As the patient will be flying home by commercial air upon release from treatment, you discuss air travel after scuba diving. After a single dive, a 12-h minimum surface time is recommended before flying on commercial aircraft or 18 h after multiple dives. However, at least 24 h is recommended. The DMO assures you that the patient will not be flying for several days.

Although the extent of the crew chief's injuries seems minor, you want to be prepared to answer the patient's questions upon his return. You look into the literature to be better informed about AGE. You find there are two major causes of AGE: direct injection of a gas into the blood, such as what might occur during the catheterization of a blood vessel, and spontaneous bubble formation, as seen in DCS in underwater divers (and more rarely, aircrew).[4] According to Henry's Law, the increased pressure experienced at depth by a diver allows more gas to dissolve in the blood and tissues than the lower pressure at the surface. With the decreasing pressure as the diver ascends from depth, less gas stays dissolved. This leads to gas bubbles evolving from the tissues of the body. The more rapidly a diver ascends, the faster gas will evolve and the less likely that the forming bubbles can be released safely. A rapid ascent raises the chances of harmful consequences, including the occurrence of AGE.[5]

AGE in divers can result from bubbles entering the arteries directly after the pulmonary barotrauma of ruptured alveoli. It may also occur if bubbles in the venous circulation pass into the arterial circulation through a patent foramen ovale. Alternatively, there can be so many nitrogen bubbles present in the veins that the pulmonary capillaries cannot exchange gas into the alveoli before blood passes into the arterial system.[6]

Increased risk for DCI includes deep or long-duration underwater dives, especially when the dives include vigorous physical activity as seen in military operations. Boyle's Law states that as ambient pressure decreases, the volume of a gas increases. An uncontrolled ascent can be provocative for AGE, especially if the diver holds their breath. Here the trapped air can overinflate the lungs due to the rapid air expansion with ascension, resulting in pulmonary barotrauma. Resulting gas bubbles can move through the arteries to other organs such as the heart or brain and block blood flow, causing a myriad of symptoms such as chest pain, confusion, unconsciousness, weakness, numbness, and tingling. Additionally, gas may make its way to the tissues just under the skin, becoming palpable bubbles called subcutaneous emphysema.[6–8]

The fundamental pathology present during an episode of AGE is caused by two major mechanisms.[2] The first cause is a physical blockage of blood flow by the presence of the gaseous mass. The second is mechanical endothelial damage to the vessel because of the bubble acting as a foreign substance, inducing inflammatory and coagulation cascades.[2] Damage to the endothelium triggers many mechanisms, including the release of C3a and C5a anaphylatoxins during complement activation, increases in prostaglandin and leukotriene production, platelet and leukocyte activation, and fibrin release with endothelium adhesion. This cascade causes impairment of the microcirculation, vasospasm followed by vasodilation, and damage to the blood brain barrier.[9] Both mechanisms can lead to hypoxia in the surrounding tissues, with potentially life-threatening consequences in vital organs such as the brain or heart.[4]

In contrast, DCS is not caused by rupture of lung tissue and air being introduced into the arteries. In DCS, there is a spontaneous evolution of dissolved nitrogen gas bubbles in the blood and other tissues as the diver begins to head for the surface per Henry's Law. At deep-sea levels, high ambient pressure forces nitrogen gas to equilibrate in the diver's tissues. Slow ascent allows tissues to gradually re-equilibrate to the ambient pressure and release nitrogen slowly and safely. The bubbles that can form during a rapid ascent press on surrounding structures, compress nerve endings, impede venous return, and produce inflammatory responses as a foreign body would. These insults have wide-ranging consequences with symptoms that may include fatigue, rash, shortness of breath, confusion, joint pain, skin pruritis, numbness, tingling, muscle weakness, an impaired gait, or difficulty walking.[1,8]

If the patient has skin itching or burning and/or joint or muscle pain, this is considered Type 1 DCS and Treatment Table V may be used. However, if a patient is suspected to have an AGE or Type 2 DCS (circulatory, respiratory, or neurological symptoms), the standard is Treatment Table VI.[1,10]

Looking at Table IX-VII, No Decompression Limits and Repetitive Group Designators for No-Compression Air Dives, in the Navy Diving Manual, you check to see if the patient's bottom depth and time required a safety stop to aid in lowering the risk of DCS. While this dive was technically a repetitive dive, the initial dive was at 15 ft (5 m) for less than 34 min. For the second dive, the diver spent 37 min beneath 72 fsw. Table IX-VII has entries for 70 ft (21 m) and 80 ft (24 m). One would need 48 min at 70 ft and 39 min at 80 ft to require a safety stop. Since the diver spent less than 39 min at 72 ft (22 m), he was not required to perform a safety stop on his way up.[1]

When comparing the Navy Diving Manual to civilian/recreational tables, the civilian/recreational tables are more conservative. The recommendation for safety stops and considerations for repetitive dives usually start after dives of 30 fsw or greater. While civilian dive tables also have entries for 70 ft and 80 ft, convention recommends rounding up. On a civilian dive table, one would need 38 min at 70 ft and 29 min at 80 ft to require a safety stop. Since the diver spent 37 min at 72 ft, he would have been required to perform a safety stop on his way up if using a civilian dive table, rather than a Navy dive table.

Despite not needing a safety stop according to the Navy dive tables, our diver ascended much more quickly than recommended (1 min and 7 s compared to the recommended 2 min and 24 s maximum ascent rate per the Navy Diving Manual), which put him at high risk for pulmonary barotrauma and subsequent AGE. However, overlap in symptom profiles makes it difficult to tell for sure that he had AGE rather than Type 2 DCS. In either case, he received the correct treatment. Unfortunately, now that the diagnosis of AGE has entered his medical record, it must be addressed by the flight surgeon. Knowing that this injury has implications for the patient's aviation career, you decide to review his service's specific aeromedical regulations as well as those of the sister services and civilian aviation organizations.

The U.S. Navy Aeromedical Reference and Waiver Guide does not specifically address AGEs but does have a guideline for DCS. A consultation with a neurologist at the Naval Aerospace Medical Institute is required prior to returning to flight duty. They also require a normal evaluation by a DMO or neurologist. Before an aviator with Type 1 DCS can fly again, they require a period of 3 d or more with no symptoms; in contrast, an episode of Type 2 DCS requires 14 d or more symptom-free. Episodes of DCS with lingering symptoms warrant caution and are disqualifying for flight duties, with the possibility of a waiver being granted after further workup, such as a neurological workup and, if necessary, a neuropsychological evaluation.[10] It should be mentioned that the Navy's Manual of the Medical Department chapter 15-84 states that AGEs are disqualifying for flight duties.[11]

The U.S. Army's Aeromedical Policy Letters state that recurrent Type 1 DCS or any case of Type 2 DCS requires a waiver, which is granted on a case-by-case basis.[12] Neurological and cognitive symptoms require neurological or neuropsychology evaluation. There is a mention of air embolism as a possible complication of lung bullae rupture in chronic obstructive pulmonary disease or tuberculosis.[13] Army Regulation 40-501: Medical Services Standards of Medical Fitness states that Type 2 DCS or air embolism with neurological involvement does not meet medical fitness requirements for flight duty.[14]

The U.S. Air Force Medicine Waiver Guide Compendium states "decompression sickness (DCS) or air embolism (AGE) with neurologic involvement by history, physical examination or evidence of structural damage on imaging studies is disqualifying. … Hypobaric chamber-induced neurologic DCS/AGE with symptom resolution within 2 weeks does not require waiver. Any altitude-induced DCS/AGE episode that requires recompression therapy and symptoms are not resolved within 2 weeks requires a waiver."[15] Any DCS or AGE with symptoms lasting longer than 2 wk also requires the aviator not to fly for at least 6 mo. Waiver requests require noncontrast magnetic resonance imagery within a month of the event, neurocognitive testing, and chest radiography to rule out lung pathology if an AGE is suspected.

The Federal Aviation Administration's 2024 Guide for Aviation Medical Examiners does not give guidance on AGE or DCS.[16] Correspondence with a regional flight surgeon revealed that clearance after an episode of AGE or DCS is decided after all the following have been received by the Federal Aviation Administration: records of all initial and follow-up evaluations, studies, and treatments, as well as a detailed provider note at least 90 d after the incident, detailing symptoms and their resolution, as well as prognosis and any recommendations for follow-up. Workup should include testing for patent foramen ovale.

The International Civil Aviation Organization's Manual of Civil Aviation Medicine discusses the pathophysiology of DCS, but there is no specific waiver guidance. It does give the following guidance for neurological conditions:

When considering neurological disorders in license holders, the medical assessor should be mindful of the following questions:

1. Does the license holder have neurological disease at all?
2. If there is a static condition, does it functionally compromise flight safety?
3. Does the condition have a progressive temporal profile that can be monitored?
4. Does the condition have the potential for insidious incapacitation?
5. Does the condition have the potential for sudden incapacitation?
6. Has the license holder recovered from the condition without functionally significant residual neurological compromise?[17]

After reviewing regulatory guidance on aeromedical dispositioning after AGE, you begin to wonder how frequent AGE injuries occur and their different etiologies.

4. Which of the following is the most likely cause of an AGE in the nondiving general population?
   A. Surgical procedures.
   B. Rapid ascent during underwater diving operations.
   C. Rapid decompression in military aircraft.
   D. Mountain climbing.

ANSWER/DISCUSSION

4. A. Nearly any procedure where access to vasculature is involved can increase the risk of developing an AGE. Central line placement and manipulation is the most common cause of iatrogenic AGE followed by thoracic surgical procedures. However, the risk is small, with one study analyzing over 4.7 million hospitalizations finding only 127 proven iatrogenic episodes of any type of gas embolism.[18] Despite its rarity, iatrogenic AGE can be very serious, with 21% mortality reported a year after the incident, although in many cases the patients were critically ill before requiring the procedure that led to the occurrence of an AGE.[18] Of particular concern to the aviation community is the nearly identical pathophysiology, but different associated history, of aerospace DCI.[19] This disease, like diving-associated DCI, is caused by formation of bubbles in the blood by an individual moving to a lower pressure environment. However, here the individual exposes themselves to a movement from a lower altitude to a higher altitude such as what can be seen in an ascending unpressurized aircraft. As one would imagine, the risk of experiencing DCI is increased if an individual recently went scuba diving and then climbed to altitude in a non-pressurized aircraft (i.e., making the drop in pressure even more profound than simply swimming to the surface).[19]

The DMO updates you on the outcome of the crew chief's treatment and you are happy to hear that the neurological symptoms have fully resolved. The DMO is certain that the crew chief suffered an AGE and has documented it in the patient's medical record. You set an appointment in your aerospace medicine clinic in a week. You perform a full neurological exam of the patient and there appears to be no sequelae from the dive accident. However, his service requires a workup to grant a waiver, and you discuss with the patient that he cannot fly until he is evaluated by a neurologist. After informing his command of your decision, you await the results of the additional workup.

The neurology note states that the patient's neurological function was normal with no remaining effects. The neurologist recommends that the crew chief be returned to full flying duties. You proceed with the completion of the necessary paperwork and submit the waiver request. You are happy to report to the crew chief that the waiver has been granted by his service and he can continue his aviation career.

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REFERENCES

1. U.S. Navy. U.S. Navy diving manual, revision 7. Washington (DC): Naval Sea Systems Command; 2018. [Accessed April 27, 2025]. Available from https://www.navsea.navy.mil/Portals/103/Documents/SUPSALV/Diving/US%20DIVING%20MANUAL_REV7.pdf.

2. Walker JR, Hexdall EJ, Murphy-Lavoie HM. Diving gas embolism. In: *StatPearls*. Treasure Island (FL): StatPearls Publishing; 2025. [Accessed April 27, 2025]. Available from https://www.ncbi.nlm.nih.gov/books/NBK482321/.
3. O'Connor P. The nontechnical causes of diving accidents: can U.S. Navy divers learn from other industries? Undersea Hyperb Med. 2007; 34(1): 51–59.
4. Alexander AM, Sankari A, Martin N. Arterial gas embolism. In: *StatPearls*. Treasure Island (FL): StatPearls Publishing; 2025. [Accessed April 27, 2025]. Available from https://www.ncbi.nlm.nih.gov/books/NBK546599/.
5. Jones MW, Brett K, Han N, Cooper JS, Wyatt HA. Hyperbaric physics. In: *StatPearls*. Treasure Island (FL): StatPearls Publishing; 2025. [Accessed April 27, 2025]. Available from https://www.ncbi.nlm.nih.gov/books/NBK448104/.
6. Bralow LM, Piehl M. Barotrauma and arterial gas embolism: a diving emergencies simulation case for emergency medicine residents. MedEdPORTAL. 2018; 14:10788.
7. Kennedy-Little D, Sharman T. Pulmonary barotrauma. In: *StatPearls*. Treasure Island (FL): StatPearls Publishing; 2025. [Accessed April 27, 2025]. Available from https://www.ncbi.nlm.nih.gov/books/NBK559293/.
8. Thalmann E. Decompression illness. (N.D.). [Accessed April 27, 2025]. Available from https://dan.org/health-medicine/health-resources/diseases-conditions/decompression-illness-what-is-it-and-what-is-the-treatment/.
9. Mukundakrishnan K, Ayyaswamy PS, Eckmann DM. Computational simulation of hematocrit effects on arterial gas embolism dynamics. Aviat Space Environ Med. 2012; 83(2):92–101.
10. Naval Aerospace Medical Institute. 10.2. Decompression sickness. In: *U.S. Navy aeromedical reference and waiver guide.* Pensacola (FL): Naval Aerospace Medical Institute; 2023. [Accessed April 27, 2025]. Available from https://www.med.navy.mil/Navy-Medicine-Operational-Training-Command/Naval-Aerospace-Medical-Institute/Aeromedical-Reference-and-Waiver-Guide/.
11. U.S. Navy. Article 15-84. Disqualifying conditions for all aviation duty. In: *Manual of the Medical Department.* Falls Church (VA): Bureau of Medicine and Surgery; 2023. NAVMED P-117. [Accessed April 27, 2025]. Available from https://www.med.navy.mil/Portals/62/Documents/BUMED/Directives/MANMED/1%20Jun%202018%20%20MANMED%20Change%20165%20(Revises%20MANMED%20Chapter%2015%20articles%2015-63%20through%2015-101).pdf?ver=8eU_q21pP-UyM-TqpP6zHA%3d%3d.
12. U.S. Army Aeromedical Activity. Decompression sickness. In: *Flight surgeon's aeromedical checklists.* Aeromedical policy letters [Mobile app]. 2021. [Accessed April 27, 2025]. Available from https://play.google.com/store/search?q=med%20standards&c=apps.
13. U.S. Army Aeromedical Activity. Chronic obstructive pulmonary disease. In: *Flight surgeon's aeromedical checklists.* Aeromedical policy letters [Mobile app]. 2021. [Accessed April 27, 2025]. Available from https://play.google.com/store/search?q=med%20standards&c=apps.
14. U.S. Army. Standards of medical fitness. Washington (DC): Department of the Army; 2019. Army Regulation 40-501. [Accessed April 27, 2025]. Available from https://armypubs.army.mil/epubs/DR_pubs/DR_a/ARN37720-AR_40-501-002-WEB-4.pdf.
15. Connolly J, Delgado A, Ford A, Lee M, Vu P. Decompression sickness and arterial gas embolism. In: *Air Force aerospace medicine waiver guide.* Wright-Patterson AFB (OH): U.S. Air Force School of Aerospace Medicine; 2025. [Accessed April 27, 2025]. Available from https://www.afrl.af.mil/711hpw/usafsam/.
16. Federal Aviation Administration. Guide for aviation medical examiners. Washington (DC): Federal Aviation Administration; 2023. [Accessed April 27, 2025]. Available from https://www.faa.gov/ame_guide/media/ame_guide.pdf.
17. International Civil Aviation Organization. Chapter 1.4: Decompression. In: *Manual of civil aviation medicine.* 3rd ed. Quebec (Canada): International Civil Aviation Organization; 2012. Doc 8984. [Accessed April 27, 2025]. Available from https://www.icao.int/publications/pages/publication.aspx?docnum=8984.
18. Bessereau J, Genotelle N, Chabbaut C, Huon A, Tabah A, et al. Long-term outcome of iatrogenic gas embolism. Intensive Care Med. 2010; 36(7): 1180–1187.
19. de la Cruz RA, Clemente Fuentes RW, Wonnum SJ, Cooper JS. Aerospace decompression illness. In: *StatPearls.* Treasure Island (FL): StatPearls Publishing; 2025. [Accessed April 27, 2025]. Available from https://www.ncbi.nlm.nih.gov/books/NBK448160/.