Aviation Decompression Sickness in Aerospace and Hyperbaric Medicine

Craig J. Kutz; Ian J. Kirby; Ian R. Grover; Hideaki L. Tanaka

INTRODUCTION: The U.S. Navy experienced a series of physiological events in aircrew involving primarily the F/A-18 airframe related to rapid decompression of cabin pressures, of which aviation decompression sickness (DCS) was felt to contribute. The underlying pathophysiology of aviation DCS is the same as that of diving-related. However, based on the innate multifactorial circumstances surrounding hypobaric DCS, in clinical practice it continues to be unpredictable and less familiar as it falls at the intersect of aerospace and hyperbaric medicine. This retrospective study aimed to review the case series diagnosed as aviation DCS in a collaborative effort between aerospace specialists and hyperbaricists to increase appropriate identification and treatment of hypobaric DCS.

METHODS: We identified 18 cases involving high-performance aircraft emergently treated as aviation DCS at a civilian hyperbaric chamber. Four reviewers with dual training in aviation and hyperbaric medicine retrospectively reviewed cases and categorized presentations as "DCS" or "Alternative Diagnosis".

RESULTS: Reviewers identified over half of presenting cases could be attributed to an alternative diagnosis. In events that occurred at flight altitudes below 17,000 ft (5182 m) or with rapid decompression pressure changes under 0.3 atm, DCS was less likely to be the etiology of the presenting symptoms.

CONCLUSIONS: Aviation physiological events continue to be difficult to diagnose. This study aimed to better understand this phenomenon and provide additional insight and key characteristics for both flight physicians and hyperbaric physicians. As human exploration continues to challenge the limits of sustainable physiology, the incidence of aerospace DCS may increase and underscores our need to recognize and appropriately treat it.

KEYWORDS: decompression sickness, aviation, high-performance aircraft, hyperbaric.

Kutz CJ, Kirby IJ, Grover IR, Tanaka HL. *Aviation decompression sickness in aerospace and hyperbaric medicine*. Aerosp Med Hum Perform. 2023; 94(1):11–17.

In 2017, the U.S. Navy experienced a significant increase of physiological episodes in aircrew related to rapid decompression of cabin pressures, ultimately leading to an extensive $50 million investigation into hypoxia, decompression sickness, and aircraft maintenance procedures.[14] Although no 'smoking-gun' was reported, a multifactorial approach to pilot safety was developed, including placement of hyperbaric chambers on Nimitz-class aircraft carriers.[10] Since this report, the incidence of physiological episodes has substantially decreased.

The underlying pathophysiology of hypobaric decompression sickness (DCS) is universally felt to be the same as that of diving-related DCS.[2,4] In brief, rapid reductions in ambient pressures result in dissolution of gases in body tissue with subsequent endovascular and tissue trauma and activation of the inflammatory cascade.[4,18,20] Canonically, this is best understood following diving or depressurization of a hyperbaric chamber.[4,19] Less familiar in clinical practice is the identification and diagnosis of altitude, or aviation-related DCS. This unique presentation falls at the intersection of aerospace and hyperbaric medicine, and thus, specialists in each field alike may be less familiar and comfortable in making this diagnosis and managing it. Often emergent referral for recompression to civilian

From the University of California–San Diego, Department of Emergency Medicine and Division of Hyperbaric Medicine, San Diego, CA, USA.

This manuscript was received for review in April 2022. It was accepted for publication in October 2022.

Address correspondence to: Craig Kutz, M.D., UC-San Diego Department of Emergency Medicine, 200 W. Arbor Dr. #8676, San Diego, CA 92103, USA; craigkutz@gmail.com.

DOI: https://doi.org/10.3357/AMHP.6113.2023

chambers are coordinated through military flight surgeons for high-performance aircraft incidents. Yet civilian emergency hyperbaric oxygen chambers may not routinely manage pilots of high-altitude, high-performance aircraft. Alternatively, flight surgeons may not consistently differentiate DCS from other diagnoses or be familiar with hyperbaric chamber operations. Thus, the goal of our study was to collate and revisit presumed aviation-related DCS cases presenting to a civilian emergency hyperbaric chamber over the past decade to further understand the phenomena encountered and better differentiate key characteristics for diagnosis and treatment within this crossroads.

DCS is a clinical diagnosis made through evaluation of a dive (or altitude) profile, predisposing risks, onset of presentation, and manifestation of symptoms to identify and treat this clinical decision.[4,19] In general, DCS symptoms present broadly, manifesting most commonly as musculoskeletal pain, paresthesias, or fatigue; however, serious neurological or cognitive deficits may arise in more advanced cases.[18,25] Hyperbaric oxygen therapy (HBOT) continues to be the gold standard for treatment in severe cases for both hyper- and hypobaric DCS refractory to ground level oxygen and continues to be an AHA level I recommendation.[9,19] HBOT is a multifaceted approach to DCS treatment including immediate bubble volume reduction, increased diffusion differential for tissue inert gases, reduction in inflammatory signaling, ischemic tissue oxygenation, and mitigation of nervous system edema.[4,9,19] In recent years, however, less emphasis has been placed on physical bubble compression.[4,18] To date, documented cases of fatal hyperbaric DCS far outweigh that of hypobaric DCS exposures.[11,21] However, serious morbidity continues to be reported related to aviation or rapid altitude decompression.[12] High-performance aircraft pilots, such as fourth- and fifth-generation fighter jets and legacy aircraft such as the U-2, continue to be the vast majority of cases and can present with mission- or career-ending pathology.[1,3,10]

The University of California-San Diego (UCSD) Hyperbaric Medicine Center is the only 24-h emergency treatment hyperbaric chamber in the southern-most end of California. It is within close proximity of two military air bases in San Diego, CA, USA, and thus was involved in the diagnosis and treatment of a series of aviation-related incidents from 2010 to 2020. This retrospective, single-center case series aimed to review the chain of diagnosed aviation DCS in an effort to appropriately identify and treat aviation DCS. Although this study was not aimed to fully elucidate the pathophysiology of aviation DCS, our goal was to provide better understanding of key features in patient presentation for both flight physicians and hyperbaricists alike.

METHODS

Approval was obtained from the UCSD Institutional Review Board (protocol #800207) for this retrospective analysis for all cases used in this study. No written consent was required per university and Institutional Review Board ethical guidelines.

Utilizing a case series, cross-sectional study design, we retrospectively collected medical records using EPIC Slicer Dicer and logbooks of the UCSD multiplace hyperbaric chamber billing ICD 10 codes: Caissons Disease Decompression Sickness (T70.3) or Air Gas Embolism (T79.0XXA). From August 2010 to August 2020, 21 cases were seen at an academic, multiplace hyperbaric chamber in San Diego and involved altitude or aviation technology (e.g., skydiving, high-performance aircraft, hypobaric chamber). This 24-hour emergency treatment hyperbaric chamber is located approximately 12 mi from the Marine Corps Air Station Miramar (KNKX) and approximately 3 mi from Naval Base Coronado's North Island Naval Air Station (KNZY). In addition, the UCSD Hyperbaric Medicine Division provides treatment for various cases from the southwestern United States and Hawaii. Recompression treatment tables used were determined by fellowship-trained, board-certified Undersea and Hyperbaric Medicine physicians, with additional hyperbaric oxygen treatments determined on a case-by-case basis until maximum improvement of symptoms was observed. Initial diagnosis was based on case presentations, symptoms, circumstances of flight, and coordination with local military commanding officers and flight surgeons.

Of the 21 cases in our retrospective case series, 1 case was excluded in which a mechanic was on ground level with rapid pressurization and decompression of an F/18 cabin. Two additional cases were excluded from our DCS case series due to diagnosis by original provider as "Air Gas Embolism". Two pilots were seen for two separate events and deemed to represent two unique presentations. The data collected retrospectively included age, sex, military service, symptoms, flight ceiling, altitude at time of the decompression event as reported by the flight surgeon or patient, cabin pressure, time from the decompression event to onset of symptoms, time from the decompression event to presentation to UCSD's Hyperbaric Medicine Division, use of ground level oxygen, treatment profiles, additional treatments, and outcomes. Flight details provided at time of presentation to an emergency room were limited to information within the public domain. In some cases, altitudes of decompression were unknown and were listed as 'unknown decompression event'. Pressures at altitude were approximated and normalized with an assumption of 15°C as specific barometric pressure and temperature during flights were not collected.

Cases were independently and retrospectively reviewed by physicians experienced in both aviation medicine and hyperbaric medicine, including one civilian physician, two former military flight surgeons (U.S. Air Force and U.S. Navy), and one active Canadian Armed Forces physician. All reviewers were fellowship trained in Undersea and Hyperbaric Medicine. Individuals were provided standardized summary reports for each case and required to identify a nominal designation as: 1) "Decompression Sickness"; or 2) "Alternative Diagnosis Favored" (**Fig. 1**). Each reviewer was then required to list key presentations, symptoms, or flight details in each case that led to their specific outcome. These features were then collated for assessment related to the diagnosis.

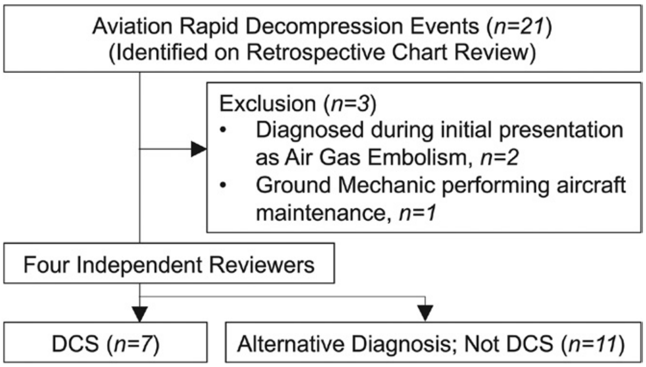

Fig. 1. Flow chart for patient selection and inclusion and exclusion criteria for study. DCS, decompression sickness.

Table I. Demographics of Aviation Decompression Events Including Military Service and Airframes.

	REVIEWER DCS	ALTERNATIVE DIAGNOSIS	TOTAL
Age			
N	7	11	18
Mean (std)	35.1 (6.84)	31.8 (4.49)	33.1 (5.58)
Median	36	31	32
Range	26-45	26-42	26-45
Gender, *N* (%)			
Male	6 (85.7)	11 (100)	17 (94.4)
Female	1 (14.3)	--	1 (5.6)
Military Service, *N* (%)			
U.S. Navy	3 (42.9)	3 (27.3)	6 (33.3)
U.S. Marines	3 (42.9)	7 (63.6)	10 (55.6)
U.S. Army	-	1 (9.0)	1 (5.6)
Other	1 (14.3)	--	1 (5.6)
Airframe, *N* (%)			
F/18	6 (85.7)	8 (72.7)	14 (77.8)
F/18 Super Hornet	--	2 (18.2)	2 (11.1)
T/38, Other	1 (14.3)	--	1 (5.6)
HAHO	--	1 (9.0)	1 (5.6)

DCS, decompression sickness; HAHO, high altitude high opening.

Statistical Analysis

Data, when applicable, was expressed using descriptive statistics for parametric variables and frequencies and percentages for nonparametric variables. Two-tailed Chi-squared/Fisher's exact test was used to identify significant variables ($P < 0.05$). Analysis was performed with GraphPad Prism 9 v. 9.3.1 (GraphPad Software, San Diego, CA, USA) and MedCalc Software Ltd, v 20.027 (MedCalc Software Ltd, Ostend, Belgium). A threshold of P-value < 0.05 was used for statistical significance. Outliers were identified using modified z-scores and Grubbs test, or extreme studentized deviate.

RESULTS

Over a 10-year period, 21 cases of aviation-related rapid decompression events were treated at the UCSD Hyperbaric Medicine Division in San Diego, CA, USA. Of those, 18 cases were diagnosed at time of presentation by fellowship-trained and board-certified hyperbaric physicians as "Decompression Sickness". The patient demographics are outlined in **Table I**.

Of the total cases reviewed retrospectively for this study, seven cases were thought by at least one reviewer to represent DCS based on history, physical exam, and circumstances of the flight. All 18 cases in this study were comprised of patients from government branches, including U.S. Navy, U.S. Marine Corps, foreign military army, and the National Aeronautics and Space Administration (NASA). Airframes primarily included the McDonnell Douglas F/A-18 Hornet, a twin-engine supersonic fighter and attack jet with multi-person cockpit configuration. Other aircraft included the McDonnell Douglas and Boeing F/A-18E Super Hornet, a twin-engine multirole fighter jet with single- or two-seat configuration and advanced derivatives to the F/A-18, and the Northrop T/38 Talon twinjet supersonic jet trainer. One case involving a high-performance airframe also included exposure to a high-altitude hypobaric chamber as an inciting factor. Additionally, one case of an aviation-related event involved a high-altitude military parachutist involved in high altitude-high opening (HAHO) free fall. Presenting symptoms and key physical exam findings are outlined in **Table II**. All of the cases were initially diagnosed and treated as DCS within a civilian multiplace chamber using U.S. Navy treatment tables at time of presentation (**Fig. 2**).

This retrospective review by a panel of experts in aviation medicine and hyperbaric medicine identified specific cases felt to represent DCS based on circumstances of presentation. Cases felt by at least one reviewer to be most consistent with decompression sickness as etiology of presentation represented 7 of 18 cases, or less than half. Notably, only two of the cases, or 11.1%, were unanimously agreed to be DCS by all four reviewers (**Table III**).

Consistently, subjects were described as "feeling drunk or hung over". After retrospective review, there was no significant difference between cases felt to represent DCS vs. alternative diagnosis in subjective symptoms, including joint pain, fogginess, confusion, or paresthesias. Primarily, physical exam findings that endorsed objective presentations were more likely to be favored by reviewers as DCS, including neurological deficit, coordination abnormality, or decline in cognitive function.

In the subgroup of DCS cases, a change in pressure during rapid decompression equivalent to at least 0.3 atm (χ^2, P-value <0.05, CI 95%) reflected statistically significantly increased risk that the presentation represented DCS. For example, Case 1 in Table III was judged by all four reviewers to be consistent with DCS. The pilot experienced a change in pressure of 0.38 atm, resulting from three rapid decompression events from a cabin pressure of 8000 ft (2438 m; approximately 0.75 atm at 15°C) to 26,000 ft (7925 m; approximately 0.37 atm at 15°C). To the contrary, Case 8 (not listed) was unanimously judged to favor an alternative diagnosis for symptoms. This pilot experienced a change in pressure of 0.19 atm resulting from decompression events in a cabin pressure of 5000 ft (1524 m; approximately 0.83 atm at 15°C) to 12,000 ft (3658 m; approximately 0.64 atm at 15°C). In fact, in cases judged by at least one reviewer to be

Table II. Symptoms and Physical Exam Findings in Subgroup Analysis for Decompression Sickness vs. Alternative Diagnosis.

	DECOMPRESSION SICKNESS			ALTERNATIVE DIAGNOSIS		
	No.	DCS (%) (*N* = 7)	TOTAL (%) (*N* = 18)	No.	DCS (%) (*N* = 11)	TOTAL (%) (*N* = 18)
Joint Pain	5	71.4	27.8	5	45.5	27.8
Fogginess	3	42.9	16.7	8	72.7	44.4
Difficult Concentrating	3	42.9	16.7	3	27.3	16.7
Lightheaded	2	28.6	11.1	2	18.2	11.1
Headache	2	28.6	11.1	5	45.5	27.8
Speech Abnormality	2	28.6	11.1	1	9.1	5.6
Paresthesias	2	28.6	11.1	7	63.6	38.9
Myalgias	2	28.6	11.1	2	18.2	11.1
Gait Instability	2	28.6	11.1	0	-	-
Pruritits	1	14.3	5.6	0	-	-
Vertigo	1	14.3	5.6	0	-	-
Rash	1	14.3	5.6	0	-	-
Fatigue	1	14.3	5.6	1	9.1	5.6
Vision Changes	0	-	-	3	27.3	16.7
Tinnitus	0	-	-	1	9.1	5.6
Shortness of Breath	0	-	-	1	9.1	5.6
Loss of Conscious	0	-	-	1	9.1	5.6
Chest Pain	0	-	-	1	9.1	5.6
Neurological Deficit	3	42.9	16.7	0	-	-
Coordination/Gait Deficit	2	28.6	11.1	0	-	-
MMSE < 30	3	42.9	16.7	0	-	-

MMSE: Mini-Mental State Exam.

consistent with DCS, the change between flight altitude pressure and rapid decompression pressures exceeded 0.3 atm (**Fig. 3**).

Additional flight data, as shown in **Table IV**, indicates that if the maximum altitude of the airframe was equal to or below 17,000 ft (5182 m) during the rapid decompression event, the reviewers were less likely to agree upon the diagnosis being decompression sickness with 95% confidence (χ^2, *P*-value <0.05). However, this strength of association was not significant for the cabin decompression altitude reported [*P*-value 0.266, CI 95% equal to or above 15,000 ft (4572 m)]. Thus, in general, a rapid decompression event required at least a maximum flight ceiling of 17,000 ft for sufficient pressure differentials in cabin pressure to favor decompression sickness as the plausible etiology for symptoms.

DISCUSSION

Aviation or hypobaric DCS is encountered less frequently than diving DCS, most likely because civilians have less access to high-performance military flights and unpressurized high-atmosphere sorties. Often, recognition and treatment are a collaborative effort between flight surgeons and hyperbaric physicians, yet circumstances in presentations may still lay outside of individual medical subspecialty expertise. Confounding the diagnosis is less familiarity and exposure to military operations and high-performance technology by the civilian physicians involved in care.

DCS continues to be a clinical diagnosis. Multiple attempts at predictive models date back to as early as 1908.[4,5] These early

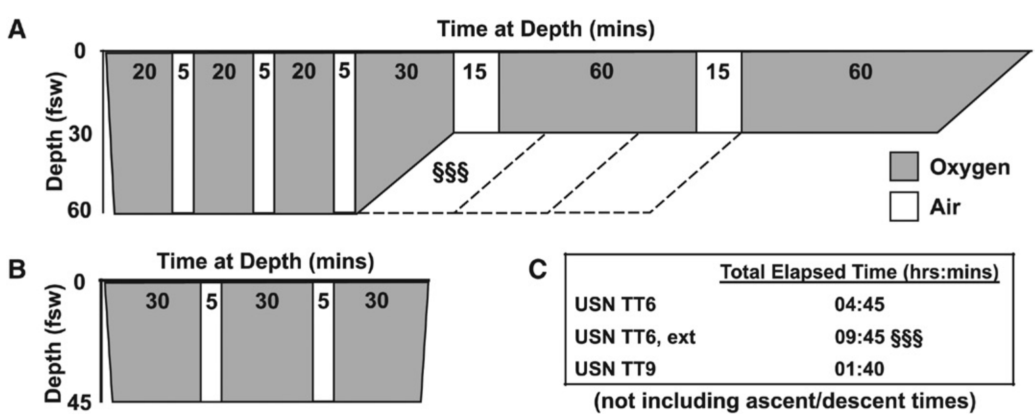

Fig. 2. U.S. Navy Treatment Tables for decompression sickness showing total time allocated for each treatment. A) U.S. Navy Treatment Table 6 (USN TT6) with possible extension (§§§) of treatments to a total of 585 min outlined with dotted lines [i.e., every one extension (ext) at 60 feet of sea water (fsw) adds an additional three 20-min oxygen periods with two 5-min oxygen breaks at 30 fsw]. B) U.S. Navy Treatment Table 9 (USN TT9). C) Duration in hours:minutes of each table.

Table III. Selected Cases That Reviewers Felt Represented Decompression Sickness.

PATIENT DATA; AIRFRAMES	AIRCRAFT ALTITUDE (ft)	CABIN ALTITUDE (ft)	DECOMPRESSION ALTITUDE (ft); [NO. EXPOSURES]	PRESSURE CHANGE (atm)	PRESENTATION	TREATMENT
Number of Reviewers Favor DCS (4 of 4)						
Case						
1) 40-year-old male pilot F/18	29,000	8,000	26,000 [3]	0.38	Symptoms: fogginess, lightheaded, headache, abnormal speech, confusion Onset: at altitude Exam: MMSE <30	TT6
15) 45-year-old female pilot; Hypobaric Chamber; Pressure Suit; T/38 (+12-hours)	65,000 25,000	35,000 13,000	Unknown N/A	0.94	Symptoms: joint pain, myalgias, paresthesias Onset: >1 h on the ground; at altitude Exam: sensation deficit	TT6, ext TT9
Number of Reviewers Favor DCS (≥1 of 4)						
Case						
3) 36-year-old male pilot F/18	35,000	8,000	16,000 [>10]	0.2	Symptoms: fogginess, speech abnormality, focal extremity weakness, gait instability, difficulty concentrating Onset: ≤1 h on the ground Exam: MMSE <30, neurological deficit, gait deficit	TT6 TT6, ext TT9 TT9
5) 26-year-old male pilot F/18	23,700	8,000	23,700 [1]	0.35	Symptoms: paresthesias, joint pain Onset: >1 h on the ground Exam: no pertinent findings	TT6
12) 39-year old male pilot F/18 F/18 (+48-hours) F/18 (+24-hours)	 1,000 22,000 22,000	 1,000 8,000 8,000	 33 fsw [30] 33 fsw [10] n/a	 1.26	Symptoms: nausea, myalgia, headache, vertigo, rash, fogginess, confusion Onset: at altitude, >1 h on the ground Exam: MMSE <30, positive sharpened Romberg	TT6 TT5
13) 28-year old male pilot F/18	22,000	8,000	20,000 [1]	0.28	Symptoms: joint pain, lightheadedness Onset: at altitude Exam: no pertinent findings	TT6
17) 32-year-old male pilot	16,000	8,000	15,000 [1]	0.18	Symptoms: fatigue, joint pain Onset: >1 h on the ground Exam: sensation deficit	TT6

Flight profiles, changes in cabin pressure for given rapid decompressions, and presenting symptoms and exam findings, as well as treatments, are listed.
DCS, decompression sickness; MMSE, Mini-Mental State Exam; TT, United States Navy Treatment Table; ext, extensions; fsw, feet of sea water.

decompression models by physiologist Haldane provided early diving tables and described a theoretical "2:1 supersaturation" ratio.[5] Essentially, a pressure differential of 2:1 was required for inert gas saturated in tissues to exceed environmental pressures. This early model has been adapted multiple times and hyperbaric medicine still traditionally teaches that the threshold for developing diving DCS must exceed approximately 20 fsw, or a pressure differential of 0.6 atm.[4,19,24] However, the unique environment and circumstances associated with aviation DCS makes this model difficult to extrapolate. The U.S. Air Force compiled a large database on over 3000 subject exposures in a hypobaric chamber to develop an Altitude Decompression Sickness Risk Assessment Computer (ADRAC).[22,26] In this report, sigmoidal regression indicated development of venous gas embolism (VGE) at as low as 12,000 ft (3658 m); however, incidence of DCS threshold was approximately 16,000 ft to 18,000 ft (4877 to 5486 m).[26] Conkin et al. also published probabilistic DCS models to encompass a wider range of DCS incidence, including high altitude hypobaric environments.[7] Yet, due to the inherent multifactorial presentation and unknown confounders in high-performance aircraft, aviation DCS continues to be difficult to diagnose and models in DCS theory are still lacking.

Our study identified 18 events diagnosed and treated as aviation DCS over the past decade ranging from 2010 to 2020. As Table II and Table IV show, the presentations, symptoms, and flight circumstances were broad. Our retrospective review involved four independent civilian and military reviewers with dual backgrounds in hyperbaric and aerospace medicine, with the goal of differentiating key characteristics in the presentation that may assist in the diagnosis. Reflective of the difficulty in diagnosing aviation DCS, only two cases in our entire series were unanimously felt to be attributed to DCS (Table III). Less than half of the total cases were felt to represent DCS by at least one reviewer, likely reflecting both the

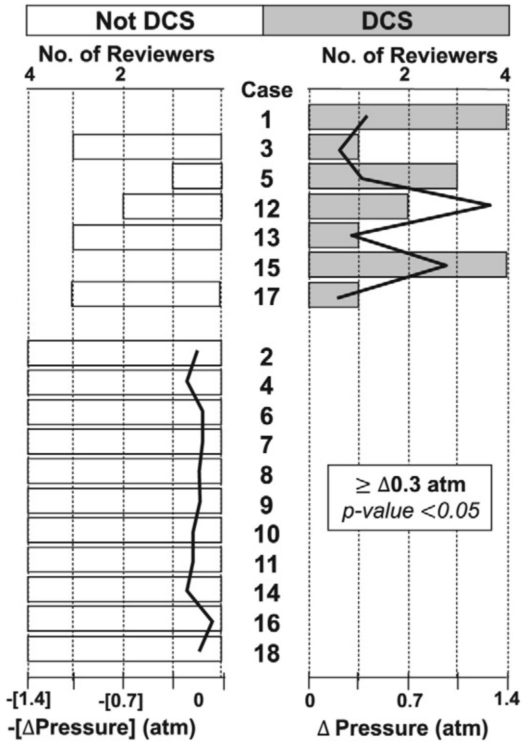

Fig. 3. Number of reviewers designating DCS vs. alternative diagnosis (Non-DCS). Reviewers reported as nominal values. Pressure changes from cabin altitude to decompression altitude for each case reported as change in pressure (atm). Right sided indicates changes in pressure for cases diagnosed as DCS by at least one reviewer. Left sided (reported as inverse values) indicates changes in pressure of cases that no reviewers felt was DCS. This figure excluded one outlier based on his flight profile experiencing brief episodes below sea level due to overpressurization, making his flight profile brief hyperbaric conditions. *P*-value based on 95% CI; Δ, change; DCS, decompression sickness.

difficulty and unfamiliarity in diagnosis by typical civilian hyperbaric physicians at time of presentation. Alternative diagnoses considered included (but were not limited to) hypoxia, air gas embolism, trauma, contaminated gas, nonbiological, or substance withdrawal.

In this case series, all were treated with recompression therapy, as at the time of presentation they were felt to represent clinically significant aviation DCS. Although no complications were experienced during this series of treatments, the risk-benefit of recompression in coordination with resource management is not trivial. The U.S. Navy Diving Manual recommends treatment of DCS with Treatment Table 6, a recompression profile with a duration of 285 min, with a maximum possible duration of 585 min if extensions are required (Fig. 2).[15] Further, six cases were admitted to the inpatient hospital for residual symptoms or continued monitoring, of which only three were judged to be aviation DCS by at least one reviewer. Significant resource allocation and evacuation to recompression chambers are used for the diagnosis of DCS with continued symptoms despite ground level oxygen.[20] Alternative treatments have been proposed, but are still not universally adopted.[6,8] Aviation DCS remains a high-profile concern for military and governmental authorities.[3,9,13] Thus,

Table IV. Flight Profile Including Maximum Altitude, Changes in Pressure, Decompression Altitude, and Timing for Onset of Symptoms for Both DCS and Alternative Diagnosis (Non-DCS) Cases.

	REVIEWER DCS No. (*N* = 6)	ALTERNATIVE DIAGNOSIS No. (*N* = 11)	χ^2 *P*-VALUE
Δ Altitude Pressure (atm)			
≥0.3	3	0	<0.05*
Maximum Flight Altitude (ft)			
≤17,000	1	9	<0.05*
Decompression Altitude (ft)			
≥18,000	4	7	0.900
≥15,000	6	9	0.266
Symptom Onset			
≤1 h on the ground	1	7	0.064
>1 h on the ground	3	2	0.169
In flight	2	2	0.482

Case 15 was excluded from calculations due to extremes in altitude experienced.
DCS, Decompression Sickness; Δ, Change; χ^2, Chi-squared.
*Significant.

a formal diagnosis of DCS can be career altering, as such with Navy divers, where a neurological DCS event can permanently disqualify from future missions.[15] Alternatively, in our case series, we identified multiple events where an alternative differential diagnosis should have been considered. For instance, Case 16 was unanimously felt to represent possible substance withdrawal, such as alcohol, due to a toxicological syndrome of tongue fasciculations, tremors, and tachycardia—symptoms traditionally inconsistent with DCS.[4,19] Noting the low number of cases overall, sample bias can limit conclusions taken from this study; however, the consideration of alternative management of presentations other than DCS should be deliberated. These cases reinforce our need to better understand proper identification of aviation DCS.

The underlying mechanism behind aviation DCS is complex. In fact, the underlying propagation of DCS or arterial gas embolism (AGE) in diving continues to be of some debate amongst hyperbaric physicians, despite reports of DCS as early as the 1840s.[15,18,23] Thus, we attempted to simplify key features in cases felt to favor DCS in an attempt to assist recognition and diagnosis. For instance, we found that objective physical exam findings such as neurological deficits, coordination abnormalities, or cognitive delays favored DCS (Table III). In addition, Fig. 3 shows exposure to change in pressure during rapid decompressions of greater than or equal to 0.3 atm favors DCS. This case series indicates the maximum altitude of flight below 17,000 ft (5182 m) is less likely to be diagnosed as DCS, which is in agreement with prior U.S. Air Force studies.[22,26] Certainly inherent confirmation bias in altitude (i.e., reviewers trained in identifying 18,000 ft/5486 m as a minimum altitude to develop DCS) could skew this simplification in flight altitude for aviation DCS. However, this finding, in coordination with changes in pressures, gives a good foundation for both civilian and military to consider broader differentials with cases presenting outside of these parameters.

As with diving DCS, not one single test or historical presentation can formally make the diagnosis and, to date, the underlying propagation of disease continues to be of some debate.[18] There is still more to learn about aviation DCS. The underlying pathophysiology is complex. In flight, the differential diagnosis is wide and not readily appreciated, as evidenced by the findings in the Navy root-cause analysis of physiological events experienced by aircrew in the last decade.[10,14] Alternative pathophysiology in aviation DCS has included oscillations in pressure of the central nervous system from rapid decompression-recompression, which may mimic traumatic brain injury from blasts, or through alveolar barotrauma from substantial rapid high-altitude decompression.[16,17] Regardless, research is limited and more needs to be performed.

In conclusion, this study is not meant to identify the underlying pathophysiology or cause of aviation DCS, as the sample size ultimately limits any major conclusions. In addition, retrospective reviews of charts inherently induce bias or limitations based on the limited information provided. However, key associations in flight profile showed significant likelihood in agreement for diagnosis of DCS. Flight altitudes under 17,000 ft (5182 m) or reported differential cabin pressure changes less than 0.3 atm during rapid decompression should raise the consideration of an alternative diagnosis for the presenting symptoms.

Aviation physiological events continue to be multifactorial and difficult to diagnose, in particular as it relates to DCS. Aviation DCS overlaps the subspecialty fields of aerospace and hyperbaric medicine. This study aimed to better understand this phenomenon and provide additional insight and key characteristics for both flight physicians and hyperbaric physicians to utilize. As human exploration continues to challenge limits of sustainable physiology, such as space exploration, the incidence of aerospace DCS will increase and underscores our need to recognize and properly treat it.

ACKNOWLEDGEMENTS

The authors would also like to acknowledge Jay Duchnick, RN CHT, Charlotte A. Sadler, MD, Peter J. Witucki, MD, and the UCSD Hyperbaric Medicine Division staff for their contributions to this study.

Financial Disclosure Statement: The authors have no competing interests to declare.

Authors and Affiliations: Craig J. Kutz, M.D., Ph.D., Ian R. Grover, M.D., and Hideaki L. Tanaka, M.D., FACEP, Department of Emergency Medicine, and Ian J. Kirby, M.D., CCFP, Division of Hyperbaric Medicine, University of California-San Diego, San Diego, CA, USA.

REFERENCES

1. Auten JD, Kuhne MA, Walker 2nd HM, Porter HO. Neurologic decompression sickness following cabin pressure fluctuations at high altitude. Aviat Space Environ Med. 2010; 81(4):427–430.
2. Barratt MR, Pool SL. Principles of clinical medicine for space flight. New York: Springer; 2008.
3. Bendrick GA, Ainscough MJ, Pilmanis AA, Bisson RU. Prevalence of decompression sickness among U-2 pilots. Aviat Space Environ Med. 1996; 67(3):199–206.
4. Bennett PB, Brubakk AO, Neuman TS, Elliott DH. Bennett and Elliott's physiology and medicine of diving, 5th ed. New York: Saunders; 2003.
5. Boycott AE, Damant GC, Haldane JS. The prevention of compressed-air illness. J Hyg (Lond). 1908; 8(3):342–443.
6. Butler WP, Topper SM, Dart TS. USAF treatment table 8: treatment for altitude decompression sickness. Aviat Space Environ Med. 2002; 73(1):46–49.
7. Conkin J, Gernhardt ML, Abercromby AF, Feiveson AH. Probability of hypobaric decompression sickness including extreme exposures. Aviat Space Environ Med. 2013; 84(7):661–668.
8. Dart TS, Butler W. Towards new paradigms for the treatment of hypobaric decompression sickness. Aviat Space Environ Med. 1998; 69(4):403–409.
9. Davis JC, Sheffield PJ, Schuknecht L, Heimbach RD, Dunn JM, et al. Altitude decompression sickness: hyperbaric therapy results in 145 cases. Aviat Space Environ Med. 1977; 48(8):722–730.
10. Eckstein M. Navy clear on causes of physiological events in pilots. Final recommendations released for physiologic events mitigation. 2020. [Accessed 2022 March 19]. Accessed from https://news.usni.org/2020/06/18/navy-clear-on-causes-of-physiological-events-in-pilots-final-recommendations-released-for-pe-mitigation.
11. Fryer DI. Pathological findings in fatal sub-atmosphere decompression sickness. Med Sci Law. 1962; 2(2):110–123.
12. Gibbons JA, Ramsey CS, Wright JK, Pilmanis AA. Case history of serious altitude decompression sickness following rapid rate of ascent. Aviat Space Environ Med. 2003; 74(6, Pt. 1):675–678.
13. Gribble MD. A comparison of the "high-altitude" and "high-pressure" syndromes of decompression sickness. Br J Ind Med. 1960; 17:181–186.
14. Hudson L. Navy 'not declaring victory' on physiological episodes. Inside Defense; Feb. 7, 2018. [Accessed Nov. 3, 2022]. Available from https://insidedefense.com/daily-news/navy-not-declaring-victory-physiological-episodes.
15. Kraft S. U.S. Navy Diving Manual, Rev. 7, 0910-LP-115-1921. Washington (DC): Naval Sea Systems Command; 2016.
16. Luft UC, Clamann HG, Adler HF. Alveolar gases in rapid decompression to high altitudes. J Appl Physiol. 1949; 2(1):37–48.
17. McGuire SA, Sherman PM, Brown AC, Robinson AY, Tate DF, et al. Hyperintense white matter lesions in 50 high-altitude pilots with neurologic decompression sickness. Aviat Space Environ Med. 2012; 83(12):1117–1122.
18. Mitchell SJ, Bennett MH, Moon RE. Decompression sickness and arterial gas embolism. N Engl J Med. 2022; 386(13):1254–1264.
19. Moon RE. Hyperbaric oxygen therapy indications, 14th ed. North Palm Beach (FL): Best Pub. Co.; 2019.
20. Moon RE, Sheffield PJ. Guidelines for treatment of decompression illness. Aviat Space Environ Med. 1997; 68(3):234–243.
21. Neubauer JC, Dixon JP, Herndon CM. Fatal pulmonary decompression sickness: a case report. Aviat Space Environ Med. 1988; 59(12):1181–1184.
22. Pilmanis AA, Petropoulos L, Kannan N, Evans F, Christodoulides N. Altitude Decompression Sickness Risk Assessment Computer (ADRAC) development. Houston (TX): NChris Software Solutions; 1999.
23. Thom SR, Bennett M, Banham ND, Chin W, Blake DF, et al. Association of microparticles and neutrophil activation with decompression sickness. J Appl Physiol (1985). 2015; 119(5):427–434.
24. Van Liew HD, Flynn ET. Direct ascent from air and N2-O2 saturation dives in humans: DCS risk and evidence of a threshold. Undersea Hyperb Med. 2005; 32(6):409–419.
25. Vann RD, Butler FK, Mitchell SJ, Moon RE. Decompression illness. Lancet. 2011; 377(9760):153–164.
26. Webb JT. Documentation for the USAF School of Aerospace Medicine Altitude Decompression Sickness Research Database. Brooks AFB (TX): Physiology Branch, School of Aerospace Medicine; 2010.