



Decompression Sickness (DCS) Risk Mitigation OCHMO-TB-037 Rev D

Executive Summary

Decompression Sickness (DCS) also known as “the bends”, is a mission-critical medical risk caused by the formation of inert bubbles during rapid reductions in ambient pressure. In spaceflight, the most significant pressure drops occur during transitions from cabin pressure to the lower pressures of extravehicular activity (EVA) suits. Several factors can increase an individual's susceptibility to DCS, including the presence of a patent foramen ovale (PFO), body fat %, hydration, and exercise type. DCS is effectively mitigated through a prebreathe protocol and if not properly managed, it can lead to musculoskeletal pain, neurological impairment, cardiopulmonary compromise, cognitive impairment, risk to mission outcomes/success, and death.



Houston We Have a Podcast:

The NASA research into preventing decompression sickness for astronauts who will walk on the Moon in future Artemis missions.

[Ep269: Locked In, Pressure Low | NASA](#)



Relevant Technical Requirements

NASA-STD-3001 Volume 1, Rev C

- [V1 3003] In-Mission Preventive Health Care
- [V1 3004] In-Mission Medical Care
- [V1 5001] Medical Training
- [V1 5002] Crewmember Training
- [V1 5003] Crew Medical Officer Medical Training

NASA-STD-3001 Volume 2, Rev F

- [V2 6002] Inert Diluent Gas
- [V2 6003] O₂ Partial Pressure Range for Crew Exposure
- [V2 6006] Total Pressure Tolerance Range for Indefinite Crew Exposure
- [V2 6007] Rate of Pressure Change
- [V2 6008] Decompression Sickness (DCS) Risk Identification
- [V2 6009] Decompression Sickness Treatment Capability
- [V2 6017] Atmospheric Control
- [V2 6022] Atmospheric Monitoring and Alerting Parameters
- [V2 7043] Medical Capability
- [V2 9053] Protective Equipment
- [V2 11100] Pressure Suits for Protection from Cabin Depressurization
- [V2 11032] LEA Suited Decompression Sickness Prevention Capability
- [V2 11036] Suited Atmospheric Monitoring and Alerting

Decompression Sickness Mechanism

Decompression sickness can be understood by the basic gas law principle described by Henry’s Law, which states that the amount of gas dissolved in a liquid is directional proportional to the partial pressure of that gas above the liquid.

$$C = kP$$

C= concentration of dissolved gas
k= Henry’s Law Constant
P= partial pressure of gas

At cabin pressure, historically 14.7 psia, nitrogen equilibrates between the lungs and blood, dissolving in plasma and diffusing into the tissues. At the higher pressure, each breath contains more compressed air molecules resulting in a buildup of nitrogen, a physiologically inert gas. When ambient pressure is rapidly reduced, (e.g., transitioning from cabin pressure to an EVA suit, historically 4.3 psia) the partial pressure of nitrogen falls rapidly, and this sudden equilibrium disruption forces an increase rate of nitrogen elimination. If the off-gassing exceeds the rate of elimination via exhalation, nitrogen starts to form bubbles in blood and tissues which is where the manifestation of DCS symptoms occur. Bubbles may appear in extravascular (tissue or interstitial) and intravascular compartments. There are two main types of intravascular bubbles:

Venous Gas Embolism (VGE)	Arterial Gas Embolism (AGE)
Origin: bubbles form from dissolved gas in tissues during decompression Pathway: venous return → pulmonary circulation Clinical Effects: often asymptomatic if low bubble load but high load can lead to coughing and shortness of breath Severity: subclinical or mild, can become serious if high bubble load	Origin: originates from lung over-expansion or from right to left shunting of a VGE Pathway: system arterial circulation Clinical Effects: acute, severe symptoms such as stroke-like neurological, loss of consciousness, seizures, cardiac ischemia Severity: potentially catastrophic, often life threatening



2

Venous Gas Embolism (VGE)

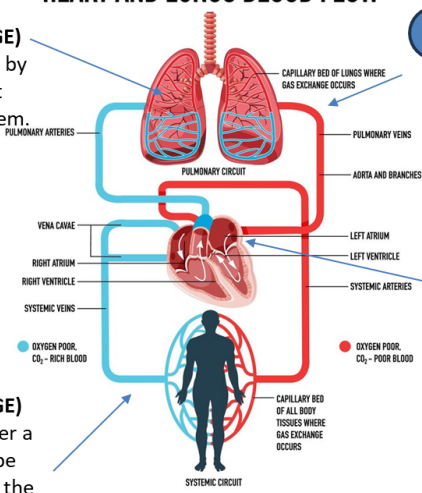
Most VGE can be “filtered” by the lungs, which prevent passage to the arterial system.

1

Venous Gas Embolism (VGE)

Any remaining Nitrogen after a prebreathe protocol can be released when the crew is in the suit at a lower pressure.

HEART AND LUNGS BLOOD FLOW



3

Arterial Gas Embolism (AGE)

VGE that are not filtered by the lung are arterial gas emboli (AGE). AGE put the astronaut at risk of vascular blockages and resulting ischemic damage to brain or other organs

4

Patent Foramen Ovale

PFO is a right to left shunt between the atria (hole in the heart), venous emboli gas (VGE) may pass from the right atrium (venous) to the left atrium (arterial).

Adapted from Heart and Lungs Blood

Circulation Diagram: Vector Stock Images

Classification/Symptoms

The gas bubbles formed during the rapid reduction of pressure have various physiological effects and can obstruct the blood vessels, trigger inflammation, and damage tissue, resulting in symptoms of DCS. NASA presently classifies DCS into two categories:

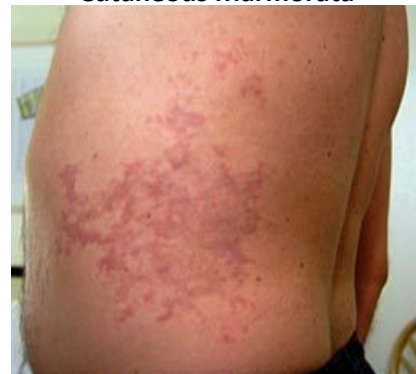
Type I

- Itching
- Musculoskeletal pain
- Mild rashes

Type II

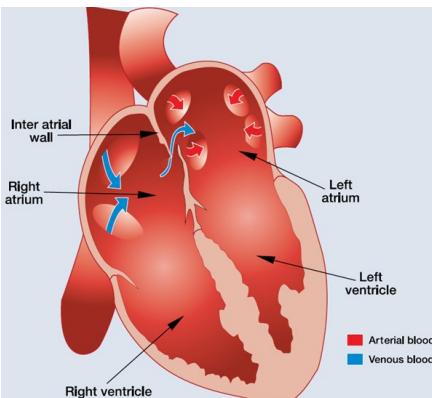
- Neurological symptoms
 - Numbness
 - Weakness
 - Cognitive issues
- Inner ear problems
- Cardiopulmonary issues
- Cutaneous Marmorata-mottled patterned skin rash

Cutaneous Marmorata



Diagnosing Decompression Sickness. Divers Alert Network, 2020

Pathophysiology



Understanding PFO. Divers Alert Network, 2021

Although the pathophysiology of DCS is not entirely understood, it includes right to left shunting of VGE via several mechanisms, one of which is a patent foramen ovale (PFO). A PFO is a shunt between the right and left atrium of the heart and is a remnant feature of the natal heart. All humans are born with a PFO, but approximately 75% of the PFOs fuse following childbirth (Steiner, 1998). With the remaining 25% of the population whose PFO does not fuse, approximately 6% are considered to be large (>2 mm) and the diameter can also increase in age (Hagen, 1984). A PFO raises concern because theoretically a VGE may pass from the right to left atrium, bypassing normal lung filtration, which can allow bubbles in the arterial system leading to a neurological event. Currently, NASA does not screen out individuals with PFOs. For more information: [Assessment of Patent Foramen Ovale \(PFO\) as Related to Decompression Sickness \(DCS\) in the Spaceflight Environment and During Ground Testing](#),

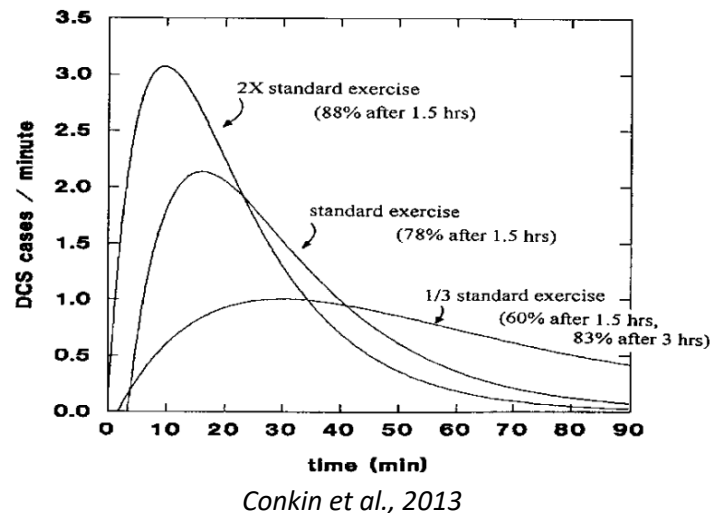
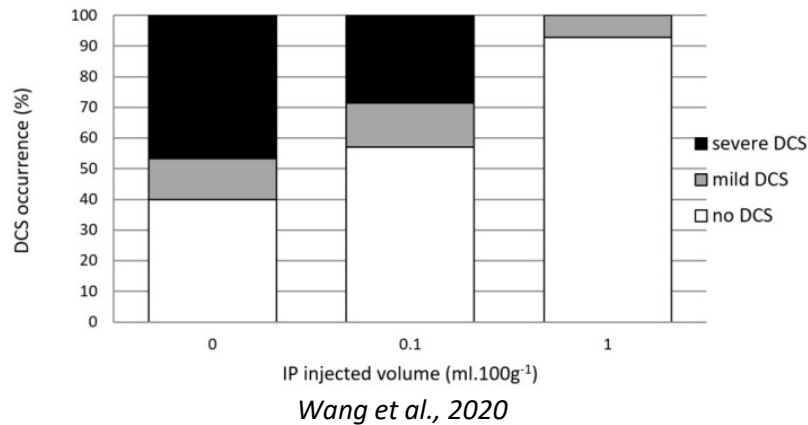


Predisposing Risk

DCS has many predisposing factors such as hydration, body fat %, and exercise type.

Hydration

Hydration plays a significant role in DCS risk. Dehydration reduces plasma volume and can increase blood viscosity, leading to impaired inert gas transport and decreasing bubble removal from the body. Conversely, proper hydration promotes effective gas washout and reduces DCS.

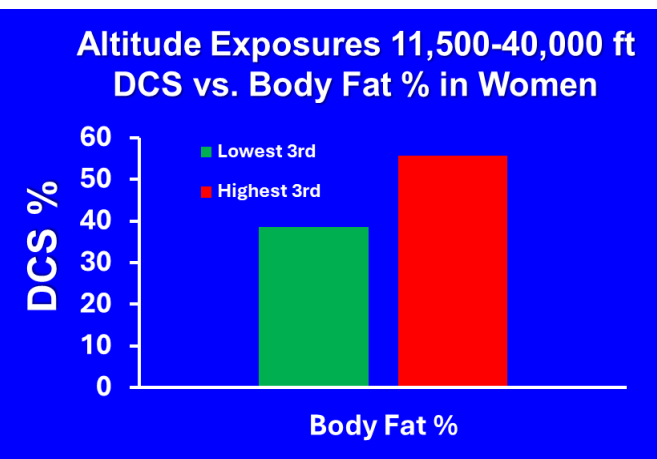


Exercise

Pre-exposure exercise promotes removal of inert gasses by increasing circulation and tissue perfusion. Contrarily, vigorous or resistive exercises after decompression can exacerbate bubble growth by promoting tissue microtrauma and increasing perfusion gradients.

Body Fat Percentage

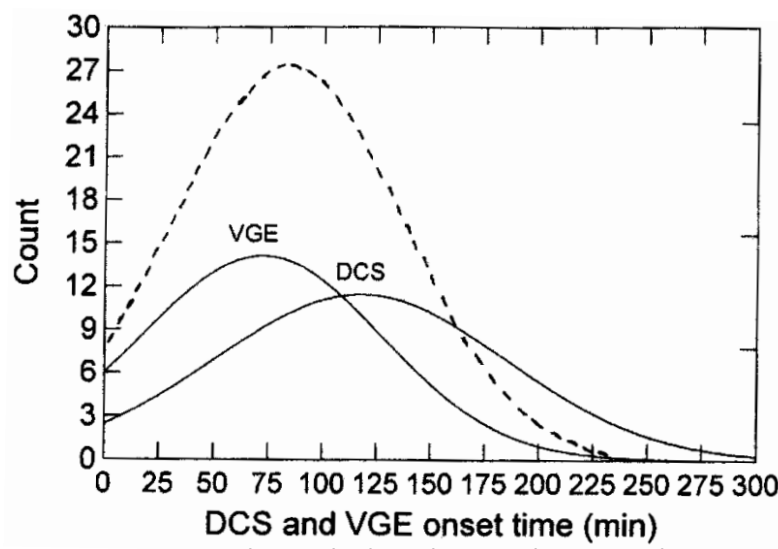
Higher body fat contents can increase DCS risk because nitrogen is significantly more soluble in fat than in water. Higher nitrogen contents stored in fat leads to excessive nitrogen bubble formation thus increasing DCS risk.



Webb JT, et al., 2003

DCS Detection

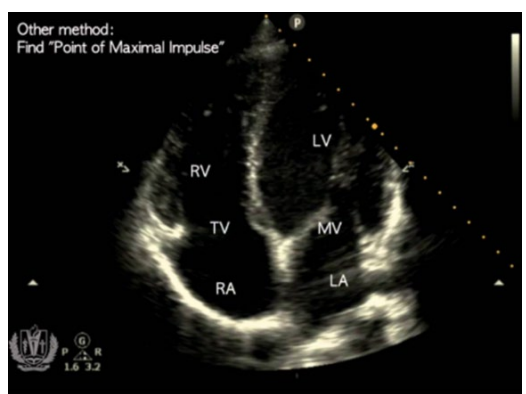
DCS is typically diagnosed based on symptom presentation because the presence of VGE or AGE does not necessarily indicate DCS. Many individuals have detectable VGE’s without symptoms, while others may have symptoms without detectable bubbles. Generally, low bubble loads are associated with lower DCS risk and high bubbles are associated with higher risk, but DCS risk associated with bubble count accuracy is location dependent where the subclavian sites are more accurate compared to precordial sites. The bubble load (quantity and persistence of bubbles) may be used to indicate decompression stress, therefore potential DCS risk can be identified using the Eftedal-Brubakk (EB) scale.



Conkin et al., 2013
Time of VGE and DCS onset in 78 exposures in which both VGE and DCS were present (solid curve) and in 150 exposures in which only VGE was present (dashed curve). The curves, all of which are skewed to the right, are the best-imposed normal distributions on histograms.

The EB scale grades VGE presence through doppler or ultrasound imaging. The NASA-modified scale ranges from 0-7 each identifying different bubble loads and its correlated DCS risk. Higher grades on the EB scale indicate an increased DCS risk.

Eftedal-Brubakk Scale	
Grade	Definition
0	No observable bubbles
1	Occasional bubble
2	At least 1 bubble every 4 heart cycles
3	At least one bubble every heart cycle
4	Not more than one third of every image
5	Not more than two thirds of every image
6	Near whiteout; individual bubbles still discerned
7	“White-out”: single bubbles cannot be discriminated



Apical 4 Chamber View on Transthoracic Echocardiography (Cardiac Ultrasound).
YouTube.



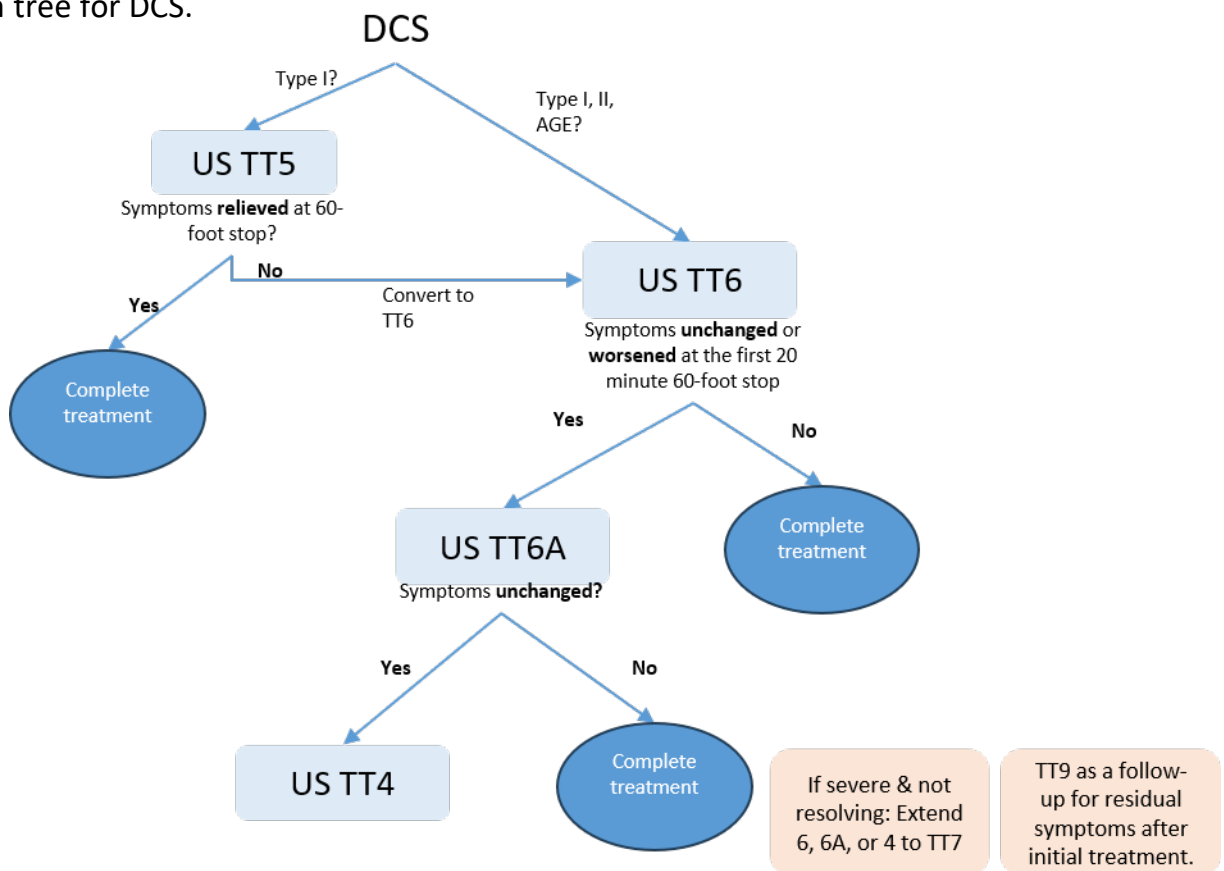
Treatment

Recompression therapy by hyperbaric therapy (HBOT) is the terrestrial treatment for DCS and the U.S. Navy Protocols are widely adopted treatment methods. The U.S. Navy Treatment Tables (TT) involve administering 100% oxygen at increasing pressures within a hyperbaric chamber to:

- Reduce bubble volume in the body
- Increase absorption of bubbles into the body fluid and exhalation of inert gas from the lungs
- Increase oxygen supply to cells in peripheral tissue

In addition to this treatment, oral or intravenous administration of electrolytes are recommended for DCS, except for pulmonary DCS cases. Also, for AGE treatment, intravenous or intramuscular administration of lidocaine is shown to be useful for brain function recovery.

While a hyperbaric chamber is not available during spaceflight, crewmembers exhibiting DCS symptoms may undergo a treatment similar in principle to the Navy table treatments. Increasing the pressure in the suit and cabin pressure may be combined to resolve symptoms as a minimum of 16.4 psia may alleviate symptoms but the protocol is scenario dependent. Below is a terrestrial decision tree for DCS.

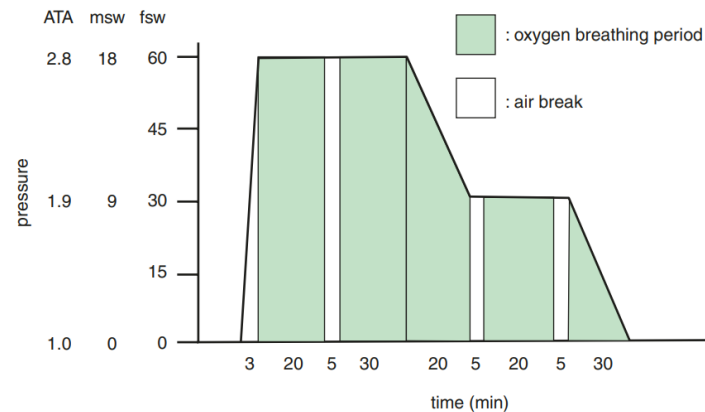


*Graphic based on U.S. Navy protocol

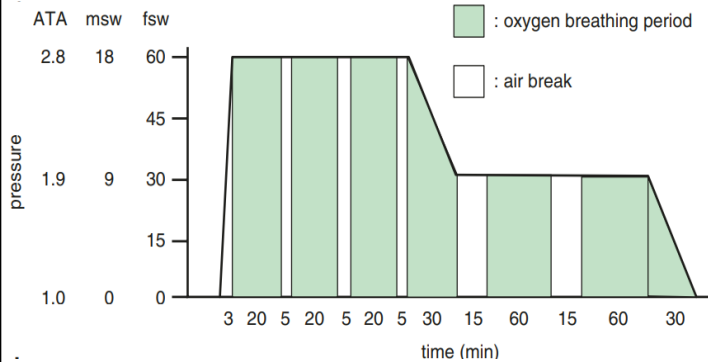


DCS Treatment timeline graphics:

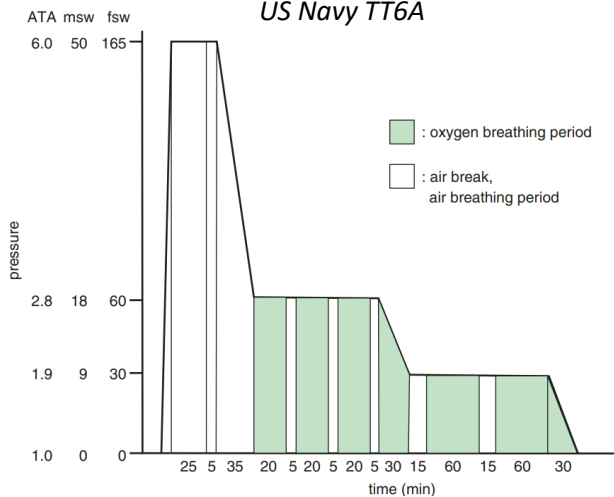
US Navv TT5



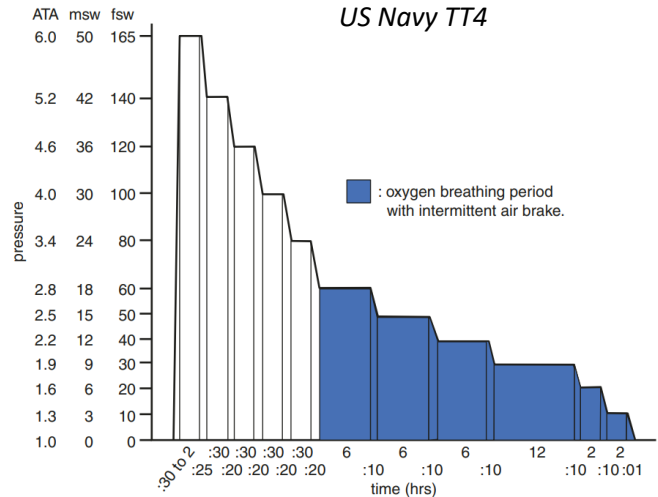
US Navy TT6



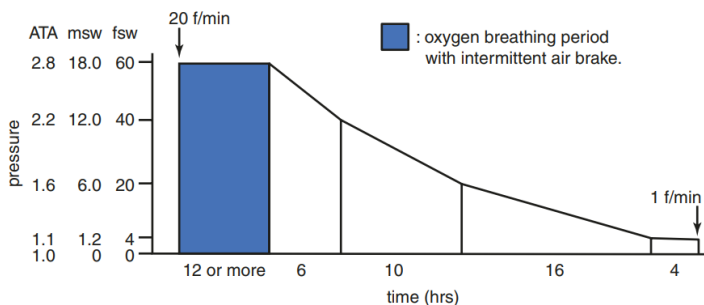
US Navy TT6A



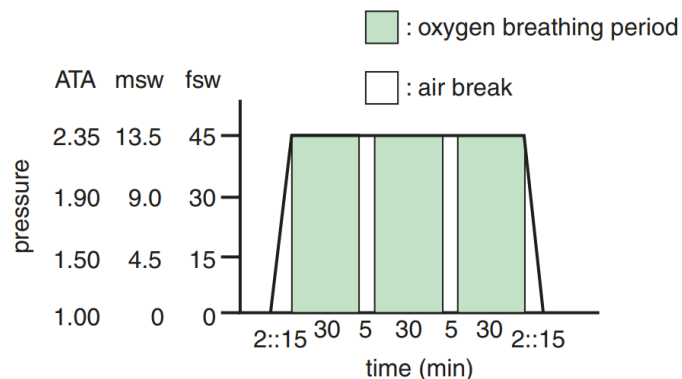
US Navy TT4



US Navy TT7



US Navy TT9

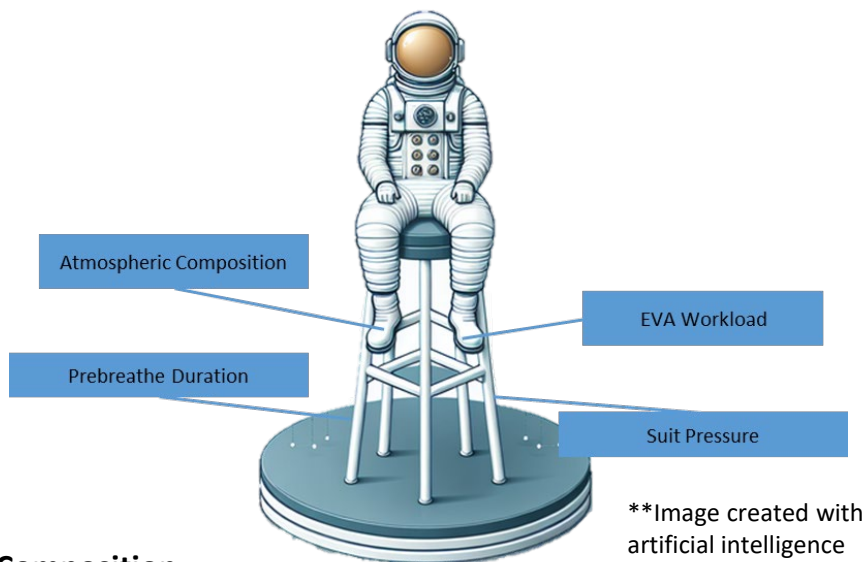




Prevention

DCS Risk Mitigation

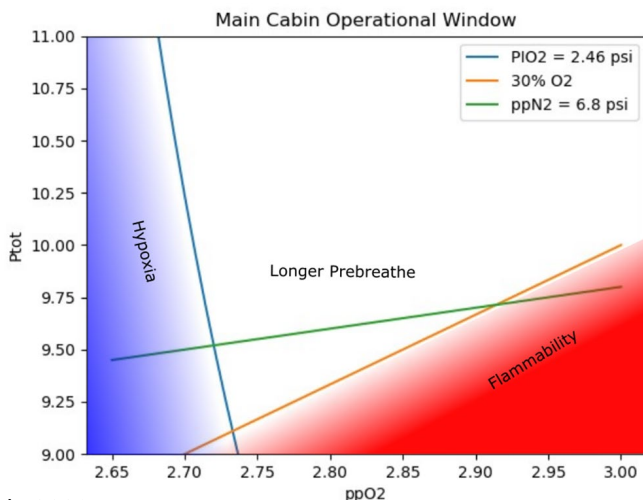
There are **four** independent elements that contribute to DCS risk in spaceflight and properly balancing these elements mitigate DCS risk during EVAs.



1. Atmosphere Composition

Different habitat atmospheres influence DCS risk by altering the partial pressure of nitrogen and oxygen. Changes in total pressures affects the amount of dissolved oxygen and nitrogen in tissue, directly affecting prebreathe times. Atmospheric conditions must also consider other factors such as flammability, crew comfort, and long-term crew health. Cabin atmospheric composition is bounded by three constraints

- Flammability limit (**must stay** to the left of the orange 30% O₂ line)
- Hypoxia limit (**must stay** to the right of the blue P_IO₂ = 2.46 psi line)
- ppN₂ limit (**prefer to stay** below green ppN₂ = 6.8 psi, minimizes DCS risk)



Garbino et al., 2023



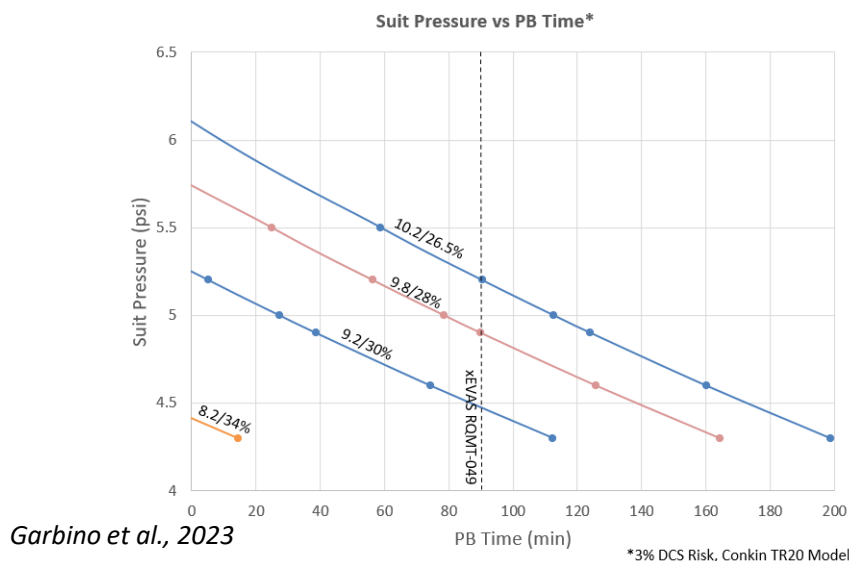
Prevention (continued)

2. EVA Workload

High intensity workload especially involving the lower body during an EVA due to increased perfusion in large muscle groups, such as ambulation, can promote bubble formation in tissues due to increased circulation. Proper workload management is critical in DCS risk management.

3. Suit Pressure

In-suit pressure determines the differential pressure between the habitat which directly impacts DCS risk and prebreathe duration. Higher suit pressures reduce DCS risk, but limits dexterity and endurance while lower suit pressures significantly improve mobility but has an increased risk of nitrogen bubble formation.



4. Prebreathe Duration

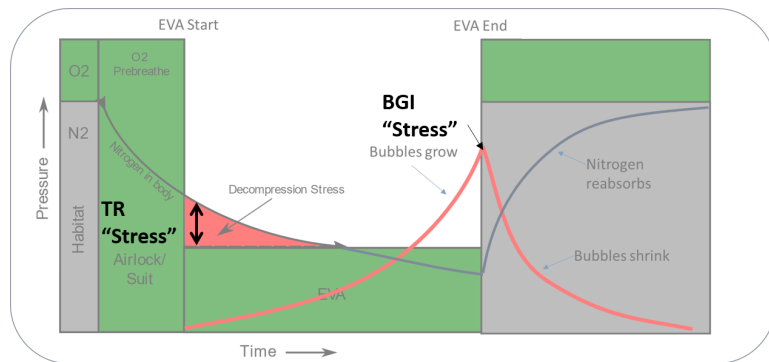
To mitigate DCS risk in spaceflight, a prebreathe (PB) protocol of variable amounts of time is used prior to a decompression event. PB works by eliminating nitrogen inhalation in ambient air by replacing it with 100% oxygen, therefore reducing alveolar nitrogen partial pressure. With alveolar partial pressure nearing zero, nitrogen from tissues diffuse across the gradient between alveoli and tissue and is then mobilized into the circulation and subsequently expired, progressively decreasing total body nitrogen. Over time, this reduces supersaturation at the time of decompression by limiting bubble production, therefore reducing the overall DCS risk. The effectiveness of PB is dependent on maintaining a zero-nitrogen alveolar gradient which means any mask leak, seal breach, or glove/suit configuration issue that allows the crewmember to inhale ambient cabin air is classified as a break in prebreathe (BiPB). Even brief BiPB rapidly reintroduces nitrogen into arterial blood, disrupting washout and elevating bubble growth risk. Operationally, a BiPB imposes steep compensatory PB time or can force a complete protocol restart, putting the entire EVA timeline at risk.



Quantifying DCS Stress

NASA utilizes both empirical tissue tension models and biophysical bubble growth models to quantify decompression stress, design prebreathe protocols, and predict true physiological nitrogen washout. The majority of cases present themselves between 60-240 minute and inflammatory responses can last greater than 24 hours.

Garbino et al., 2026



1. The Tissue Ratio (R-value), first used by Haldane at the end of the 19th century to define diver ascent limits, is used to quantify decompression stress by evaluating nitrogen tension relative to suit ambient pressure across tissue compartments with varying half-lives ($t_{1/2}$) (Conkin 1994, Conkin et al. 1998). This method estimates how much nitrogen gas could potentially come out multiple tissue compartments with different half-lives when pressure changes. Acceptable R-values vary by suit pressure, historically an EMU suit at 4.3 psi has an $R \leq 1.65$.

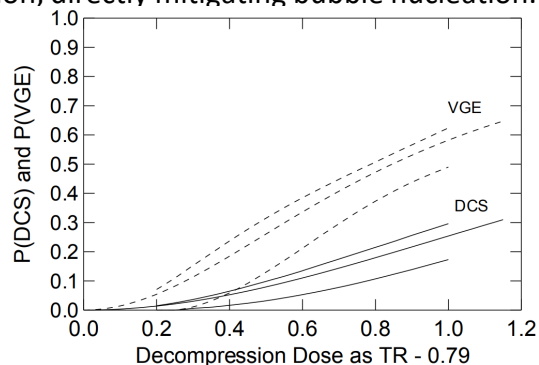
$$R = \frac{P_{N2}}{P_{suit}}$$

P_{N2} : initial absorbed tissue
 P_{suit} : total spacesuit pressure

2. During a PB, nitrogen elimination follows an exponential curve with a tissue compartment half-life time ($t_{1/2}$). The half-life estimation is typically 360-minutes as it was selected because it yielded the greatest correlation between the proposed R-value model and DCS incidence from NASA and U.S. Air Force altitude chamber tests. Replacing ambient air with 100% oxygen reduces alveolar ppN_2 to near zero, creating a steep gradient. Tissue nitrogen diffuses into capillary blood, transport to lungs, and is expired. This ultimately reduces the nitrogen supersaturation, directly mitigating bubble nucleation.

$$R(t) = R(0) \exp\left[-\ln(2) \frac{t}{t_{1/2}}\right]$$

Conkin et al., 2013





Denitrogenation Prebreathe

To define the true dose through diffusion-based physics and mass-balance, NASA uses the Tissue Bubble Dynamics Probability (TBDM) model, a biophysical model of bubble growth. This model applies mathematical and statistical analyses to estimate the likelihood and severity of bubble formation in tissues. When inputting relevant durations, rates, pressures and gas compositions, the model outputs a bubble growth index (BGI). The BGI is the time varying ratio of bubble radius to an initial 3- μm radius of the bubble. This is calculated throughout the exposure, and the peak value is typically used as the primary measure of decompression stress. BGI provides significant prediction of DCS and VGE data ($p < 0.1$). While TBDM models offer valuable predictive insights, they exhibit substantial variability and are validated through human testing.

Bubble Growth Equation:

$$\frac{dR}{dt} = \frac{-\frac{\alpha D}{h(r,t)} \left[P_a - vt + \frac{2\gamma}{r} + \frac{4}{3}\pi r^3 M - P_{Total} - P_{metabolic} \right] + \frac{rv}{3}}{P_a - vt + \frac{4\gamma}{3r} + \frac{8}{3}\pi r^3 M}$$

R = Bubble Radius (cm)

T = Time

α = Gas solubility ((mL gas)/(mL tissue))

D = Diffusion Coefficient (cm^2/sec)

$h(r,t)$ = Bubble Film Thickness (cm)

P_a = Initial Ambient Pressure ($\text{dyne}/\text{cm}^2 * \text{cm}^3$)

v = Ascent/Descent Rate (dyne/cm)

M = Tissue Modulus of Deformability ($\text{dyne}/\text{cm}^2 * \text{cm}^3$)

P_{total} = Total Inert Gas Tissue Tension (dyne/cm^2)

$P_{metabolic}$ = Total Metabolic Gas Tissue Tension

Over the years, NASA has tested and validated various protocols:

Past NASA Decompression Protocols for Prevention of DCS *NASA has never experienced a Type II event in spaceflight*

In-Suit 4-Hour Prebreathe

Astronaut breathes 100% O_2 in the spacesuit at 14.7 psia for 4 hours.

Campout Protocol

Significantly reduces the required in-suit prebreathe duration by having EVA crewmembers "camp out" in the ISS airlock at 10.2 psia, 26.5% O_2 during the night prior to their EVA. For various operational reasons, the time at 10.2 psia is limited to 8 hours and 40 minutes.

Exercise Protocol

Intense, short exercise regimen at 14.7 psia while breathing 100% O_2 combined with in-suit prebreathe at 10.2 psia.

In-Suit Light Exercise (ISLE) Protocol

A longer period of mild exercise in the EMU. The ISLE protocol shares many steps with the exercise prebreathe protocol but differs in that 40 minutes are spent breathing 100% O_2 by mask followed by a 20-minute depressurization to 10.2 psia.



Statistical Validation Framework (Bayesian vs Frequentist) of Validating PB Protocols

Ground chamber validation testing of prebreathe protocols must satisfy the statistical confidence criteria outlined in NASA-STD-3001 [V2 6008].

[V2 6008] Each program **shall** define mission unique DCS mitigation strategies to achieve less than 4% probability of DCS occurrence with 95% confidence by using the following ground chamber test criteria:

- a. No serious DCS in ground exposures
- b. VGE shall be assessed to determine decompression stress.

To validate that a prebreathe protocol limits DCS risk to $< 4\%$ probability with 95% statistical confidence (assuming 0 DCS events occur during ground chamber testing):

Frequentist Calculation ($n = 74$)

- **Assumption:** Zero prior knowledge. The protocol is treated as a complete unknown, evaluating *only* the new trial data.
- **Drawback:** Requires 74 human exposures in a hypobaric chamber per protocol which is resource-intensive and operationally slow.

Bayesian Calculation ($n = 47$)

- **Assumption:** Incorporates prior evidence from decades of historical NASA/U.S. Air Force hypobaric chamber trials, physiological models, and ISS flight data (e.g., ISLE and Campout protocols).
- **Benefit:** Reduces human subject exposure requirements by 27 fewer chamber tests while meeting the exact same 95% statistical confidence threshold.

Future Options

NASA is currently exploring alternative parameters and conditions through the Exploration Atmosphere (EA) study to shorten the amount of time spent on PB. These test simulate the pressure transition during cabin to suited pressure changes, and the results focus on nitrogen washout efficiency, DCS risk mitigation, and operational feasibility. The results from these test will inform the Artemis mission, suit design constraints, and risk posture to further ensure prebreathe protocols are both effective and efficient.

Saturation Atmosphere	Microgravity Prebreathe* (h:mm)	Planetary Prebreathe*
14.7 psi, 21% O2	"ISS" 4:00 (resting)	6:30-7:00
10.2 psi, 26.5% O2	"CAMP-OUT" 0:40	3:00-3:30
8.2 psi, 34% O2	0:00-0:15	0:00-0:30
5.0 psi, 100% O2 (Apollo, Gemini)	0:00	0:00

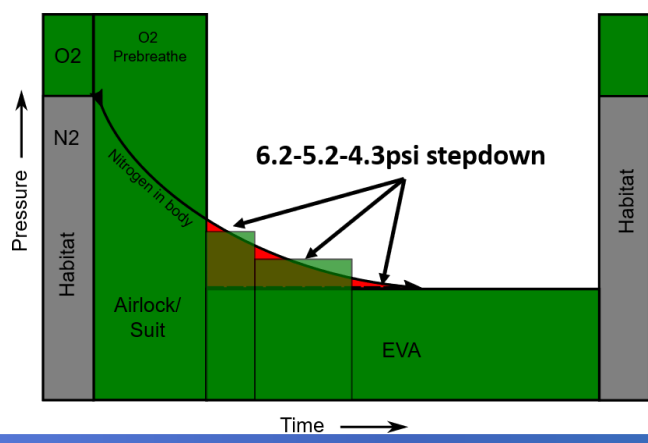
Garbino et al., 2023

EA-1/EA-2 (2022-2023)

Unvalidated estimates (i.e., not yet available for flight use)

Future Option: Working PB

The Working (or "Step-Down") Prebreathe Protocol is a staged decompression strategy designed to mitigate the risk of DCS during EVAs. Unlike resting PB, the step-down approach pairs an elevated initial spacesuit pressure with active surface task execution, incrementally stepping down suit pressure throughout the duration of the EVA. By beginning the EVA at a higher pressure, initial decompression stress and bubble growth risk are kept low when tissue nitrogen is at its peak. As the crew member actively works on 100% O₂, metabolic gas exchange accelerates denitrogenation, allowing suit pressure to be stepped down in stages.



Garbino et al., 2026



Back-Up



Major Changes Between Revisions

Rev C → Rev D

- Updated information to be consistent with NASA-STD-3001 Volume 1 Rev C and Volume 2 Rev F

Rev B → Rev C

- Updated information to be consistent with NASA-STD-3001 Volume 1 Rev C and Volume 2 Rev D

Rev A → Rev B

- Updated information to be consistent with NASA-STD-3001 Volume 1 Rev B and Volume 2 Rev

Original → Rev D

Slide 1

- Revised Executive Summary to emphasize physiological mechanics and mission risk.

Slide 2-3

- Added gas law mechanisms (Henry's Law), VGE vs. AGE comparison table, cardiopulmonary circulation diagram, DCS symptom classifications (Type I/II and Cutis Marmorata), and PFO risk overview.

Slide 4-5

- Added predisposing risk factors (hydration, exercise, body fat %) and DCS detection methods

Slide 6-7

- Treatment capabilities with US Navy Treatment Table decision logic

Slide 8-9

- Added 4 factors contributing to DCS mitigation

Slide 10-13

- Added slide with biophysical modeling, statistical validation, and working prebreathe



View the current versions of NASA-STD-3001 Volume 1 & Volume 2 on the [OCHMO Standards website](#)

Referenced Technical Requirements

NASA-STD-3001 Volume 1 Revision C

- [V1 3003] In-Mission Preventive Health Care** All programs shall provide training, in-mission capabilities, and resources to monitor physiological and psychosocial well-being and enable delivery of in-mission preventive health care, based on epidemiological evidence-based probabilistic risk assessment (PRA), individual crewmember needs, clinical practice guidelines, flight surgeon expertise, historical review, mission parameters, and vehicle-derived limitations. These analyses consider the needs and limitations of each specific vehicle and design reference mission (DRM) with particular attention to parameters such as mission duration, expected return time to Earth, mission route and destination, expected radiation profile, concept of operations, and more. In-mission preventive care includes, but is not limited to: (see NASA-STD-3001, Volume 1 Rev C for full standard).
- [V1 3004] In-Mission Medical Care** All programs shall provide training, in-mission medical capabilities, and resources to diagnose and treat potential medical conditions based on epidemiological evidence-based PRA, individual crewmember needs, clinical practice guidelines, flight surgeon expertise, historical review, mission parameters, and vehicle-derived limitations. These analyses consider the needs and limitations of each specific vehicle and design reference mission (DRM) with particular attention to parameters such as mission duration, expected return time to Earth, mission route and destination, expected radiation profile, concept of operations, and more. In-mission capabilities (including hardware and software), resources (including consumables), and training to enable in-mission medical care, and behavioral care, are to include, but are not limited to: (see NASA-STD-3001, Volume 1 Rev C for full standard).
- [V1 5001] Medical Training** Medical training shall be provided to crewmembers, flight surgeons (FSs), mission control support staff, and other ground support personnel (GSP).
- [V1 5002] Crewmember Training** Beginning with the crewmember candidate year, general medical training, including but not limited to, first aid, cardiopulmonary resuscitation (CPR), altitude physiological training, carbon dioxide exposure training, familiarization with medical issues, procedures of spaceflight, psychological training, toxicology, medical equipment, and supervised physical conditioning training shall be provided to the astronaut corps.
- [V1 5003] Crew Medical Officer Medical Training** Crewmembers who have received a mission assignment as a Crew Medical Officer (CMO) shall be provided with detailed and specific medical training, including but not limited to, health issues, space physiology, behavioral health, medical procedures, medical equipment, toxicology, and countermeasures.

NASA-STD-3001 Volume 2 Revision E

- [V2 6002] Inert Diluent Gas** Cabin atmospheric composition shall contain at least 30% diluent gas (assuming balance oxygen).



View the current versions of NASA-STD-3001 Volume 1 & Volume 2 on the [OCHMO Standards website](#)

Referenced Technical Requirements

NASA-STD-3001 Volume 2 Revision F

- [V2 6003] O₂ Partial Pressure Range for Crew Exposure** The system shall maintain inspired oxygen partial pressure (P_{iO_2}) in accordance with Table 6.2-1—Inspired Oxygen Partial Pressure Exposure Ranges.
- [V2 6006] Total Pressure Tolerance Range for Indefinite Crew Exposure** The system shall maintain the pressure to which the crew is exposed to between $34.5 \text{ kPa} < \text{pressure} \leq 103 \text{ kPa}$ ($5 \text{ psia} < \text{pressure} \leq 15.0 \text{ psia}$) for indefinite human exposure without measurable impairments to health or performance.
- [V2 6007] Rate of Pressure Change** For pressure changes $>1.0 \text{ psi}$, the rate of change of total internal vehicle pressure shall not exceed 13.5 psi/min .
- [V2 6008] Decompression Sickness (DCS) Risk Identification** Each program shall define mission unique DCS mitigation strategies to achieve less than 4% probability of DCS occurrence with 95% confidence by using the following ground chamber test criteria:
- No serious DCS in ground exposures
 - VGE shall be assessed to determine decompression stress.
- [V2 6009] Decompression Sickness Treatment Capability** The system shall provide DCS treatment capability.
- [V2 6017] Atmospheric Control** The system shall allow for local and remote control of atmospheric pressure, humidity, temperature, ventilation, and ppO_2 .
- [V2 6022] Atmospheric Monitoring and Alerting Parameters** The system shall display real-time values for pressure, humidity, temperature, ppO_2 , and ppCO_2 data to the crew locally and remotely.
- [V2 7043] Medical Capability** A medical system shall be provided to the crew to meet the medical requirements of NASA-STD-3001, Volume 1.
- [V2 9053] Protective Equipment** Protective equipment shall be provided to protect the crew from expected hazards.
- [V2 11100] Pressure Suits for Protection from Cabin Depressurization** The system shall provide the capability for crewmembers to wear pressure suits for sufficient duration during launch, entry, descent (to/from Earth, or other celestial body) and any operation deemed high risk for loss of crew life due to loss of cabin pressurization (such as in mission dockings, operations during periods of high incidence of Micrometeoroids and Orbital Debris (MMOD) or complex vehicle maneuvers).
- [V2 11032] LEA Suited Decompression Sickness Prevention Capability** LEA spacesuits shall be capable of operating at sufficient pressure to protect against Type II decompression sickness in the event of a cabin depressurization.
- [V2 11036] Suited Atmospheric Monitoring and Alerting** Suits shall monitor suit pressure, ppO_2 , and ppCO_2 and alert the crewmember when they are outside safe limits.



Reference List

1. Blogg, Samantha & Gennser, Mikael & Møllerlækken, Andreas & Brubakk, Alf. (2014). Ultrasound detection of vascular decompression bubbles: The influence of new technology and considerations on bubble load. *Diving and hyperbaric medicine : the journal of the South Pacific Underwater Medicine Society*. 44. 35-44. Conkin J. (2001). Evidence-based approach to the analysis of serious decompression sickness with application to EVA astronauts. NASA Technical Publication 2001-210196, Houston: Johnson Space Center.
2. Chapter 3: Diagnosing Decompression Sickness. Divers Alert Network. (2020, September 16). <https://dan.org/health-medicine/health-resource/dive-medical-reference-books/decompression-sickness/diagnosing-dcs/>
3. Conkin. J (2013). Evidence Report: Risk of Decompression Sickness (DCS). NASA Technical Publication NASA/TP-20140003729.
4. Conkin J. (2011). Preventing decompression sickness over three decades of extravehicular activity. NASA Technical Publication NASA/TP-2011-216147, Johnson Space Center.
5. Conkin J. (2020). Probability of decompression sickness and venous gas emboli from 49 NASA hypobaric chamber tests with reference to Exploration Atmosphere. Houston, TX: NASA Johnson Space Center. NASA Technical Publication NASA/TP-2020-220529.
6. Conkin J, Abercromby AFJ, Dervay JP, Feiveson AH, Gernhardt ML, Norcross JR, Ploutz-Snyder R, Wessel JH, III. Hypobaric decompression sickness treatment model. (2015). *Aerosp Med Hum Perform*, 86: 508-17.
7. Conkin J, Abercromby AFJ, Dervay JP, Feiveson AH, Gernhardt ML, Norcross J, Ploutz-Snyder R, Wessel JH, III. (2014). Probabilistic assessment of treatment success for hypobaric decompression sickness. NASA Technical Publication NASA/TP-2014-218561. NASA Johnson Space Center, Houston, TX.
8. Conkin J, Gernhardt ML, Powell MR, Pollock NW. (2004). A probability model of decompression sickness at 4.3 psia after exercise prebreathe. NASA Technical Publication NASA/TP-2004-213158. Johnson Space Center, Houston, TX.
9. Conkin J, KV Kumar, MR Powell, PP Foster, JM Waligora. (1996). A probability model of hypobaric decompression sickness based on 66 chamber tests. *Aviat Space Environ Med*, 67: 176-83.
10. Conkin J, Pollock NW, Natoli MJ, Martina SD, Wessel JH, III, Gernhardt ML. (2017). Venous gas emboli and ambulation at 4.3 psia. *Aerosp Med Hum Perform*, 88: 370-76.
11. Garbino A., Hew Yang MY., Estep P., Siders B., Dillon L., Et al. (2023) Development , Validation and Approval of A Planetary Extravehicular Activity Prebreathe Protocol: NASA Exploration Atmosphere Tests 1 & 2. NASA Technical Publication NASA/TP: 20230015380. Johnson Space Center, Houston, TX.
12. Garbino A. & Norcross JR., (2023). Risk of Reduced Crew Health and Performance Due to Decompression Sickness and Hypoxia. NASA Technical Publication NASA/TP-20230013523. Johnson Space Center, Houston TX.



Reference List

16. Gernhardt ML & Abercromby AF. (2008). Health and Safety Benefits of Small Pressurized Suitport Rovers as EVA Surface Support Vehicles. NASA Technical Publication NASA/TP-20080014281. Johnson Space Center, Houston, TX.
17. Hagen PT, Scholz DG, Edwards WD. (1984). Incidence and size of patent foramen ovale during the first 10 decades of life: an autopsy study of 965 normal hearts. *Mayo Clin Proc*, 59(1): 17–20.
18. Henninger D. (2010). NASA Exploration Atmospheres Working Group Recommendations for exploration spacecraft internal atmospheres: The final report of the NASA Exploration Atmospheres Working Group. NASA Technical Publication NASA/TP-2010-216134.
19. Ikomi, Fumitaka. (2019). Recompression Therapy for Decompression Sickness and Arterial Gas Embolism. 10.1007/978-981-13-7836-2_8.
20. Recommendations for Exploration Spacecraft Internal Atmospheres: The Final Report of the NASA Exploration Atmospheres Working Group. NASA Technical Publication NASA/TP-2010-216134. Johnson Space Center, Houston, TX. October 2010.
21. Steiner MM, Di Tullio MR, Rundek T, Gan R, Chen X, Liguori C, et al. (1998). Patent foramen ovale size and embolic brain imaging findings among patients with ischemic stroke. *Stroke*, 29(5): 944–8.
22. Wang Q, Guerrero F, Theron M. Pre-hydration strongly reduces decompression sickness occurrence after a simulated dive in the rat. *Diving Hyperb Med*. 2020 Sep 30;50(3):288-291. doi: 10.28920/dhm50.3.288-291. PMID: 32957132; PMCID: PMC7819728.
23. Webb JT, Krock LP, Gernhardt ML. (2010). Oxygen Consumption at Altitude as a Risk Factor for Altitude Decompression Sickness. *Aviation, Space, and Environmental Medicine*, 81(11).