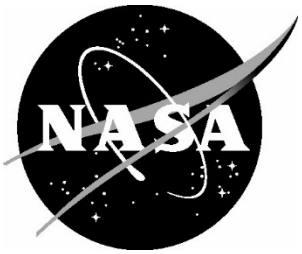
NASA/SP-20260009389



NASA Risks of Decompression Sickness and Venous Thromboembolism during Spaceflight and Patent Foramen Ovale Implications

Outcomes of Working Group Meeting – August 2026

Compiled by:

Sarah D. Taoufik, Office of the Chief Health and Medical Officer, JES Tech, Houston, Texas

Kristin M. Coffey, Office of the Chief Health and Medical Officer, KBR Systems, Houston, Texas

David R. Francisco, Office of the Chief Health and Medical Officer, NASA, Houston, Texas

September 2026

NASA STI Program Report Series

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

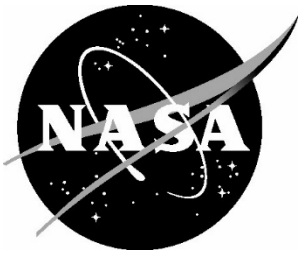
Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

.

NASA/SP-20260009389



NASA Risks of Decompression Sickness and Venous Thromboembolism during Spaceflight and Patent Foramen Ovale Implications

Outcomes of Working Group Meeting – August 2026

Compiled by:

Sarah D. Taoufik, Office of the Chief Health and Medical Officer, JES Tech, Houston, Texas

Kristin M. Coffey, Office of the Chief Health and Medical Officer, KBR Systems, Houston, Texas

David R. Francisco, Office of the Chief Health and Medical Officer, NASA, Houston, Texas

National Aeronautics and
Space Administration

Headquarters
Washington, D.C.

September 2026

The use of trademarks or names of manufacturers in this report is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

Available from:

NASA STI Program / Mail Stop 050
NASA Langley Research Center
Hampton, VA 23681-2199

NASA Presenters

Dave Francisco – Technical Fellow for Human Spaceflight Standards, *Office of the Chief Health & Medical Officer (OCHMO)*

Dr. Alex Garbino – EVA Scientist, *EVA and Environmental Physiology Lab (EEPL)*

Dr. James Pavela – Physician, *Space & Occupational Medicine Branch*

Dr. James Locke – Physician, *Space & Occupational Medicine Branch*

Invited Panel Members

Dr. Mark Crowther – Chair and Distinguished University Professor, *McMaster University Department of Medicine*

Dr. Doug Ebersole – Interventional Cardiologist, *Watson Clinic LLP*

Dr. Caroline Fife – Chief Medical Officer, *Intellicure LLC*

Dr. Mike Gernhardt – Retired Astronaut, *NASA*

Dr. Stephan Moll – Professor of Medicine, Division of Hematology-Oncology, *University of North Carolina School of Medicine*

Dr. Richard Moon – Professor of Anesthesiology; Professor of Medicine, Division of Pulmonary, Allergy, and Critical Care Medicine; Medical Director Center for Hyperbaric Medicine & Environmental Physiology, *Duke University*

Dr. Steven Nissen – Chief Academic Officer of the Heart, Vascular, and Thoracic Institute, *Cleveland Clinic*

Dr. Mark Joshua Rosenberg – Assistant Professor, Department of Neurology; Director, Division of Aerospace and Performance Neurology; Campus Director, South Carolina Space Grant Consortium, *Medical University of South Carolina.*

Dr. Joan Saary – Director, Division of Occupational Medicine, Dept of Medicine, *University of Toronto*; Associate Professor, *Division of Occupational Medicine*; Associate Professor, *Dalla Lana School of Public Health*; Chair, AFC Aerospace Medicine, *Royal College of Physicians and Surgeons of Canada*

Dr. David Southerland – Diving Medicine, *United States Navy - Naval Sea Systems Command*

Dr. Philip Wells – Professor, Chair and Chief, Department of Medicine, *The University of Ottawa*

NASA/CSA/ESA/JAXA Attendees

NASA	CSA	ESA	JAXA
Kristin Coffey	Raffi Kuyumjian	Alessandro Alcibiade	Hiroki Bochimoto
Doug Ebert		Bimba Hoyer	Satoshi Hayamizu
William Fernandez		Gavin Travers	Masatsugu Higuchi
Joanne Kaouk			
Craig Kutz			
Kim Lowe			
Matthew Makowski			
Karina Marshall-Goebel			
Vincent Michaud			
Shannan Moynihan			
Rob Mulcahy			
Steven Piper			
JD Polk			
Mark Prete			
Kristi Ray			
Robert Sanders			
Ashot Sargsyan			
Thomas Skinner			
Terrance Taddeo			
Sarah Taoufik			
Marlei Walton			

CSA = Canadian Space Agency
ESA = European Space Agency
JAXA = Japanese Aerospace Exploration Agency

Executive Summary

The purpose of this working group was to assemble a panel of experts to review the most recent data related to extravehicular activity (EVA) prebreathe testing and decompression sickness (DCS) events, venous thromboembolism (VTE) in-flight occurrences, and patent foramen ovale (PFO) implication as they relate to NASA's Artemis (lunar and beyond) missions. The recommendations from this working group are built upon and integrate the outcomes of the September 2024 Assessment of Patent Foramen Ovale (PFO) as Related to Decompression Sickness (DCS) in the Spaceflight Environment and During Ground Testing (NASA/SP-20240010473), the April 2026 NASA Risk of Venous Thromboembolism in Spaceflight Working Group (NASA/SP- 20260005258/REV1), and the updated DCS prevention standard reviewed by the DCS panel in NASA-STD-3001 Volume 2 Human Factors, Habitability, and Environmental Health (NASA-STD-3001 Vol 2 Rev F), with a specific focus on risk mitigation interventions such as PFO closure.

The following is a summary of the panel's recommendations:

Assessment of DCS Risk through Venous Gas Emboli (VGE)

The panel evaluated whether VGE can be used to assess decompression stress and/or the risk of DCS at altitude in partial gravity with ambulation.

> *The consensus of the group is that there is no definitive link between bubble grades and the risk of DCS at altitude for prebreathe protocols involving partial gravity and ambulation.*

VGE Predictive Value & Bubble Grading

- The negative predictive value of VGE grading is high; the complete absence of bubbles is a strong indicator of low DCS risk.

> *The panel concluded that while minimizing bubbles is desirable, the predictive value of bubble scores for DCS remains uncertain, especially for lunar surface operations.*

- A high VGE (Grade 4) has a slightly positive predictive value for DCS; however, many individuals with high bubble grades remain entirely asymptomatic.
- The timing of bubble appearance during a scan (early vs. late) may help distinguish between intracardiac shunts (such as a PFO) and intrapulmonary shunts.

Left Ventricular Gas Emboli (LVGE) Findings

- Improved imaging technology has increased the detection rate of LVGE, making it a more common finding.

- While LVGE is measurable, the panel determined it is not clinically significant enough to warrant altering current protocols. However, the presence of LVGE could indicate an underlying atrial septal defect or PFO.

PFO and DCS Risk

The panel evaluated whether a crew member with a PFO coupled with proposed DCS prebreathe protocols for Artemis faces an increased risk of a significant health event during a mission.

It was determined that a "small" PFO (Grade 1 or 2) does not pose a significant risk. There were mixed opinions on whether closing or screening out crew members with a "large" PFO (Grade 3 or above) significantly reduces the risk of a venous gas embolism (VGE) passing to the arterial side and causing a significant mission health event. The group did not recommend universal screening or exclusion of astronauts with large PFOs but emphasized the importance of risk mitigation through protocol design and ongoing data collection. If crews are assessed, they should be informed of their status and offered closure for a large PFO.

- **Evidence from Diving Data:** Diving literature indicates that a large PFO increases the risk of DCS by a factor of 5; however, the absolute risk of diving remains extremely low due to the use of established safe protocols. Translating diving data to "altitude" is difficult, as no definitive trials or studies have been conducted to determine the association between PFO and DCS at altitude (Kerut et al., 2001).
- **Paradoxical Embolism Risk:** A large PFO may increase the risk of a paradoxical embolism, but the absolute risk remains low. Current guidelines do not recommend routine closure unless there is a history of cryptogenic stroke or recurrent neurological DCS (Kottoor & Arora, 2018).
- **Protocol Efficacy:** Conservative protocols are considered effective in preventing DCS and may provide protection to individuals with small PFOs.

Panel Recommendations for Ground-Based Studies & Treatment

Ground-based studies should no longer remove subjects from research solely due to the presence of LVGE. Protocols should balance subject safety with population representativeness, and subjects must be fully informed of their LVGE status and any associated risks.

- **Safety Review:** Ground-based testing protocols should undergo a comprehensive review to confirm subject safety.
- **Treatment Efficacy:** The current treatment protocols for DCS should be formally tested to prove their efficacy.

VTE and PFOs in Spaceflight Risk Assessment

The panel discussed whether a PFO increases VTE risk in altitude or hypoxic environments.

Hypercoagulability at Altitude: It was noted that high altitude and hypoxia can increase hypercoagulability and VTE risk. However, studies of populations living at altitude equivalents that NASA is considering (< 8,000 feet) do not show clinically significant increases in VTE rates compared to sea level, despite some biomarker evidence of hypercoagulability. Studies looking at higher altitudes (> 8,000 feet) do indicate increased VTE rates, though studies involving healthy populations equivalent to astronauts are limited (Feng et al., 2026).

The consensus was that the presence of a PFO is not considered a major risk factor for VTE formation, nor for complications from an embolism traveling from an initial formation site in the left internal jugular or cerebrum at normoxic or proposed hypoxic space habitats. No changes to astronaut selection criteria regarding PFOs are recommended with respect to VTE.

Blood Flow Dynamics: VTEs experienced in spaceflight have historically occurred in the internal left jugular and the cerebral sinuses; no lower extremity thromboses have been experienced in spaceflight to date. Due to the structure of the heart and the upper-body nature of thromboses seen in space, it was determined that a PFO does is not expected to significantly increase the risk of further complications from a VTE.

Specifically, blood flow from the inferior vena cava streams directly toward the interatrial septum and the fossa ovalis. Conversely, the crista interveniens directs superior vena cava (SVC) flow away from the interatrial septum. This flow away from a PFO further minimizes the relevance of a PFO when an embolism originates in the upper body (Borden, Coon, & Lang, 2012; Montrief et al., 2020).

Pre- and Post-EVA Pharmaceutical Usage

The panel assessed current pre- and post-EVA pharmacological strategies for preventing DCS and managing pain. The discussion critically examined the use of aspirin for DCS mitigation and assessing the risks of concurrent VTE prophylaxis with apixaban. Furthermore, the panel identified a need for definitive clinical guidelines regarding the prevention and treatment of EVA-related pain and inflammation to avoid contraindicated drug interactions.

The panel concluded that clear clinical guidance is required regarding medication use for all crewmembers prior to Extravehicular Activities (EVAs). Specifically, protocols must address the use of aspirin for Decompression Sickness (DCS) prevention and pain relief. Additionally, guidance is needed for the pre- and post-EVA use of analgesics (acetaminophen, ibuprofen, naproxen, celecoxib), as these medications have the potential to mask DCS symptoms.

- **Aspirin for DCS Prevention:** NASA currently administers aspirin prior to EVAs to mitigate DCS risk. Animal studies indicate that nitrogen bubbles interact with thrombocytes, causing adhesion and activation that can contribute to microvascular obstruction and DCS-related damage (Westerweel, Fjen, & Van Hulst, 2013). Because aspirin has potent antithrombotic effects on platelet function, it may reduce this microvascular obstruction. However, while organizations like the Divers Alert Network (DAN) recognize its theoretical benefit (Buzzacott & Chimiak, 2017), the practice is supported primarily by limited animal studies rather than human clinical trials.
- **Bleeding Risks and Drug Interactions:** Clear guidelines are necessary to address the concurrent use of aspirin and prophylactic apixaban (used for Venous Thromboembolism [VTE] prevention), as combining them significantly increases bleeding risks. Furthermore, if traditional NSAIDs (such as ibuprofen and naproxen) are used alongside preventive aspirin, they can competitively bind to the COX 1 enzyme, reducing aspirin's protective antiplatelet efficacy while further elevating the risk of gastrointestinal and general bleeding.
- **Pain Management Recommendations:** For managing pain associated with spacesuits and EVAs, the panel suggests acetaminophen as the first line option. Celecoxib may be considered as a secondary option for targeted inflammation and pain relief before escalating to other NSAIDs.

References

Assessment of Patent Foramen Ovale (PFO) as Related to Decompression Sickness (DCS) in the Spaceflight Environment and During Ground Testing. (2024). *NASA/SP-20240010473*. Available at: https://www.nasa.gov/wp-content/uploads/2024/09/pfo-dcs-summary-report-august-2024.pdf?emrc=851cc3

Assessment of Risk of Venous Thromboembolism during Spaceflight. (2025). *NASA/Special Publication – NASA/SP-20250001074/REV1*. Available at: https://www.nasa.gov/wp-content/uploads/2025/04/venous-thromboembolism-vte-report-rev1-april-2025.pdf

Buzzacott P, & Chimiak J. (2017). Effects of Aspirin on Diving. *Divers Alert Network* [DAN]. Available at: https://dan.org/alert-diver/article/effects-of-aspirin-on-diving/

Edmund K Kerut, William T Norfleet, Gary D Plotnick, Thomas D Giles, Patent foramen ovale: a review of associated conditions and the impact of physiological size, *Journal of the American College of Cardiology*, Volume 38, Issue 3, 2001, Pages 613-623.

Feng J, Zhang N, Yang G, Wang X, Chen J, Li F, Dai R and Yi H (2026) Venous thromboembolism at high altitude: mechanisms, risk stratification, and precision prevention. *Front. Physiol*. 17:1851375. doi: 10.3389/fphys.2026.1851375

Kottoor SJ, Arora RR. Cryptogenic Stroke: To Close a Patent Foramen Ovale or Not to Close? *J Cent Nerv Syst Dis*. 2018 Dec 16;10:1179573518819476. doi: 10.1177/1179573518819476. PMID: 30574006; PMCID: PMC6297885.

Montrief T, Alerhand S, Denault A, Scott J. Point-of-care echocardiography for the evaluation of right-to-left cardiopulmonary shunts: a narrative review. *Can J Anaesth*. 2020 Dec;67(12):1824-1838. doi: 10.1007/s12630-020-01813-2. Epub 2020 Sep 17. PMID: 32944839.

NASA Office of the Chief Health and Medical Officer. *NASA-STD-3001 Volume 2, Revision F: Human Factors, Habitability, and Environmental Health*. (2026). Available at: https://www.nasa.gov/reference/nasa-std-3001v2/

Westerweel, P.E., Fijen, V.A., & van Hulst, R.A. (2013). Aspirin in the treatment of decompression sickness: what can we learn from French experience? *International maritime health, 64, 1:* 51.

William B. Borden, Patrick D. Coon, Roberto M. Lang, *Chapter 106 - Echocardiographic Evaluation of Atrial Septal Defects*, Editor(s): Roberto M. Lang, Steven A. Goldstein, Itzhak Kronzon, Bijoy K. Khandheria, Dynamic Echocardiography, W.B. Saunders, 2011, Pages 440-445.