

Carbon Dioxide as a Multisystem Threat in Long Duration Spaceflight

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BACKGROUND: Elevated partial pressure of carbon dioxide (P_{CO_2}) poses a persistent health challenge during spaceflight. Unlike Earth's environment, the International Space Station experiences P_{CO_2} levels that often exceed terrestrial safety thresholds, creating unique physiological risks for astronauts. In microgravity, localized P_{CO_2} "pockets" can form due to lack of convection, exacerbating hypercapnic symptoms such as headaches, visual disturbances, and cognitive impairments. Moreover, microgravity-induced cephalad fluid shifts amplify the impact of CO_2 -mediated cerebral vasodilation, contributing to elevated intracranial pressure and potentially exacerbating spaceflight-associated neuro-ocular syndrome. Chronic hypercapnia also raises concerns about bone demineralization and renal stone formation, compounding mission risks. As we move toward longer missions to the Moon and Mars, mitigating CO_2 -related health effects through engineering controls, physiological countermeasures, and enhanced monitoring is essential. This article discusses current evidence and calls for integrated strategies to safeguard astronaut health and mission success under the compounded stressors of CO_2 exposure and microgravity.

KEYWORDS: carbon dioxide, microgravity, spaceflight, hypercapnia, astronaut health, long-duration missions, space exploration, International Space Station.

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Spaceflight continues to stretch the boundaries of human physiology, exposing astronauts to stressors that test the limits of human health and performance. Among these, elevated partial pressure of carbon dioxide (P_{CO_2}) levels within spacecraft habitats, particularly the International Space Station, remain a persistent and underappreciated health concern.

On Earth, atmospheric P_{CO_2} averages around 0.3 mmHg, whereas aboard the International Space Station, concentrations typically range from 2.3–5.3 mmHg, with the highest recorded peak reaching 14.9 mmHg.^{1,2} NASA currently sets a 1-h average permissible P_{CO_2} at 3 mmHg; however, astronauts often experience symptoms at levels lower than those known to cause effects under terrestrial conditions.^{2,3}

Physiological Mechanisms of CO_2 Response

CO_2 is a potent respiratory stimulant and cerebral vasodilator. As it diffuses rapidly across the blood-brain barrier, CO_2 acidifies the cerebrospinal fluid by forming carbonic acid, which dissociates into bicarbonate and hydrogen ions.⁴ This decrease in cerebrospinal fluid pH activates central chemoreceptors on the ventrolateral medulla, prompting increased ventilation.⁴

Peripheral chemoreceptors in the carotid and aortic bodies respond even more rapidly to increased arterial partial pressure of CO_2 and acidosis, initiating afferent signals that drive respiratory compensation.⁴

However, this adaptive response has downstream effects. The acidosis induced by CO_2 promotes vasodilation via mechanisms involving nitric oxide, second messenger pathways, and ion channel modulation leading to increased cerebral blood flow, which in the closed environment of the cranium can elevate intracranial pressure.² Terrestrial studies suggest that every 1-mmHg increase in arterial P_{CO_2} can raise intracranial pressure by 1–3 mmHg, pushing levels toward thresholds associated with neurological compromise.⁵ In microgravity, cephalad

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fluid shifts caused by the absence of gravity further exacerbate this issue by redistributing blood volume to the upper body and brain.

Health Effects of Hypercapnia in Space

Fluid redistribution combined with CO₂-mediated vasodilation may exacerbate spaceflight-associated neuro-ocular syndrome, characterized by optic disc edema, globe flattening, and visual disturbances.⁶ Law et al. reported that each 1-mmHg increase in PCO₂ doubles the risk of headache and recommended maintaining 7-d average levels below 2.5 mmHg.²

Astronauts' subjective reports align with these findings, linking PCO₂ levels between 2.8–5.0 mmHg to symptoms such as headaches, fatigue, blurred vision, poor sleep, and nausea, with symptom severity increasing alongside PCO₂ concentration.^{2,7} At PCO₂ concentrations around 3.5 mmHg, astronauts experienced frontal headaches and chronic cough.⁷ A recent study conducted by Cole et al. found a significant link between PCO₂ levels and congestion, with congestion incidence doubling for every 1-mmHg increase in PCO₂.⁸

The relationship between increased bone resorption when compared to bone formation and the lack of mechanical loading is well-established, as the absence of weight-bearing activities accelerates bone density loss in microgravity. Hypercapnia may exacerbate this by disrupting calcium balance, further promoting bone resorption and increasing renal stone risk.⁹ This concern is further supported by new evidence of CO₂-associated calciuria and reduced bone density.⁹ Although potassium or magnesium citrate could potentially be used to mitigate renal calculus formation, data on its efficacy in the specific setting of space-based hypercapnia are limited.¹⁰ This topic continues to be an area of ongoing research, and additional studies are required to reach definitive conclusions.

Operational Implications and Cognitive Impact

Astronauts have reported malaise, sleep disruption, and cognitive sluggishness at PCO₂ levels as low as 2.8 mmHg.^{2,7} Performance decrements at these thresholds raise concerns for high-demand tasks, especially during extravehicular activity or emergency response. Furthermore, CO₂ hotspots, micro-environments with elevated local concentrations due to inadequate air mixing, are particularly worrisome in exercise areas, sleep stations, or confined work zones.¹¹

In microgravity, the lack of convection means that exhaled CO₂ can linger near the astronaut's face, further increasing the inhaled PCO₂.¹² Interestingly, some reports suggest that the heightened sensitivity to CO₂ observed during spaceflight may not only be due to the exposure itself, but also to individual predispositions to CO₂ retention, adaptation to microgravity, and fluctuations in local CO₂ levels that are not detected by fixed sensors.⁷ This adds another layer of complexity when assessing astronaut health, as individual factors such as metabolic rate, hydration status, and adaptation to space can influence the body's response to environmental CO₂.

Mitigation Strategies

Mitigating CO₂ exposure requires integrated solutions across hardware, environmental monitoring, and individualized crew countermeasures. Engineering should prioritize improved air mixing via fans, redesigned ducts, and adaptive airflow technologies. Optimizing corridors and storage areas can reduce obstructions from clutter and equipment. Retractable racks may improve accessibility and airflow and help avoid dust accumulation.

Real-time CO₂ sensors with high spatial resolution are critical for detecting localized hotspots and tracking trends. This enables timely activation of scrubbers or ventilation before harmful levels are reached. Personalized ventilation or localized scrubbers can further protect vulnerable areas such as sleeping quarters, exercise zones, and dining spaces.

Artificial intelligence can enhance CO₂ management by analyzing continuous sensor data to detect trends and predict spikes, prompting timely life support adjustments. Integrating artificial intelligence into the Environmental Control and Life Support System can dynamically optimize strategies based on astronaut profiles such as metabolic rate, activity level, or CO₂ sensitivity and evolving environmental conditions, especially during long duration missions where resupply is not feasible.

Individualized CO₂ susceptibility profiles, based on ventilatory thresholds, genetic markers, or neurovascular imaging, may help identify vulnerable crewmembers. Pharmacological agents that modulate cerebral blood flow or promote renal calcium excretion may play a future role, although their safety and efficacy require rigorous space-specific validation.

Mission planning should incorporate CO₂ risk modeling. Factoring CO₂ effects into neurocognitive performance algorithms and integrated workload tools will be essential for preserving astronaut functionality, mental health, and operational capacity. Additionally, special consideration should be given to CO₂ exposure during extravehicular activity due to unique environmental challenges.

Conclusions

As space agencies move toward long-duration missions to the Moon and Mars, CO₂ should be addressed not as a passive variable, but as an active contributor to physiological strain. A comprehensive approach that integrates adaptive engineering, predictive physiology, and real-time environmental monitoring will be essential to ensure astronauts not only survive, but thrive as humanity explores deeper into space.

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