Topical: Spaceflight Food System: Impacts to Nutritional Adequacy, Health, Performance, and Resources in Space Exploration

Authors: Grace L. Douglas[1], Brian Crucian[1], Ralph Fritsche[2], Gioia Massa[2], Mark Ott[1], Matthew Romeyn[2], Scott M. Smith[1], Raymond Wheeler[2], Sara E. Whiting[3], Sara R. Zwart[4]

Endorsers: Steven H. Platts[1], Alexandra M. Whitmire[1]

Primary Author:
Grace L. Douglas
Institution: National Aeronautics and Space Administration (NASA)
Phone: 832-729-4608
Email: grace.l.douglas@nasa.gov

Affiliations:
[1]NASA, Johnson Space Center, Houston, TX
[2]NASA, Kennedy Space Center, Merritt Island, FL
[3]KBR, Inc., Houston, TX
[4]The University of Texas Medical Branch, Galveston, TX

Abstract

The space food system is critical for crew health and performance, but it is a red risk for Mars. Fundamental research is required simultaneously in shelf stable foods, *in situ* food growth systems, and in mass reduction strategies to ensure provisioning of food systems that meet resource requirements, while serving as a countermeasure to health and performance decrements as astronauts adapt to spaceflight. Research is required to understand the effects of potential exploration food systems on crew health and performance, which will inform food resource/risk trades and impact mission success.

Introduction

Despite high physical standards and training protocols, physiological and behavioral decrements have been documented in astronauts on both short (1-2 weeks) and long (6+ month) missions in spaceflight, including dysregulation of the immune system, cardiovascular and musculoskeletal deconditioning, ophthalmic changes, weight loss, and increased stress and fatigue. Optimizing food and nutrition intakes are key underpinnings for the proper function and performance of all physiological systems and the resulting physical and behavioral health and performance outcomes of astronauts. Much has been learned about the role of nutrition in human health on Earth over the past hundred years, from the identity and role of specific vitamins to the importance of the quantities of some nutrients to immune function. The requirements for providing adequate nutrition to astronauts seem obvious. However, providing a safe, reliable, and nutritious food system that promotes health and performance for space exploration missions remains a challenge [1]. In fact, food is one of the greatest resource and logistical challenges, which is part of why it remains a “red” risk for Mars missions [2].

There are three key concepts leading to this red risk status for the food system.

1. The food system itself. There is no precedent for providing a shelf stable food system that maintains safe, nutritious, and acceptable food for at least five years to meet operational logistics requirements (e.g., food production, packaging, prepositioning for launch, prepositioning in space). The International Space Station (ISS) foods have a shelf life of 1.5 to 3 years before some quality parameters and nutrient contents degrade to unacceptable levels. For comparison, the U.S. combat rations meals-ready-to-eat (MREs) are expected to have a 3 year shelf life but their use is limited to up to 21 consecutive days to prevent performance and health impacts from extended consumption [3]. Limited use timelines are not an option for space exploration missions. Likewise, supplements are not a solution to replace a food system as they do not provide calories, they do not replace the thousands of bioactive compounds in a variety of whole foods, and they can also degrade over time [4].

In addition to the standard food system on ISS, resupply vehicles bring fresh produce and other preference and holiday foods on a regular basis, which provides around 20-25% of the foods that crew consume. Astronauts often comment on the importance of fresh produce and crew preference selections, but these will not be available on long-duration exploration missions [4].

2. The impact of the food system on health and performance. Food must be consumed to be nutritious. Although commonly assumed that high performers will eat whatever it takes, food quality, familiarity, variety, and food centric celebrations become more important to crew with distance from Earth, length of mission, and isolation [5]. Astronauts often don't eat enough, and weight loss is the first order result. Weight loss has averaged 5% of body mass in most spaceflight programs to date [6, 7]. Weight loss is an indicator of nutritional intake and nutritional status. Astronauts are in peak physical condition at launch and they exercise for up to two hours daily in spaceflight, so weight maintenance is critical to their health and performance [6]. Astronauts are expected to work at extremely high cognitive and physical levels, but to date there have been limited studies during flight investigating links between dietary intake, weight loss, and health and performance outcomes, including sleep. Although there may be performance decrements in spaceflight (indicated by loss of muscle mass, related to both inadequate food intake and exercise), and there are health decrements, there have been limited or no investigations on the specific role of food intake. For example, it is well established that ISS astronauts manifest diminished T and NK cell function during spaceflight as well as persistent inflammation and the reactivation of latent viruses [8, 9]. Select crews experience clinical symptoms including atopic dermatitis, atypical allergy, and various infectious diseases [10, 11]. Despite potential links to the food system [12], studies investigating this phenomenon in relation to nutritional status in spaceflight are lacking. This is more concerning given that quality of some foods and some nutrients degrade over time [13, 14], and investigations into food system limitations, intake over time, and health and performance in healthy, high-performing, populations are extremely limited.

3 – The impact of the food system on resources. In conflict with the first two concepts, all vehicle programs need to reduce resource requirements (e.g. mass, power, volume, crew time) to enable space missions. Food is one of the greatest resource consumers of human spaceflight, primarily impinging on mass and volume. This is further confounded by the fact that there is an inverse relationship between food density and nutritional value; that is, the most nutritious foods are often the least calorically dense, and the most acceptable food systems that promote the best quantity and quality of intake require a wide variety of healthy and high-quality choices.

These challenges have all been reviewed in more detail previously [15].

Space vehicle programs tend to focus on this third concept, as this can enable or prevent a mission at the outset. Unfortunately, although reductions in food quantity and quality often seem an easy solution, history has shown that these type of reductions are a primary cause for mission failure and loss of life [16]. Despite this, given Artemis mission planned durations, and lack of data indicating a health and performance link, Artemis vehicle programs (e.g., Orion, Gateway, Human Landing System) are reducing food resources. For one example, Artemis missions may not have hot water on any phase of the mission. This comes despite longer anticipated mission durations than Apollo missions, even though Apollo astronauts were adamant in stating that hot water was non-negotiable[17]. In another example, the crew may not have any capability to heat food at all for some phases of the mission. These trades are being made by programs with the expectation that decrements may be seen in weight loss, but there are no spaceflight studies that quantify the risk, especially links between cognitive or physical performance decrements and inadequate food intake or nutritional status. It is noteworthy that a team of interdisciplinary scientists recently, when formulating a countermeasure protocol for deep space missions specific to rectify the immune problem, specifically included the importance of maintaining nutritional status [18, 19].

There is ground-based evidence linking food and nutrition intake and cognitive and physical performance, but most of these studies were done with elderly, malnourished, or otherwise ill populations. Few studies have been conducted with healthy, high-performing populations, where the goal would be to understand where physical and cognitive decrements may begin in relation to inadequate nutritional intake, especially at planned levels of exercise and energy restriction expected on Artemis missions. Military studies indicate physiological decrements beginning at 10% body mass loss, but studies were completed more than 20 years ago, generally with younger populations, and with less sensitive measures than exist today. These studies also led the military to restrict use of these limited food systems to 21 days [3, 20].

The lack of spaceflight data in this area becomes a bigger risk for Mars, where behavioral impacts from an inadequate food system may become more apparent. In addition to the increasing psychosocial importance of food with mission duration, diet impacts the composition and dynamics of the gastrointestinal (GI) microbiota [21, 22]. Evidence suggests that the resulting GI microbiota and associated metabolites may influence the brain, mood, and behavior through interaction with the gut-brain axis [23], the immune system [24-26], or through production of odorants that act as social cues [27]. Diet, the microbiome, and associated metabolites may also influence the immune system, impacting inflammation and disease state [28, 29]. Fundamental research is needed to understand how a spaceflight diet and individual crew food selection may impact these factors and resulting crew health and performance.

Recommendations

Given these risks, we suggest research in all three key areas:

1 – Food Systems that provide a safe, nutritious, and acceptable variety of foods, with a minimum 5-year shelf life for both prepackaged foods or *in situ* grown foods (seeds, growth systems, etc.) are needed. Fundamental research is required to ensure a wide variety of prepackaged foods will have the required shelf life and that salad crop systems will be validated for safety and reliability and efficiently integrated with the vehicle systems.

Prepackaged Foods: Research is needed to reach a minimum 5-year shelf life for a wide variety of prepackaged foods, which includes processing, packaging and efficient vehicle cold storage.

Supplemental Salad Crops: Research into systems are needed to produce safe, acceptable, reliable and nutritious fresh salad crops within vehicle constraints [30]. Fundamental research needs to be conducted into food crop growth and microbiomes, how they change over time, and how they change in response to the spaceflight environment, including radiation. The impacts of the microbiome and radiation to crop growth and safety will be especially important as the extensive processing and microbiological testing done with foods on the ground is resource heavy and will not be transferrable to spaceflight. Requirements and safety protocol research and development are needed for microbiological safety. Development of genetically modified crops specifically for spaceflight will require NASA specific stakeholder agreement and policy development prior to use in spaceflight. Technology gaps and roadmaps for salad crop systems have been defined in detail previously [30, 31].

2 – Food and Nutrition Impacts to Crew Health and Performance need to be researched to determine food system risk/resource trades with crew health and physical, behavioral, sleep, and cognitive performance. This includes risk/resource trades with dietary countermeasures for space radiation exposure and other drivers of oxidative stress [32]. Fundamental work needs to be done in relation to the current spaceflight food system as well as any alternative or resource-reduced food systems in a spaceflight environment. Health and performance trades with resource restrictions can then be effectively investigated and understood in relation to mission risk. It is expected that this would provide information on decrements, such that a program could make a well-informed decision to accept a food resource trade associated with a defined decrement on some mission or mission segments (such as those with ground support teams), or increase the food system resources to support crew performance and mission success on other mission segments (such as a mission phase that expects high performance with no ground support team). Crew health and performance includes behavioral health and performance, and the role of fresh produce availability, food acceptability, and choice.

3 – Resource reduction will likely affect requirements for conditioned food storage. Current data indicates that cold storage will be needed for at least some of the food system. This will require fundamental investigation into passive versus active refrigeration trades, and development and vehicle system integration of more efficient solutions in the near term to meet the current Mars mission timelines. Similarly, data are needed to determine the mission scenario where integrating some bioregenerative systems (e.g. crops) starts to trade better than prepackaged foods, and/or having some supplemental fresh salad crops trades better for crew health, wellbeing, and performance.

Resource reduction will also include food system impacts on water and air systems. Closing the water loop beyond current ISS technology would require significant research and development, and increase the mass of ECLSS water recycling hardware [33]. To generate savings over time to make this a worthwhile trade, the resulting reduction in mass of water to be launched in fully hydrated, ready-to-eat foods such as retort thermostabilized pouches would need to be significantly reduced. The feasibility of this trade, and the acceptance of a significantly greater portion of rehydratable foods versus the current proportion of ready-to-eat foods by crew, needs to be determined. Further, this work needs to occur on a rapid timeline to make critical trade decisions that impact vehicle design decisions on the Mars mission timeline. In addition, impacts to crew acceptance, intake, health, and performance need to be investigated in association with implementation of any reduced resource food system, demonstrating the tight link between the three research areas presented here.

In situ grown foods will have additional impacts on air and water systems. Growth of salad crops in an open system like the Veggie on ISS will add additional burden to spacecraft water processing systems in the form of transpired water vapor from the crops. Closing this system, as is done in NASA's Advanced Plant Habitat, transfers this recycling capability to the hardware, but it doesn't eliminate the need. At the same time crops can reduce the atmospheric recycling requirements from a vehicle, though the impacts of this will likely only be seen when crop production reaches a scale larger than is used on the ISS [34].

Concluding Statements

The food system is critical for crew health and performance, but it is a red risk for Mars. Research is required simultaneously in shelf stable foods, *in situ* food growth systems development, and in mass reduction technologies to ensure provisioning of adequate nutrients and variety. Research is also required to fundamentally understand the impacts of potential exploration food systems on all aspects of crew health and performance, from the immune system to brain function, which ultimately will impact mission success.

References

1. Douglas, G.L., S.R. Zwart, and S.M. Smith, *Space food for thought: Challenges and considerations for food and nutrition on exploration missions.* J Nutr, 2020. **150**(9): p. 2242-2244 https://doi.org/10.1093/jn/nxaa188.
2. Patel, Z.S., et al., *Red risks for a journey to the red planet: The highest priority human health risks for a mission to Mars.* npj Microgravity, 2020. **6**(1) https://doi.org/10.1038/s41526-020-00124-6.
3. Friedl, K.E. and R.W. Hoyt, *Development and biomedical testing of military operational rations.* Annu Rev Nutr, 1997. **17**: p. 51-75 https://doi.org/10.1146/annurev.nutr.17.1.51.
4. Smith, S.M., et al., *Human Adaptation to Spaceflight: The Role of Food and Nutrition, 2nd edition (NP-2021-03-003-JSC)*. 2021, Houston, TX: National Aeronautics and Space Administration Lyndon B. Johnson Space Center.
5. Stuster, J., *Behavioral issues associated with long-duration space expeditions: review and analysis of astronaut journals: experiment 01-E104 (Journals)*. 2010: National Aeronautics and Space Administration, Johnson Space Center.
6. Smith, S.M., et al., *Human adaptation to spaceflight: The role of food and nutrition. 2nd edition (NP-2021-03-003-JSC)*. 2021, Houston, TX: National Aeronautics and Space Administration Lyndon B. Johnson Space Center.
7. Zwart, S.R., et al., *Body mass changes during long-duration spaceflight.* Aviat Space Environ Med, 2014. **85**(9): p. 897-904 https://doi.org/10.3357/ASEM.3979.2014.
8. Mehta, S.K., et al., *Latent virus reactivation in astronauts on the international space station.* npj Microgravity, 2017. **3**(1): p. 11.
9. Crucian, B., et al., *Alterations in adaptive immunity persist during long-duration spaceflight.* npj Microgravity, 2015. **1**(1): p. 1-10.
10. Crucian, B., et al., *A case of persistent skin rash and rhinitis with immune system dysregulation onboard the International Space Station.* The Journal of Allergy and Clinical Immunology: In Practice, 2016. **4**(4): p. 759-762. e8.
11. Crucian, B., et al., *Incidence of clinical symptoms during long-duration orbital spaceflight.* International journal of general medicine, 2016. **9**: p. 383.
12. Crucian, B.E., et al., *Countermeasures-based Improvements in Stress, Immune System Dysregulation and Latent Herpesvirus Reactivation onboard the International Space Station–Relevance for Deep Space Missions and Terrestrial Medicine.* Neuroscience & Biobehavioral Reviews, 2020. **115**: p. 68-76.
13. Catauro, P.M. and M.H. Perchonok, *Assessment of the long-term stability of retort pouch foods to support extended duration spaceflight.* Journal of food science, 2012. **77**(1): p. S29-S39.
14. Cooper, M., M. Perchonok, and G.L. Douglas, *Initial assessment of the nutritional quality of the space food system over three years of ambient storage.* npj Microgravity, 2017. **3**(1): p. 17.
15. Douglas, G.L., S.R. Zwart, and S.M. Smith, *Space food for thought: challenges and considerations for food and nutrition on exploration missions.* The Journal of Nutrition, 2020. **150**(9): p. 2242-2244.
16. Feeney, R.E. and C.S. Houston, *Polar journeys: the role of food & nutrition in early exploration.* Arctic, 1998. **51**(4): p. 386.
17. Scheuring, R.A., et al., *The Apollo Medical Operations Project: Recommendations to improve crew health and performance for future exploration missions and lunar surface operations.* Acta Astronautica, 2008. **63**(7-10): p. 980-987.
18. Crucian, B.E., et al., *Immune system dysregulation during spaceflight: potential countermeasures for deep space exploration missions.* Frontiers in immunology, 2018. **9**: p. 1437.

19. Makedonas, G., et al., *Specific immunologic countermeasure protocol for deep-space exploration missions.* Frontiers in immunology, 2019. **10**: p. 2407.
20. Marriott, B.M., *Not eating enough: Overcoming underconsumption of military operational rations*. 1995: National Academies Press.
21. David, L.A., et al., *Diet rapidly and reproducibly alters the human gut microbiome.* Nature, 2014. **505**(7484): p. 559-563.
22. Lozupone, C.A., et al., *Diversity, stability and resilience of the human gut microbiota.* Nature, 2012. **489**(7415): p. 220-230.
23. Cryan, J.F., et al., *The microbiota-gut-brain axis.* Physiological reviews, 2019.
24. Cruz-Pereira, J.S., et al., *Depression's unholy trinity: dysregulated stress, immunity, and the microbiome.* Annual review of psychology, 2020. **71**.
25. Sylvia, K.E. and G.E. Demas, *A gut feeling: microbiome-brain-immune interactions modulate social and affective behaviors.* Hormones and behavior, 2018. **99**: p. 41-49.
26. Rothhammer, V., et al., *Microglial control of astrocytes in response to microbial metabolites.* Nature, 2018. **557**(7707): p. 724-728.
27. Bienenstock, J., W.A. Kunze, and P. Forsythe, *Disruptive physiology: olfaction and the microbiome–gut–brain axis.* Biological Reviews, 2018. **93**(1): p. 390-403.
28. Murota, K., Y. Nakamura, and M. Uehara, *Flavonoid metabolism: The interaction of metabolites and gut microbiota.* Bioscience, biotechnology, and biochemistry, 2018. **82**(4): p. 600-610.
29. Alexander, M. and P.J. Turnbaugh, *Deconstructing Mechanisms of Diet-Microbiome-Immune Interactions.* Immunity, 2020. **53**(2): p. 264-276.
30. Anderson, M.S., et al., *Key gaps for enabling plant growth in future missions.* AIAA SPACE and Astronautics Forum and Exposition, 2017: p. 5142.
31. Douglas, G.L., R.M. Wheeler, and R.F. Fritsche, *Sustaining Astronauts: Resource Limitations, Technology Needs, and Parallels between Spaceflight Food Systems and those on Earth.* Sustainability, 2021. **13**(16): p. 9424.
32. Zwart, S.R., et al., *The Role of Nutrition in Space Exploration: Implications for Sensorimotor, Cognition, Behavior and the Cerebral Changes due to the Exposure to Radiation, Altered Gravity, and Isolation/Confinement Hazards of Spaceflight.* Neuroscience & Biobehavioral Reviews, 2021.
33. Douglas, G., M. Johnson, and J. Broyan, *Space food system water content: considerations for ECLSS water system closure.* 50th International Conference on Environmental Systems, ICES-2021-130, July 12-15, 2021.
34. Anderson, M.S., M.K. Ewert, and J.F. Keener, *Life support baseline values and assumptions document.* NASA/TP-2015–218570/REV1, 2018.