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Assessment of nutritional intake during space flight and space flight analogs

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Abstract

Maintaining adequate nutrient intake during space flight is important not only to meet nutrient needs of astronauts but also to help counteract negative effects of space flight on the human body. Beyond these functions, food also provides psychosocial benefits throughout a mission. Dietary intake data from multiple space programs, including the Space Shuttle and the International Space Station, are discussed. These data arise from medical monitoring of dietary intake and crew health, as well as from research protocols designed to assess the role of diet in counteracting bone loss and other health concerns. Ground-based studies are conducted to better understand some of the negative issues related to space flight. Examples of ground-based studies are extended-duration bed rest studies, vitamin D supplementation studies in Antarctica during 6-month winterovers, and 10- to 14-day saturation diving missions on the floor of the ocean. The use of weighed food records, diet diaries, barcodes and food-frequency questionnaires to assess nutritional intake of space crewmembers is described. Provision of food and nutrients in space flight is important for many body systems including the cardiovascular, musculoskeletal, endocrine, and immune systems. Key areas of concern during long-duration space flight include loss of body mass, bone and muscle loss, radiation exposure and oxidative damage, nutrient intake during spacewalks (extravehicular activity), depletion of nutrient stores, and inadequate dietary intake. Initial experimental research studies using food and nutrition as a countermeasure to aid in mitigating these concerns are underway. Beyond their importance for the few individuals leaving the planet, these studies have significant implications for those remaining on Earth.

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Keywords: space flight; microgravity; nutrient intake; International Space Station

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1. Introduction

Throughout history, exploration missions have often succeeded or failed according to the degree to which nutrition was considered and/or understood. The story of scurvy is a classic example of how a single nutrient deficiency led to more sailor deaths in the so-called age of sail than all other causes of death combined, including shipwreck [1]. The importance of nutrition on space exploration missions will be even more critical, given that no food will be found by travelers on these journeys. Food provision for the entire mission will need to be carefully planned to ensure that there will be enough food, and that the micro- and macronutrients will remain stable for the duration of the mission. A packaging failure and oxidation of macronutrients could mean the difference between a successful mission and an early end to a mission.

Space flight is associated with many physiological changes, as a result of the microgravity environment, including space motion sickness, fluid shifts, congestion and altered taste and smell. The environment of the spacecraft (including the spacecraft cabin, radiation, lack of ultraviolet light exposure, carbon dioxide exposure, and the spacesuit atmosphere) can affect nutrition and nutritional requirements for long-duration missions.

Because nutritional status is subject to so many influences, monitoring nutritional status on extended-duration (>30 d) space missions is important to ensure crew health and productivity, and ultimately mission success. We review herein findings from the first half-century of human space flight with regard to several key nutritional issues, and discuss some of the methods that have been used to assess dietary intake during space flight.

2. Space Food System

The International Space Station (ISS) food system provides a menu with a cycle of 8-16 days. Food items are supplied by all of the international partner space agencies (CSA - Canadian Space Agency; ESA - European Space Agency; JAXA - Japanese Aerospace Exploration Agency; Russian Space Agency; and NASA - US National Aeronautics and Space Administration), with the majority of items at this time coming from the latter two. Foods are packaged in single-serving containers and are intermediate-moisture foods, or are in natural form, thermostabilized, dehydrated, or irradiated [2, 3]. A “standard menu” has been developed for ISS missions, and is periodically re-assessed based on food item additions and deletions. Crewmembers are allotted “bonus containers” which contain either additional space foods, or commercially available products which meet space food constraints (e.g., shelf life). Thus, the food system is designed to fulfill defined nutritional requirements that have been derived from space flight research, extrapolated from speculation about the effects of space flight on nutrient needs, or applied directly from ground-based Dietary Reference Intakes for micronutrients and World Health Organization (WHO) recommendations [3-11]. A key concern for space flight, and a limitation of the food system, is providing adequate amounts of vitamin D (see details below).

3. Dietary Intake Assessment Techniques

3.1. Food Frequency Questionnaire

During flight, crewmembers are asked to record their dietary intake once per week using a Food Frequency Questionnaire (FFQ) designed for use with the space food system. The questionnaire asks how many servings of each food item were consumed in the past week. This FFQ has been validated in a ground-based model of long-duration space flight [12]. Given the closed food system (with repetitive menu cycle), known portion sizes, and precise nutrient content for each food item in the system, the FFQ designed for space flight is much more reliable than a standard food questionnaire.

A unique FFQ is developed for each Expedition to the ISS and is based on the specific menu for the crew on board, as well as foods potentially on board from earlier crews. Each crew is allowed to bring bonus foods that are based on individual preference and can consist of favorite foods from the ISS standard menu or food items that are available off the shelf and meet strict microbiological and environmental requirements, thus allowing slightly different foods to be available for each Expedition. Nutrient analyses by the NASA Johnson Space Center Water and Food Analytical Laboratory are used to categorize foods in the FFQ to optimize data from the nutrients of interest (energy, water, protein, iron, calcium, potassium, sodium). Once the FFQ is filled out by the crewmember and submitted (it is a web-based program), the data are down-linked and an algorithm is applied to determine nutrient content.

3.2. Dietary Intake Monitoring for Flight Research Protocols

Occasionally, flight research protocols will have time periods when detailed dietary intake records are required. These records have been obtained in several ways, including the use of bar codes, food diaries and weighed food records. The most common method of recording food intake during flight is the use of a barcode system, where each food item contains a label. Using the barcode reader takes more time than completing the FFQ (5 minutes per meal, as opposed to 5-10 minutes per week), but it provides a more accurate record. A number of issues surround the use of barcodes, including ensuring that all items on board have labels, and that the reader recognizes these codes. Supermarket customers may be familiar with barcodes and the apparent ease of this system, but most do not realize that this requires an extensive computer system, with programming and a large database for the correct item (and price) to appear at the register.

Some crewmembers of their own volition have chosen to log their entire food intake into a spreadsheet or word processor program, instead of using the FFQ or bar code readers. By choosing this method of recording food intake, we have an exact day to day diary of each crew member’s intake. Food diaries are more accurate than the FFQ, but take much more time and dedication to complete on a daily basis.

3.3. Dietary Intake Monitoring for Ground-Based Protocols

Ground-based models that have utilized dietary intake monitoring include bed rest, studies in Antarctica, and 10-14 day saturation dive studies (NASA Extreme Environment Mission Operations, or NEEMO studies). During bed rest studies conducted at NASA, a research dietitian prescribes a diet to meet nutrient requirements and actual dietary intake is precisely determined by weighed food records in a clinical research center [13]. We have also conducted two vitamin D studies at McMurdo Station in Antarctica where a questionnaire was utilized to determine vitamin D intake from foods and supplements [14, 15]. The questionnaire listed all known food sources of vitamin D that would be available to the subjects at the McMurdo cafeteria during the 6-month expedition and asked the subjects to provide the number of servings of those particular foods each day for a 7-day period. Three of these diet logs were completed (early, middle, and late during the 6-month study).

Dietary intake recording during NEEMO missions has varied. For one mission (NEEMO V), crewmembers were asked to record all dietary intake during the entire 14-day mission [16]. For that particular mission, crewmembers were provided space foods (or space flight-like foods, meaning that some food items were provided in bulk instead of individually wrapped). Scales were provided and crewmembers were trained by a research dietitian how to accurately record dietary intake.

4. Findings from Space Flight

4.1. Energy Intake

Inadequate energy intake has been observed in astronauts since the Apollo moon missions of the late 1960s, during which the average energy intake was 64 ± 14% of the amount recommended [4, 17]. Crews on the Space Shuttle (1981-2011) and the Russian space station Mir (1994-1998), and some crews on the ISS (2001-present), have also not met energy intake requirements, on average consuming about 70% of estimated energy requirements (**Figure 1**) [18]. Although inadequate intake has often been considered a foregone conclusion, many crews have managed to maintain energy intake at more than 90% of predicted requirements (in some cases at more than 100%), indicating that energy intake can be maintained on orbit [3, 19]. Not unexpectedly, inadequate energy intake during flight was associated with body weight loss [18]. Crewmembers who consumed adequate energy maintained their body weight, and furthermore, recent findings have documented that long-duration crewmembers who consumed adequate energy intake and used the resistance exercise equipment on board managed to maintain their body mass, with improved body composition (increased lean tissue, and reduced fat) [3]. Short-duration flight studies have shown that energy requirements during flight are not significantly different from ground requirements [20].

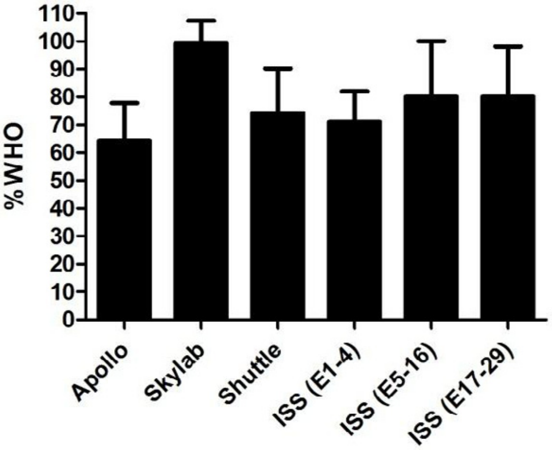

Fig. 1: Energy intake, expressed as a percentage of World Health Organization predicted requirements [21], across multiple space programs. ISS, International Space Station. E, Expedition. Data are mean ± SD.

The average energy intake of the 15 U.S. ISS crewmembers was 74 ± 11% of the WHO prediction for energy requirements [4]. Energy intake among U.S. ISS crewmembers has been increasing in recent years relative to the intake of the crews on the first four 4- to 6-month expeditions (Figure 1). The reason for concern about chronic inadequate energy intake is that weight loss could occur over an extended period, along with possible accelerated muscle and bone loss. Although many crewmembers have lost weight during flight, many others have maintained body weight during flight, indicating that it is possible to maintain weight (Figure 2).

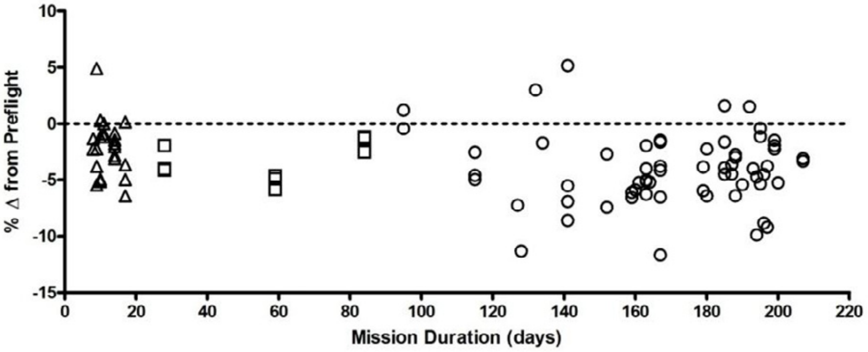

Fig. 2: Body weight loss of astronauts in several space programs (squares, Skylab; triangles, Shuttle, circles, Mir and International Space Station; n=97 total crewmembers). Each data point represents an individual crewmember's body weight loss at landing expressed as a percentage of pre-flight weight.

4.2. Homocysteine, B12, and Folate

Changes in astronaut vision have recently been identified, and have been described as the single biggest clinical issue in the history of human space travel [22]. The predominant theory used to explain these vision changes is that fluid shifts, perhaps secondary to other effects, lead to increased intracranial pressure, which ultimately impinges on the optic nerve or the eye itself. Resistance exercise may play a role in this, by leading to transient increases in headward fluid movement (during compressions). Cabin carbon dioxide (CO_2) levels may also play a role in this pathophysiology, in that increased exposure to CO_2 will increase blood flow into the head. Cabin CO_2 levels on the ISS can reach ten times the concentration on Earth. Recently, biochemical evidence documented changes in circulating metabolites of the one-carbon metabolism pathway (including homocysteine and methylmalonic acid to assess vitamin B12 status) in astronauts with vision issues. These biochemical differences existed before flight [23]. Furthermore, preflight circulating concentrations of serum folate and some of the one-carbon intermediates were related to the change in refraction observed after long-duration space flight [23]. Follow-up testing to evaluate the incidence in astronauts of polymorphisms in the one-carbon metabolism pathway, and to relate these to vision changes and related physiology, is underway.

4.3. Sodium

Another nutritional factor being considered in relation to the vision issues of space flight is sodium. The intake of sodium in the space food system is very high (average intakes of >5 g sodium per day, with individual intakes of 12-13 g sodium per day). NASA has sought to reformulate many of the U.S.-provided space foods to reduce their sodium content, with an overall goal of reducing sodium intakes from the U.S. food items to about 3 g/day. As of this writing, almost all of the foods have been reformulated, and in the coming 12-18 months the food on orbit should all have the newer formulation. Challenges remain, including educating crewmembers about the importance of minimizing sodium intake (and not adding salt back with the salt shaker, or sodium-rich condiments like soy sauce) and working with international partners to help lower sodium content of foods provided by the many countries involved in the ISS program. Nonetheless, this represents a major change in the U.S. space food system, one that will likely have far-reaching health implications, beyond vision.

4.4. Nutrition, Exercise, and Bone

Although bone loss remains a critical challenge to astronaut health on space missions, recent evidence has shown some promise for nutrition and exercise to help in counteracting these losses [3]. Crewmembers who ate well (>90% of estimated energy requirements), had adequate vitamin D status, and exercised using the "Advanced Resistive Exercise Device" maintained bone mineral density after 4- to 6-month space missions. The typical increase in bone resorption was still observed, but the resistance exercise tended to increase bone formation ($P = 0.06$). This increased remodeling rate (that is, increased formation and resorption) allowed bone mineral density to be maintained, but leaves open the question of whether the remodeled bone is as strong as it was before flight. Nonetheless, this marks the first time bone has been shown to respond to any countermeasures during actual space flight, and provides hope that basic health practices—exercise and nutrition—can provide a potentially viable suite of countermeasures.

Specific nutrients may also play a role in optimizing bone response during flight. Two experiments are being conducted with ISS astronauts to test dietary countermeasures: one to examine the effects of lowering sodium intake, and the other to evaluate the effect of the dietary animal protein-to-potassium ratio on bone health. The hypotheses of both experiments are based on extensive literature in non-space research, as well as on results of experiments using ground-based models of space flight, including bed rest [24-28].

Another potential bone loss countermeasure is dietary omega-3 fatty acids [29], although controlled studies have yet to be attempted during flight. Besides the possibility that they may help bone, evidence also exists that omega-3 fatty acids may help counteract muscle loss of space flight, and may even help protect against radiation and cancer risks. It is a particular advantage that all of these benefits could be provided in a single dietary countermeasure that has virtually no side effects.

Vitamin D is a critical nutrient for long-duration space travelers, who lack both good food sources of vitamin D and ultraviolet light exposure, given that the spacecraft are shielded to block ultraviolet light [18, 30]. Accordingly, vitamin D supplements (800 IU per day) are provided for the crewmembers, and these have been shown to maintain vitamin D status [3]. Maintaining vitamin D status and preventing bone loss are still two separate issues, as we do not expect that maintaining vitamin D status alone will prevent bone loss.

Vitamin K has also been proposed as a countermeasure for space flight-induced bone loss because evidence from a few crewmembers showed decreased vitamin K status [18, 30], but more recent studies have shown that vitamin K status does not change in space flight and in ground analog studies [31]. This finding suggests again that, whereas avoiding deficiency is indeed important, few if any documented benefits accrue beyond the provision of adequate nutrition.

4.5. Iron

Evidence shows that during space flight, iron homeostasis is altered [18]. Red blood cell mass decreases within the first 2 weeks of flight, and this event is accompanied by increased serum ferritin, decreased transferrin receptors, and increased serum iron—all of which indicate increased iron storage during space flight. Not only is iron availability increased as a result of neocytolysis of red blood cells [32, 33], but iron content of the space food system is very high because many of the commercial food items in the ISS menu are fortified with iron [18]. The mean iron content of the standard ISS menu is 20 ± 6 mg/day. The defined space flight requirement for iron is 8-10 mg/day for both men and women [18, 34], which is higher than the current U.S. Dietary Reference Intake for males of 8 mg/day [8]. For reference, the highest tolerable iron intake is 45 mg/day, and some crewmembers had overall mission averages in the range of 35 mg/day, with some weeks' iron intake exceeding 47 mg/day. Iron excess, even a moderate excess, can contribute to increased oxidative damage. For example, evidence exists of oxidative stress being associated with low doses of iron consumed over a long duration, such as from flour fortification [35, 36].

5. Summary

Adequate nutrition is critical for human health, and this is true for those on Earth and those traveling in space. Adequate nutrient intake is especially important for space travelers because of the length of time crewmembers are exposed to a limited, mostly closed, food system. Many nutrition-related concerns exist, including the potential for inadequate energy intake, macronutrient imbalance, vitamin and mineral deficiencies or excesses, and environmental factors.

Early explorers discovered the importance of nutrition, often at their peril. Nutrition is even more critical to those exploring beyond our planet, as no food will be found along the way. Understanding nutrition requirements for space travelers and ensuring that the food system contains these nutrients in adequate amounts, that no deficiencies or excesses exist in crewmember nutritional status, and that the nutrients are stable throughout the duration of the flight, are but a few of the critical issues. The food system must contain these nutrients—and must contain foods that are palatable and of sufficient variety to minimize negative crew responses. It is important to optimize nutrient intake to mitigate negative effects of space flight on the body, while ensuring that nutrition does not have a negative impact on other countermeasures, and that those same countermeasures do not have a negative impact on nutritional status. Beyond defining nutrient requirements for space travelers, and providing a food system that will support these requirements, it will also be critical to have a means of tracking dietary intake during missions. It will not be easy to ensure that all of these aspects of nutrition, and more, are accounted for, but all will be required for mission success.

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