Annu. Rev. Nutr. 1992. 12:257–78

NUTRITIONAL QUESTIONS RELEVANT TO SPACE FLIGHT[1]

Helen W. Lane

Biomedical Operations and Research Branch, NASA–Johnson Space Center, Houston, Texas 77058

Leslie O. Schulz

Department of Health Sciences, University of Wisconsin at Milwaukee, Wisconsin 53201

KEY WORDS: body composition, energy requirements, nutrient requirements

---

CONTENTS

INTRODUCTION

Space exploration represents a new frontier in the nutritional sciences, where the research questions are evolving with the duration and complexity of the

[1]The US government has the right to retain a nonexclusive, royalty-free license in and to any copyright covering this paper.

missions. Humans have been eating in space since cosmonaut Yuri Gagarin's 108-minute flight in 1961. Americans were first propelled into orbit in the Mercury Program (1963), but given its relatively short duration (34 hours for the longest flight), nutritional concerns were minor and nutrients provided as dry, bite-sized, and tubed foods sufficed (37). The Gemini Program (1965–1966) brought forth new issues as mission durations extended to two weeks and the heavy physical demands of extravehicular activities were introduced. In addition to the need for oxygen and water, innovative technology was required to provide for the packaging, preserving, and storing of food. (See Table 1 for summary of American space program.)

The longer-duration flights of the Apollo Program (1968–1973) provided an opportunity to study in greater depth a number of physiological changes, including cardiovascular deconditioning and bone demineralization, that had been identified in the Gemini Program (15, 43). Also, vestibular disturbances were added to the inventory of significant physiological findings incident to space flight; previously, no American astronaut had reported symptoms of space motion sickness (7). During the Apollo 15, 16, and 17 flights, balance studies including energy intake and fecal losses, body weight changes, biochemical analyses, and body volume measurements were conducted. Although meal menus and food selections were expanded in terms of variety and food acceptability was evaluated, crude analysis of the food indicated that energy intake in flight was less than optimal, as expressed by loss of body fat and body mass (40, 44).

The three Project Skylab missions (1973–1974) of 28, 59, and 84 days duration offered further opportunities to study the energy and nutrient requirements of astronauts. Detailed metabolic studies in Skylab provided important additional information regarding the cardiovascular, musculoskeletal, hematologic, vestibular, and endocrine alterations experienced in flight. These balance experiments were coordinated with the Skylab food system consisting of 70 foods from which the crew could select their in-flight diets. Food types included frozen, thermostabilized, and freeze-dried foods, and menus were planned in 6-day cycles. The extensive food needs of the 84-day mission led to the inclusion of a high-calorie food bar stowed in the command module to augment energy intake (18).

Table 1 History of manned US space flights

Year	Flight program	Flight length
1961–1963	Mercury	15 min–34 hours
1965–1966	Gemini	5 hours–14 days
1968–1972	Apollo	5–13 days
1973–1974	Skylab	28, 59, and 84 days
1981–present	Space Shuttle	4–10 days

The space shuttle, the principal component of the Space Transportation System, had its inaugural orbital flight in 1981. Flights of the world's first reusable spacecraft thus far have been of limited duration (4–10 days) but have included studies related to nutrition and metabolism. From the time of the Mercury flights to the present shuttle, there has been steady progress in the development of space food systems. Shuttle foods comprise menus geared to the personal preferences of each crewmember and consist primarily of commercially available food items.

Plans for the immediate future include the US space station *Freedom*, where optimal nutrition will be essential for maintaining crew health, productivity, and morale. It is estimated that space station crews will consist of four to six individuals whose tours of duty will be 90 to 180 days. Data from bed rest studies (45) suggest that the number of 90-day tours an astronaut would be permitted is influenced by the possibility that bone and muscle losses may be irreversible, as well as by the danger of exposure to total radiation doses of up to 10–15 rems over a 90-day period.

And the challenge is only beginning. A lunar base, and eventually manned flights to Mars, will require missions lasting up to three years in duration. Thus, the negative physiological effects of microgravity must be overcome by appropriate countermeasures. In addition, the logistical problems associated with providing sufficient food and fluids during long missions will be addressed by the use of regenerative life support systems, which will include small hydroponic gardens. Human nutrient requirements in space therefore must be quantified and the best means of providing those nutrients identified. Overall, to ensure the safety of the crew and the success of longer space missions, the following nutritional questions must be satisfactorily addressed: (*a*) What role does nutrition play in counteracting the major physiological effects of microgravity? (*b*) How does the space environment influence total energy needs and the requirements for specific macro- and micronutrients? and (*c*) What is the most effective system to meet nutritional needs in space?

NUTRITION AS A COUNTERMEASURE TO EFFECTS OF MICROGRAVITY

Methods of Investigation

To determine whether nutritional modifications can play a role in countering some of the major physiological effects of microgravity (see Table 2), it will be necessary to understand the mechanisms involved as humans adapt to the space environment. Technically, to do so would involve observing the process of change in its entirety, without intervention. However, it is not possible to avoid intervention in studies of human responses to the stresses of space flight because medical personnel are responsible for ensuring the health, well-being, and optimum performance of the crews under observation. As a

Table 2 Microgravity effects on the body

Space motion sickness	Experienced by 60–70% of astronauts and cosmonauts; produces malaise, headache, anorexia, nausea, and vomiting. Symptoms appear early in flight and last about 2–7 days.
Cardiovascular deconditioning	Cephalad shift of fluid estimated at 1.5 to 2.0 liters from the lower extremities. Decreased orthostatic tolerance; increased heart rate, decreased pulse pressure, tendency toward spontaneous syncope.
Hematological changes	Reduction in plasma volume and red blood cell mass.
Bone mineral loss	Skeletal changes and loss of total body calcium have been observed in both humans and animals who have flown from one week to more than 237 days in space.
Muscular deconditioning	Loss of lean tissue and decreased muscle strength.

result, some type of intervention is invariably required. In addition, data collection in flight is extremely limited with respect to sample size—only a small number of individuals have flown in space. Plus, the extensive demands on crew time and, in most instances, the relatively short duration of missions limit opportunities for scientific observation.

Because of these limitations, changes in vestibular and cardiovascular function, hematological indices, and the effects of space radiation and microgravity on basic biological processes are being studied through complemental in-flight and ground-based research. A number of simulations and analogs for microgravity have been developed for both human and animal studies on ground (see Table 3). By allowing tighter control over conditions and longer observation periods, ground-based models have provided a great deal of information regarding the adaptation of humans to microgravity.

Body Composition

Several of the physiological changes associated with space flight manifest themselves in changes in body composition. Body composition is classically compartmentalized into fat mass and fat-free mass; the latter includes muscle, organs, blood and bones. Space flight presents a unique challenge for quantifying body composition changes since fluid, bone, muscle, and adipose tissue levels all vary independently of one another in space, and body weight loss does not follow classical patterns (see below).

Body mass has been measured during space flight using the device depicted in Figure 1. The first of these body-mass measurements, taken during 28- to

Table 3 Ground-based research models

Method	Explanation	Selected references
Humans		
Bed rest	The most widely used analog for microgravity in human studies—although not a true simulation, since gravity is still present—does induce many physiological changes similar to space flight.	35, 46
Head-down tilt (−4° to −12°)	To elicit some of the early physiological effects of microgravity with greater fidelity.	19, 21, 35
Water immersion	Used mostly for studies of acute renal and circulatory changes associated with space flight. Other methods are usually preferred because problems with maintaining hygiene and precise thermal control, and skin maceration impair feasibility of long-term studies.	9, 11
Dry immersion	Used by Soviet scientists to address limitations of water immersion; subjects are protected from water contact by a thin, plastic sheet.	10
Animals		
Partial or whole-body casts—confinement in small cages	Hypokinesia is produced by immobilization; particularly useful for studies of circulatory dynamics and the musculoskeletal system.	6, 23
Hind-limb suspension	To more accurately reproduce events in space while minimizing problems associated with immobilization.	4
In vitro	Study of cells by means of rotation.	5
Mathematical models	Can be used to generate computer simulations.	28

84-day Skylab missions, revealed 0.91 kg to 3.64 kg losses of preflight body weight ($n = 9$) (see Figure 2). Analysis of the components of that weight loss was based on both direct whole-body measurements and on indirect metabolic balance data. A conclusion from that analysis was that more than half of the weight loss was derived from fat-free mass and the remainder from fat stores (25, 27). About half the total weight loss that occurred within the first two days of flight was due to water loss. The remaining, later loss occurred more gradually over the duration of the missions and was attributed to both fat and protein depletion. All studies of fluid balance during microgravity have indicated a decrease in total body fluids of approximately 500 to 900 ml (26).

Figure 1 Measuring body mass in space during a Space Shuttle mission (NASA photo #S40-205001).

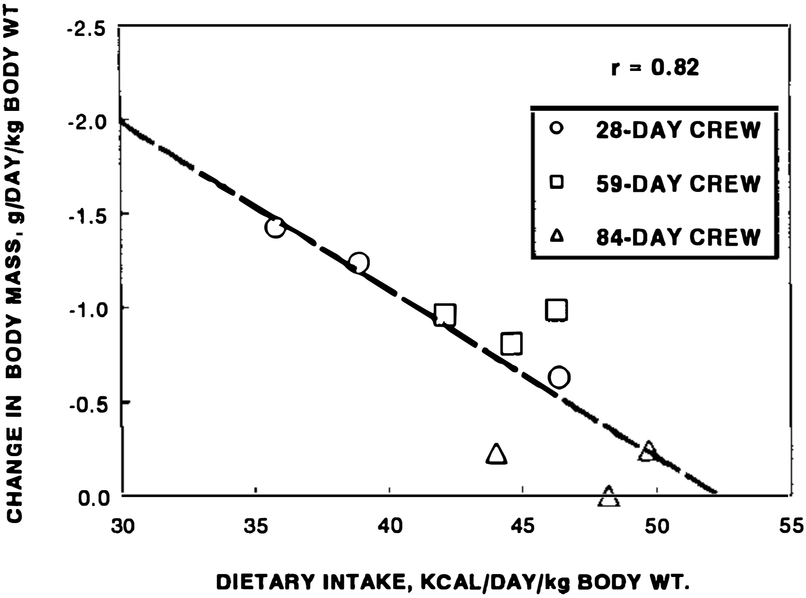

Figure 2 The change in body weight as a function of energy intake for the nine Skylab crewmembers.

This decrease is attributed in part to a 6 to 13% decrease in plasma volume found at landing (16), but it also involves a flight-induced loss of lean body mass (25).

Atrophy of skeletal muscles, especially those used for locomotion, maintaining posture, and counteracting gravity on Earth, occurs during space flight (14). This is reflected by reductions in muscle volume, mass, strength, exercise capacity, and neuromuscular coordination. Disturbances in protein turnover are suggested by the combined observations of skeletal-muscle atrophy, marginal or negative balances of nitrogen and potassium, and a persistent rise in urinary excretion of nitrogen and 3-methylhistidine (14).

Bone loss appears to progress in rough proportion to mission length; the greatest loss determined to date is about 20% (45). In the Skylab 4 mission, the negative calcium balance reached nearly 300 mg per day by flight day 84 (42). Both compact and trabecular bone are lost from the os calcis (heel); the level of loss and rate of recovery vary between sites, from complete recovery of bone mass in the calcaneus to continued deficits in the spine measured up to 6 months after landing. The documented negative calcium balances due to increased urinary and fecal calcium suggest bone resorption during microgravity exposure. Similar losses of bone calcium have been observed during horizontal bed rest (47). In one 19-week bed rest study (13), calcitonin therapy neither prevented negative calcium and phosphorus balances nor increased serum levels of parathyroid hormone (PTH). However, supplementing calcium and phosphorus intake (total intakes 1800 mg per day and 3000 mg per day, respectively) resulted in calcium and phosphorus balances significantly less negative than those in control subjects. Further, these mineral supplements reduced urinary excretion of hydroxyproline, which is typically elevated during bed rest. The apparent lack of hormonal control over the bone demineralization process during bed rest in this study agrees with other observations that neither PTH nor 1,25-dihydroxyvitamin D_3 are activated during bed rest (H. Lane, unpublished data). Because the artificial lighting systems on the US space shuttle and the Soviet space station *Mir* do not activate vitamin D, this vitamin will probably have to be provided through the diet in order to maintain appropriate levels in crewmembers.

The problem of reduced plasma volume upon reentry may be partially alleviated by water and electrolyte replenishment shortly before landing. Both the US and USSR space programs recommend that crewmembers prepare for landing by ingesting approximately one liter of drinking water made isotonic after ingestion by simultaneously swallowing coated tablets of sodium chloride. Postflight studies have indicated that this practice significantly decreases the degree of cardiovascular deconditioning as shown by the postflight blood pressure and heart rate response to a passive standing test (3). Additional fluids and electrolytes are given to returning crewmembers within the first 2 hours after landing in order to further reduce the body fluid volume deficit (34).

Nutrition and Exercise

Appropriate nutrition combined with exercise is likely to be the most effective countermeasure for the changes associated with body composition. In-flight exercise combined with sufficient energy intake is the primary countermeasure being tested against muscle atrophy. An increase in exercise level was imposed during each of the Skylab missions (0.5, 1.0, and 1.5 hours per day), and successive improvements were seen after flight with respect to indicators of muscular deconditioning (50). During the first manned Skylab mission only the bicycle ergometer was used (Figure 3). During the second mission, isokinetic devices were added, and during the last and longest mission daily use of a treadmill was included. Leg-muscle strength declined after both the first and second Skylab missions, but significant improvements were noted in all crewmembers after the last mission. The effect of space flight on precise measures of muscle strength, endurance, and exercise capacity is being

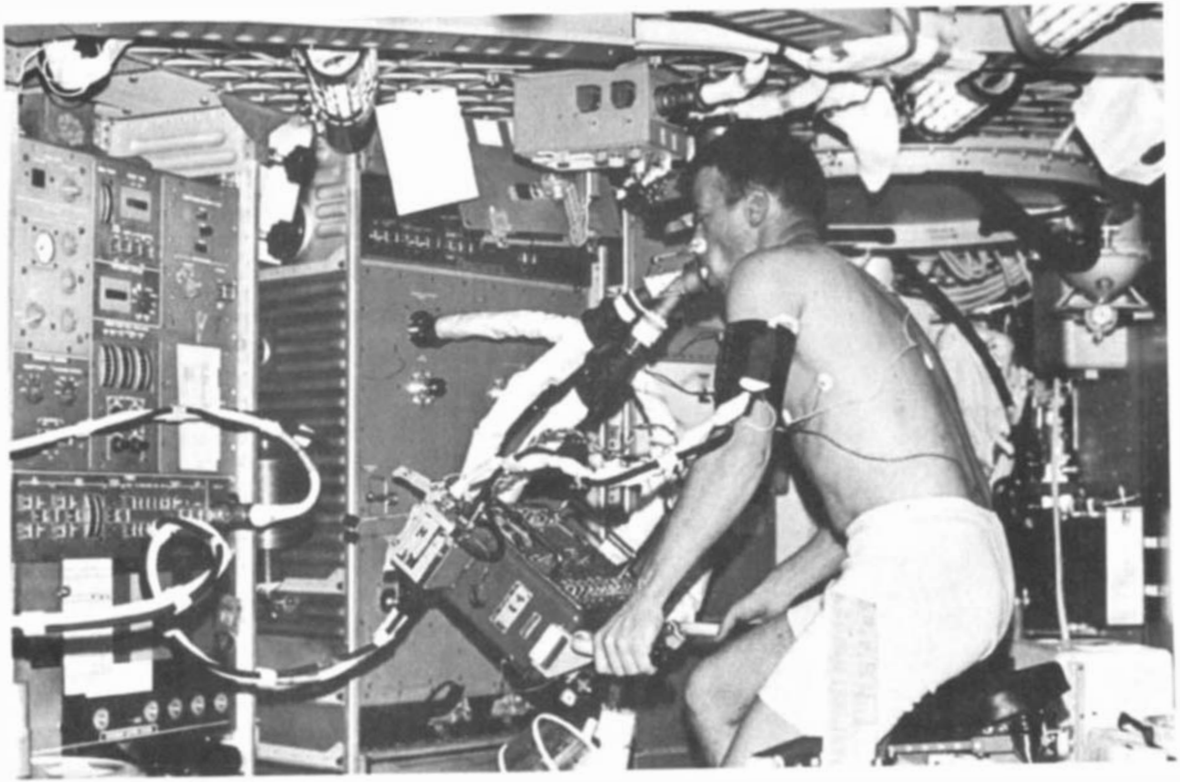

Figure 3 A Skylab crewmember exercising on the cycle-ergometer during flight (NASA photo #SL2-3-227).

studied actively at this time in the US Space Shuttle Program in order to protect crews' ability to leave the vehicle promptly, without help, after landing.

Weight-loading exercise and artificial gravity conferred by centrifugation designed to counteract the loss of gravitational and muscular stress are being investigated for their potential to limit the negative effects of space flight on the skeleton as well. However, Skylab results and preliminary data from the Soviet space program suggest that bungee cords and other devices simulating weight-bearing are not effective in preventing skeletal mineral losses during space flight (45).

Because aerobic exercise can also prevent cardiovascular deconditioning, customized in-flight aerobic exercise protocols are also being developed for use on shuttle flights. Maintenance of adequate balances of energy, protein, fluids and electrolytes assumes increasing importance because of mandatory strenuous exercise during flight.

NUTRITIONAL REQUIREMENTS IN SPACE

Energy

Energy deficits and body weight losses that were easily sustained on short missions cannot be tolerated on missions of long duration. The original hypothesis that life in microgravity would significantly decrease energy requirements has not held true (29). Whereas it was logical to assume that physical activity in a weightless environment would require less energy than at 1 *g*, total energy requirements are determined by numerous factors other than those associated with counteracting the force of gravity. Space flight can be expected to influence several of these factors. For example, the loss of lean body mass associated with weightlessness would be expected to decrease basal metabolic rate—yet energy utilization does not appear to decrease. The stress of changes in environmental factors such as humidity, pressure, and temperature may also play a role. In addition, the extent of physical activity may well be altered by the restricted area available or by the demands of extravehicular activity.

Weight loss is one of the most consistent findings in astronauts returning from space flight. However, it is important to differentiate whether weight losses related to space travel occur as a result of decreased energy intake, increased energy expenditure, or weightlessness per se. Energy intake for all Apollo astronauts averaged about 25 kcal/day per kg body weight (40). Weight changes following recovery indicated that each man lost about 0.15 kg of fat each day in flight, for an average deficit of about 19 kcal/day per kg body weight. The energy intake of astronauts under ground-based conditions and during hypobaric exposure indicated an energy requirement that was not significantly different from the in-flight requirement when adjusted for weight loss (40).

Measurements of food consumption on Gemini (2), Apollo (40), and the Russian flights of Vostok, Voskhod, and Soyuz (52) have all indicated considerably diminished energy intake in flight. Since it has generally been the case that more food was available in flight than was actually consumed, low intake cannot be explained by lack of availability. Space motion sickness, with its associated symptoms such as stomach awareness, nausea, and vomiting, undoubtedly plays a role. Yet, while these symptoms are common reactions to weightlessness, they are not experienced universally and some crewmen who reported no problems lost weight while assuming that their energy intake was adequate. If these symptoms are not the only reason crewmembers restrict their food intake, possibly the mechanisms by which the body regulates energy intake in proportion to energy expenditure are affected by weightlessness. Energy utilization should therefore be quantified in space through the use of techniques such as excretion of doubly labeled water, calorimetry, and computer-controlled diet records.

A detailed examination of energy balance was conducted during Apollo 17 (17). The urine and fecal excretions of the crewmembers were collected and returned to Earth for analysis, with records of fluid and dietary intake to allow estimation of the energy and fluid balance of each crewmember during the mission. The liquid intake-output data were considered with other methods of measuring body fluid volumes to determine whether body weight loss was a result of negative water balance or negative energy balance. The results indicated that water loss could not be the only cause of the weight loss; body tissue had been lost as well. Unlike bed rest, loss of adipose tissue predominated over loss of lean body mass (27).

The detailed nutritional studies performed during the three Skylab missions included analysis of detailed dietary records in combination with metabolic balance studies (32). The energy levels of Skylab menus were determined directly using bomb calorimetry and indirectly by calculating from crewmembers' records the amounts of carbohydrate, protein, and fat consumed. Energy levels in feces were determined by bomb calorimetry, and these data were used to calculate energy availability. Apparent metabolizable energy intake was determined by energy in the diet minus energy found in urine and feces.

Less body weight was lost as mission duration—and energy intake—increased from the first through the third Skylab mission (see Figure 2). Weight loss and body composition data from Skylab support the notion that body fat losses result mainly from negative energy balance while lean body mass and its fluid, muscle, and electrolyte constituents are reduced during space flight primarily as a result of weightlessness. Since the in-flight diet was intentionally increased on each Skylab mission, along with the time devoted to exercise, energy intake varied dramatically among the nine crewmen (35.8 to 49.7 kcal/day per kg body weight). Five of the subjects decreased their mean energy intake during flight (compared to preflight intake), and these subjects lost 75% more weight than the other four crewmen who increased or maintained their diet at preflight levels. Body fat losses were greatest for those crewmen who had the lowest energy intake. Changes in dietary sodium, potassium, and nitrogen between preflight and in-flight phases were insignificant and bore no relationship to the major tissue losses (24). However, in-flight intake of carbohydrate was higher (and fat intake lower) than preflight levels (in-flight carbohydrate 412 ± 60 g per day versus 363 ± 52 before flight; in-flight fat 83 ± 14 g per day versus 110 ± 10 before flight). These changes in intake, which probably resulted from differences in food choice among crewmembers, may have influenced energy utilization (24).

Protein

The only direct measures of nitrogen balance during flight were those taken during the Skylab missions. Like energy balance, nitrogen balance became progressively more negative during Skylab flights (24, 29). Urinary excretion of nitrogen, potassium, and 3-methylhistidine during flight indicated that muscle degradation may have been partially responsible for loss of lean body mass. Excretion of nitrogen in the feces, however, was no different in flight than before flight (24, 29). Muscle atrophy may account for some of the loss of body nitrogen, particularly in crewmembers who do not exercise. However, Skylab crewmembers who did exercise as well as consume high levels of energy and protein during flight still remained in negative nitrogen balance (24).

In attempts to clarify the causes of protein loss during flight, Soviet scientists are examining plasma levels of free essential and nonessential amino acids in cosmonauts after lengthy space flights (38, 39, 51). Plasma samples taken from male cosmonauts before flight, immediately upon landing, and later after flight showed decreased levels of plasma amino acids after flights of at least 75 days, with greater decreases found after longer flights. The plasma amino-acid levels in one crewmember who flew for 185 days reportedly dropped below normal levels. These decreases took place despite consumption of large amounts of proteins and essential amino acids (20) and regular in-flight exercise.

Biochemical studies in rats exposed to microgravity on shuttle flights and on the Soviet Kosmos missions (30, 31) have revealed increased blood levels of glucose, blood-urea nitrogen (BUN), creatinine, and cholesterol compared to levels observed in ground-based control animals. In addition, hepatic glycogen stores in the exposed rats showed a threefold increase.

However, access to animals after landing is frequently delayed for hours or days, and thus readaptation to normal gravity may be confounding these results. Elevated BUN and creatinine levels possibly may be related to a suspected decrease in renal clearance in flight (16). Also, high glycogen stores may stem from an abundance of free amino acid precursors released through protein turnover. In sum, some evidence, albeit indirect, exists to support the supposition that protein turnover may be altered in microgravity.

Stuart and co-workers (49) evaluated the effect of horizontal bed rest on whole-body protein synthesis using the [1-^{13}C]leucine constant-infusion method. In this method, [1-^{13}C]leucine is infused through an artery, and blood samples are collected at a vein. Blood levels of $^{13}CO_2$ (with ^{13}C from leucine) and [α-^{13}C]ketoisocaproic acid (KIC), the transamination product of leucine, can be used to calculate the rates of leucine oxidation and turnover (53). Thus, the calculated nonoxidative [1-^{13}C]leucine disappearance is equated with protein synthesis. Stuart found that bed rest, like microgravity, induced negative nitrogen balance despite consumption of 30 kcal and 0.6 g protein per kg of body weight per day, respectively. Bed rest increased leucine oxidation and decreased nonoxidative disappearance of plasma leucine, suggesting that bed rest may increase protein catabolism and suppress protein synthesis. However, when subjects were fed protein at levels comparable to those consumed during space flight (1.0 g protein per kg per day) (48), bed rest had no effect on leucine oxidation, nonoxidative leucine disappearance, or nitrogen status. However, astronauts still show evidence of negative nitrogen balance despite consuming up to 1.5 g of protein per kg of body weight and 40 to 50 kcal per kg of body weight during flight. It would be interesting to see whether bed rest with head-down tilt, which simulates fluid shifts and cardiovascular changes similar to those seen in microgravity, also affects measures of protein metabolism.

Fluids, Electrolytes, and Minerals

One of the most well-described effects of microgravity upon humans is the redistribution of body fluids from the lower extremities to the central torso and head. Head-down bed rest induces similar fluid shifts (8, 11, 12, 36). These fluid shifts induce diuresis within 12 to 24 hours: During the first day of space flight, total body water decreases up to 3%, total blood volume decreases 3 to 11%, and plasma volume decreases 2 to 9% (16). Neurohormonal responses to signals from the atrial and arterial pressure receptors have been reported to produce negative fluid balance in head-down bed rest (36). Fluid intake has been reported to decrease during both US and Soviet space flights, suggesting that the normal thirst mechanisms may not be operating. The combined effects of fluid shifts, diuresis, decreased thirst, and resultant increases in urine concentration all suggest that requirements for fluid and electrolyte intake in space deserve careful study.

After 24 hours in flight, levels of sodium, phosphate, and calcium salts in the urine are elevated in a manner similar to that in people with a history of renal-stone formation (41). Sodium intake tends to be high in flight, since most space foods are processed (48). Maintaining adequate hydration in flight thus becomes important for this reason as well. Crewmembers in the US space program are encouraged to consume from 1500 to 2000 ml of fluids daily, despite lack of thirst; consumption of foods high in fluid content is also encouraged.

The potential for cardiac arrhythmias associated with low potassium levels has prompted careful control of potassium in the space diet; adequate intake has been documented since the second Skylab mission (48). Other minerals of interest include those associated with bone demineralization and erthyropoiesis; the two most-studied have been zinc and iron. A 5-week period of horizontal bed rest induced a significant negative zinc balance, with increasing excretion of zinc in the urine and feces over time; interestingly, calcium balance was not affected in this study (22). The increasing excretion of zinc in the presence of consistent zinc intake is suggestive of bone demineralization and implies that long space flight may also compromise zinc status and balance.

As for iron, space flight consistently induces a 15 to 25% reduction in red blood cell mass (34). As might be expected, serum ferritin levels increased, presumably because less iron is needed for erythrocyte synthesis (unpublished data); possibly, the iron stored as ferritin during flight is available for red blood cell formation upon landing. Apparently, iron intake required during space flight may be lower than that required on Earth; this supposition needs to be explored further.

Vitamins

Although space diets generally are believed to provide adequate macronutrients, little is known about the vitamin content of space foods, although efforts are made to meet minimal nutrient requirements (see Table 4). Ongoing attempts to quantify vitamin levels in the highly processed US space diets suggest that vitamin A intake in space may exceed the usual recommended dietary allowances. On the other hand, space foods contain very little vitamin D; foods higher in this essential vitamin are being developed for longer flights. Maintaining sufficient folic acid and riboflavin levels is also a concern given the lack of fresh vegetables, milk, or most milk products in present-day space diets.

Still less is known of how the physiological manifestations of space flight in humans influence vitamin requirements. The stresses associated with space

Table 4 Minimum nutrient levels supplied by Space Shuttle menus[a]

Nutrient	Amount	Nutrient	Amount
Kcal	2800	Vitamin A	5000 IU
Protein	56 gm	Vitamin D	400 IU
Calcium	800 mg	Vitamin E	15 IU
Phosphorus	800 mg	Ascorbic acid	45 mg
Sodium	150 mEq	Folacin	400 μg
Potassium	70 mEq	Niacin	18 mg
Iron	18 mg	Riboflavin	1.6 mg
Magnesium	350 mg	Thiamin	1.4 mg
Zinc	15 mg	Vitamin B_6	2.0 mg
		Vitamin B_{12}	3.0 μg

[a] Adapted from Ref. 44.

flight, including increased potential exposure to radiation, are expected to affect the turnover and thus the daily requirements for some water-soluble, and perhaps some fat-soluble, vitamins. For example, the Food and Nutrition Board of the National Research Council recently amended their recommendation of 60 mg of ascorbic acid per day to include at least 100 mg per day for people who smoke (33). Cosmonauts were shown to increase their urinary output of ascorbic acid during preflight training in hypobaric chambers (20). NASA is using these and other available data as a base for establishing micronutrient requirements for humans during space missions, with the present goal of protecting micronutrient status during 90- to 180-day tours.

Although many micronutrients can be provided by vitamin-mineral supplements, NASA encourages the use of food as the primary source of nutrients, and uses supplements only when absolutely necessary. Natural foods contain essential nonnutritive substances such as fiber and carotenoids; in addition, consumption of natural foods also provides a sense of psychological well-being that will be important during long space missions. A means of providing low-fat dairy products, which are rich in vitamins A and D, riboflavin, zinc, and calcium, is also being sought for long flights. Provision and consumption of fresh fruits and vegetables is also encouraged.

SYSTEMS FOR NUTRIENT DELIVERY IN SPACE

After 30 years of space flight, it is clear that microgravity is not a limiting factor for the consumption of prepared foods. In both the US and USSR space food systems, the emphasis is on foods with the following characteristics: minimal in-flight preparation time, minimal waste, microbial safety under ambient storage conditions, and good taste as well as nutritional soundness

(Table 4). All foods are provided in individual portions in order to meet sanitation requirements as well as tight crew schedules. An example of the food system used in space is shown in Figure 4. A typical 5-day Space Shuttle menu is shown in Table 5. Most foods in both the US and Soviet programs are preserved through canning, freeze-drying, or thermovacuum packing. A great many types of foods are flown in both space programs, with the exception of alcohol (US), carbonated beverages (US and USSR), and foods that produce excessive crumbs or do not store well at ambient temperatures. Although crews' food preferences reflect cultural differences, crews of all nationalities like fresh foods; fresh fruits and breads are supplied when possible on brief missions or during resupply to the Soviet space station. The major limiting factors in space food systems are the lack of electrical power for storage and cooking (refrigeration and freezers are usually not available), and constraints on stowage space and weight. These constraints, as well as the difficulties associated with manipulating objects in microgravity, preclude preparing food in bulk during flight for future consumption. Nonetheless, a great many foods can be provided for consumption in space despite these operational constraints.

As the space program extends the human presence farther from Earth, economic, logistic, and safety considerations will demand the increasing use of bioregenerative processes in the environmental control systems. Water and oxygen, abundant on Earth, become precious in space and must be recycled. Although high-quality air and water can be produced and recycled effectively using present-day technology, efficient chemosynthesis of food still lies ahead. During long flights and extended habitation in space, crewmembers will depend increasingly upon the biosynthesis of food; early diets will be primarily vegetarian. Providing nutritious, palatable foods within an overall regenerative life support system presents an exciting challenge.

CONCLUSIONS

The major nutritional questions relevant to space flight include identifying the role of nutrition in countering the deleterious physiological effects of microgravity, quantifying the requirements for macro- and micronutrients, and establishing the most effective system to meet nutritional needs in space (1). With respect to countermeasures designed to ensure crew safety and health, the first step is the determination of energy requirements. These investigations must take into consideration the working and living conditions in space plus the design of exercise protocols effective in preventing cardiovascular and muscular deconditioning. Studies combining different exercise regimens with various energy intakes will be needed to identify optimal

Figure 4 The Space Shuttle food system in use (NASA photo #61B-09-029).

Table 5 A sample 5-day menu for a Space Shuttle astronaut[a]

Day 1	*Day 2*	*Day 3*	*Day 4*	*Day 5*
Dried apricots (IM) Sausage pattie (R) Scrambled eggs (R) Breakfast roll (FF) Orange Drink (B) Decaf coffee w/cream & sugar (B)	Strawberries (R) Granola bar (NF) Breakfast roll (FF) Orange juice (B) Decaf coffee w/cream & sugar (B)	Dried pears (IM) Oatmeal w/brown sugar (R) Cherry drink w/A/S (×2) (B)	Instant Breakfast (FF) Dried apricots (IM) Mexican scrambled eggs (R) Cornflakes (R) Orange drink w/A/S (B) Cocoa (B)	Bran flakes (R) Granola w/blueberries (R) Orange drink (B)
Mushroom soup (R) Cheddar cheese spread (T) Rye bread (FF) Vanilla pudding (T) Macadamia nuts (NF) Lemonade (×2) (B) Banana (FF)	Shrimp cocktail Rice & chicken (R) Tortilla (×2) (FF) Crunchy peanut butter (FF) Trail mix (IM) Tropical punch (×2) (B) Crackers, plain (NF)	Macaroni & cheese (R) Tomatoes & eggplant (T) Pineapple (T) Cashews (NF) Graham crackers (NF) Grape drink w/A/S (×2) (B) Apple (FF)	Mushroom soup (R) Peanut butter (T) Grape jelly (T) White bread (×2) (FF) Fruit cocktail (T) Candy-coated peanuts (NF) Almonds (NF) Lemonade w/A/S (×2) (B)	Tuna creole (T) Tortilla (×2) (FF) Diced pears (T) Candy-coated peanuts (F) Orange-mango drink (×2) (B)
Chicken consomme (R) Beef pattie (R) Potato pattie (R) Cauliflower w/cheese (R) Tortilla (FF) Brownie (NF) Strawberry drink (B)	Spaghetti w/meat sauce (R) Potatoes au gratin (R) Italian vegetables (R) Tortilla (×2) (FF) Diced peaches (T) Candy-coated chocolates (NF) Tea/lemon w/A/S (×2) (B)	Turkey tetrazzini (R) Rice pilaf (R) Italian vegetables (R) Blueberry yogurt (T) Candy-coated chocolates (NF) Instant Breakfast (FF) Tropical punch w/A/S (×3) (B)	Chicken a la king (T) Cauliflower w/cheese (R) Asparagus (R) Chocolate pudding (T) Grape drink w/A/S (×2) (B)	Chicken consomme (R) Ham (T) Asparagus (R) Tortilla (×2) (FF) Diced peaches (T) Tapioca pudding (T) Shortbread cookies (NF) Orange-grapefruit drink (B)

[a] A/S = artificial sweetener, B = beverage, FF = fresh food, IM = intermediate moisture, NF = natural form, R = rehydratable, T = thermostabilized.

combinations. Additional studies must quantify energy expenditure during extravehicular activity.

Whether alternatives in the proportions of dietary carbohydrate, protein, or fat play a role either in metabolic efficiency in space or in preservation of optimal body composition remains to be determined. Little doubt, however, exists about the potential seriousness of muscular and skeletal changes associated with long-term exposure to microgravity. Given the complex nutrient interactions involved in maintaining these body compartments, this area of investigation demands a high priority. Additional studies are needed to determine whether protein synthesis or oxidation are affected by microgravity, and if so, the utility of interventions such as administering branch-chain amino acids must be investigated. Quantifying vitamin and mineral requirements in space will be especially important, since the nature of foods available to support missions of years in duration will probably depend heavily on genetically engineered and synthetic food sources.

The means of providing nutrients under these conditions will necessitate imagination and inventiveness on the part of nutrition scientists. Whereas nutrient needs for current missions are being met satisfactorily, the extended needs of the future will be far more challenging. Limitations on weight and storage capacity negate the possibility of sufficient provision of ready-to-eat foods. Regenerative food systems developed for closed or partially closed ecological support systems will provide novel sources of nutrients.

Many of the nutritional issues to be investigated in space will provide models for similar research on Earth. Space flight-induced changes in body composition, for example, may be useful in understanding the changes that occur with aging. Both aging and space flight invoke declines in muscle capabilities, muscle mass, and bone-mineral structure. If these losses can be countered effectively in space, similar methods might be explored for the elderly. Ample evidence exists of the similarities between bone demineralization in space and the early development of osteoporosis; collaborative efforts would strengthen research in both programs. Clinical studies of disease processes suggest that diet plays a central role in preventing muscle losses; ground-based and in-flight studies can "fill in the blanks" as to how nutritional interventions work. The role of iron and other nutrients in the formation of red blood cells, which is to be studied in space, will provide another model for elucidating the interactions among exercise, body composition, erythropoiesis, and menstruation status in women. Studies of how space flight affects the physiological requirement for vitamin C will be applicable to Earth-based situations. Task-specific studies of energy utilization planned for space may be useful in determining the energy requirements in paraplegia and quadriplegia. The nutritional information gleaned from spacecraft regenerative life-support systems will be useful in meeting the expanding nutritional needs of the world population. In summary, the space environment provides a unique opportunity to study perturbations in nutrient utilization and requirements in healthy people; the nutritional questions to be answered therein may also provide surprising answers for use at home.

ACKNOWLEDGMENTS

The editorial assistance of Christine Wogan of KRUG Life Sciences is acknowledged with thanks. Partial support for L. O. Schulz was provided by the NASA/American Society for Engineering Education Faculty Fellowship Program.

Literature Cited

1. Altman, P. L., Fisher, K. D., eds. 1986. Research opportunities in nutrition and metabolism in space. Prepared for NASA, Washington, D.C., under contract NASW 3924 by the Life Sci. Res. Off., Fed. Am. Soc. Exp. Biol., Bethesda, MD
2. Altman, P. L., Talbot, J. M. 1987. Nutrition and metabolism in space flight. *J. Nutr.* 117:421–27
3. Bungo, M. W., Charles, J. B., Johnson, P. C. 1985. Cardiovascular deconditioning during space flight and the use of saline as a countermeasure to orthostatic intolerance. *Aviat. Space Environ. Med.* 56:985–90
4. Caren, L. D., Mandel, A. D., Nunes, J. A. 1980. Effect of simulated weightlessness on the immune system in rats. *Aviat. Space Environ. Med.* 51:251–55
5. Cogoli, A., Valluchi-Morf, M., Mueller, M., Briegler, W. 1980. Effect of hypogravity on human lymphocyte activation. *Aviat. Space Environ. Med.* 51:29–34
6. Dickey, D. T., Billman, G. E., Teoh, K., Sandler, H., Stone, H. L. 1982. The effects of horizontal body casting on blood volume, drug responsiveness and +Gz tolerance in the rhesus monkey. *Aviat. Space Environ. Med.* 53:142–46
7. Dietlein, L. F. 1977. Skylab: a beginning. See Ref. 18, pp. 408–20
8. Fortney, S. M., Hyatt, K. H., Davis, J. E., Vogel, J. M. 1991. Changes in body fluid compartments during a 28-day bed rest. *Aviat. Space Environ. Med.* 62:97–104
9. Gauer, D. H. 1975. Recent advances in the study of whole body immersion. *Acta Astronaut.* 2:39
10. Gogolev, K. I., Aleksandrova, Y. A., Shul'zhenko, Ye. B. 1980. Comparative evaluation of changes in the human body during orthostatic (head-down) hypokinesia and immersion. NBD 311. *Fiziol. Cheloveka* 6:978–83 (From Russian)
11. Greenleaf, J. E. 1984. Physiological responses to prolonged bed rest and fluid immersion in humans. *J. Appl. Physiol: Respir. Environ. Exer. Physiol.* 57:615–33
12. Greenleaf, J. E., Shvartz, E., Keil, L. C. 1981. Hemodilution, vasopressin suppression, and diuresis during water immersion in man. *Aviat. Space Environ. Med.* 52:329–36
13. Hantman, D. A., Vogel, J. M., Donaldson, C. L., Friedman, R., Goldsmith, R. S., Hulley, S. B. 1973. Attempts to prevent disuse osteoporosis by treatment with calcitonin, longitudinal compression, and supplementary calcium and phosphate. *J. Clin. Endocrinol. Metab.* 36:845–58
14. Herbison, G. J., Talbot, J. M. 1984. Final Report Phase IV: Research opportunities in muscle atrophy. *NASA Contractor Report 3796*. Washington, DC: Nat. Aeronaut. Space Admin. Sci. Tech. Inf. Off. 95 pp.
15. Hoffler, G. W., Johnson, R. L. 1975. Apollo flight crew cardiovascular evaluations. See Ref. 18a, pp. 227–64
16. Huntoon, C. L., Johnson, P. C., Cintron, N. M. 1989. Hematology, immunology, endocrinology, and biochemistry. See Ref. 34, pp. 227–39
17. Johnson, P. C., Leach, C. S., Rambaut, P. C. 1973. Estimates of fluid and energy balances of Apollo 17. *Aerospace Med.* 44:1227–30
18. Johnston, R. S. 1977. Skylab medical program overview. In *Biomedical Results from Skylab, NASA SP-377,* ed. R. S. Johnston, L. F. Dietlein, pp. 3–19. Washington, DC: US Gov. Print. Off.

18a. Johnston, R. S., Dietlein, L. F., Berry, C. A., eds. 1975. *Biomedical Results of Apollo*. Washington, DC: Natl. Aeronaut. Space Admin.
19. Kakurin, L. I., Lobachik, V. I., Mikhailov, V. M., Senkevich, Yu. A. 1976. Antiorthostatic hypokinesia as a method of weightlessness simulation. *Aviat. Space Environ. Med.* 47:1083–86
20. Kalandarov, S., Markaryan, M. V., Sedova, Ye. A., Sivuk, A. K., Khokhlova, O. S. 1982. Diet of crew in Salyut-6 orbital station. *Kosm. Biol. Aviakosm. Med.* 16:10–13
21. Kotovskaya, A. R., Gavrilova, L. N., Galle, R. R. 1981. Effect of hypokinesia in head-down position on man's equilibrium function. *Space Biol. Aerospace Med.* 15:34–38
22. Krebs, J. M., Schneider, V. S., LeBlanc, A. D. 1988. Zinc, copper, and nitrogen balances during bed rest and fluoride supplementation in healthy adult males. *Am. J. Clin. Nutr.* 47:509–14
23. Kurash, S., Andzheyevska, A., Gurski, Ya. 1981. Morphological changes in different types of rat muscle fibers during long-term hypokinesia. *Space Biol. Aerospace Med.* 14:45–52
24. Lane, H. W. 1992. Critical review: metabolic energy requirements for space flight. *J. Nutr.* 102:13–18
25. Leach, C. S., Leonard, J. I., Rambaut, P. C. 1982. Dynamic of weight loss during prolonged space flight. *Physiologist* 22:S61–S62
26. Leach, C. S., Leonard, J. I., Rambaut, P. C., Johnson, P. C. 1978. Evaporative water loss in man in a gravity-free environment. *J. Appl. Physiol.* 45:430–36
27. Leonard, J. I. 1982. Energy balance and the composition of weight loss during prolonged space flight. General Electric Co. Tech. Rep. TIR-2114-MED-2012, Houston, Tex.
28. Leonard, J. I. 1985. Fluid-electrolyte responses during prolonged space flight: A review and interpretation of significant findings. General Electric Co. Tech. Rep. TIR-2114-MED-5008, Houston, Tex.
29. Leonard, J. I., Leach, C. S., Rambaut, P. C. 1983. Quantitation of tissue loss during prolonged space flight. *Am. J. Clin. Nutr.* 38:667–79
30. Merrill, A. H., Wang, E., Jones, D. P., Hargrove, J. L. 1987. Hepatic function in rats after space flight: effects on lipids, glycogen, and enzymes. *Am. J. Physiol.* 252: R222–26
31. Merrill, A. H., Wang, E., Mullins, R. E., Grindeland, R. E., Popova, I. A. 1992. Analysis of plasma from Kosmos 2044 rats. *J. Appl. Physiol.* In press
32. Michel, E. L., Rummel, J. A., Sawin, C. F., Buderer, M. C., Lem, J. D. 1977. Results of Skylab medical experiment M171-metabolic activity. See Ref. 18, pp. 372–87
33. National Research Council. 1989. *Recommended Dietary Allowances*. Washington, DC: Natl. Acad. Press. 285 pp. 10th ed.
34. Nicogossian, A. E. 1989. Countermeasures to space deconditioning. In *Space Physiology and Medicine,* ed. A. E. Nicogossian, C. L. Huntoon, S. L. Pool, pp. 294–311. Philadelphia: Lea & Febiger
35. Nicogossian, A. E., Dietlein, L. F. 1989. Microgravity: simulations and analogs. See Ref. 34, pp. 240–48
36. Nixon, J. V., Murray, R. G., Bryant, C., Johnson, R. L., Mitchell, J. H., et al. 1979. Early cardiovascular adaptation to simulated zero gravity. *J. Appl. Physiol: Respir. Environ. Exerc. Physiol.* 46:541–48
37. Popov, I. G. 1975. Food and water supply. In *Foundations of Space Biology and Medicine,* ed. M. Calvin, O. G. Gazenko, 3:22–55. Washington, DC: Natl. Aeronaut. Space Admin.
38. Popov, I. G., Latskevich, A. A. 1983. Effect of 140-day flight on blood amino acid levels in cosmonauts. *Kosm. Biol. Aviakosm. Med.* 17:23–30
39. Popov, I. G., Latskevich, A. A. 1984. Blood amino acids of cosmonauts before and after 211-day spaceflight. *Kosm. Biol. Aviakosm. Med.* 18:10–15
40. Rambaut, P. C., Heidelbaugh, N. D., Reid, J. M., Smith, M. C. 1973. Caloric balance during simulated and actual space flight. *Aerospace Med.* 44:1264–69
41. Rambaut, P. C., Johnson, P. C. 1989. Nutrition. See Ref. 34, pp. 202–13
42. Rambaut, P. C., Johnston, R. S. 1979. Prolonged weightless and calcium loss in man. *Acta Astronaut.* 6:1113–22
43. Rambaut, P. C., Smith, M. C. Jr., Mack, P. B., Vogel, J. M. 1975. Skeletal response. See Ref. 18a, pp. 303–22
44. Rambaut, P. C., Smith, M. C. Jr., Wheeler, H. O. 1975. Nutritional studies. See Ref. 18a, pp. 277–302
45. Schneider, V. S., LeBlanc, A., Rambaut, P. C. 1989. Bone and mineral metabolism. See Ref. 34, pp. 214–21
46. Shangraw, R. E., Stuart, C. A., Price, M. J., Peters, E. J., Wolfe, R. R. 1988. Insulin responsiveness of protein metabolism in vivo following bed rest in humans. *Am. J. Physiol.* 255:E548–58

47. Smith, M. C., Rambaut, P. C., Vogel, J. M., Whittle, M. W. 1977. Bone mineral measurement—Experiment M078. See Ref. 18, pp. 372–87
48. Stadler, C. R., Rapp, R. M., Bourland, C. T., Fohey, M. F. 1988. Space Shuttle food-system summary, 1981–1986. *NASA Tech. Memo. 100469,* Johnson Space Center, Houston, Tex.
49. Stuart, C. A., Shangraw, R. E., Peters, E. J., Wolfe, R. R. 1990. Effect of dietary protein on bed-rest-related changes in whole-body-protein synthesis. *Am. J. Clin. Nutr.* 52:509–14
50. Thornton, W. E., Rummel, J. A. 1977. Muscular deconditioning and its prevention in space flight. See Ref. 18, pp. 191–97
51. Ushakov, A. S., Vlasova, T. F., Miroshnikova, Ye. B., Mikhaylovs, V. M., Biryukov, Ye. N. 1983. Effect of long-term space flights on human amino acid metabolism. *Kosm. Biol. Aviakosm. Med.* 17:10–15
52. Yegorov, A. D. 1980. Results of medical studies during long-term manned flights on the orbital Salyut-6 and Soyuz complex. Presented during the 11th meeting of the Joint Soviet-American Working group on Space Biology and Medicine, Moscow. *NASA Tech. Memo. 76014*. Washington, DC: Natl. Aeronaut. Space. Admin.
53. Young, V. R., Yu, Y. M., Krempf, M. 1991. Protein and amino acid turnover using stable isotopes ^{15}N, ^{13}C, and ^{2}H as probes. In *New Techniques in Nutrition Research,* ed. R. G. Whitehead, A. Prentice, pp. 17–72. San Diego: Academic