Chapter 2
Nutrition in Space

2.1 Introduction

The popular perception is that space food is liquid and consists of a formula of easily digested macronutrients such as amino acids, fatty acids, and di- or oligosaccharides, which also contains the micronutrients required to keep a person healthy. A formula diet is different from food for astronauts in space, which sometimes in layman's terms is called "astronaut's diet." A formula diet is developed for people who, mostly because of disease, are not able to chew more solid food adequately or to digest the more complex nutrients from the food so that they can easily be absorbed in the gastrointestinal tract. Formula diets are also intended for patients who might need a huge amount of energy, which cannot easily be provided by regular food components.

Food for astronauts for their stay in space is actually very different (Fig. 2.1). It very much reflects recipes for food on Earth with the exception that it has very strict microbiological constraints. Therefore, aside from its nutritional value, its most important characteristic is the preservation process, so that space food should never provide a risk of food poisoning. To keep astronauts' food safe, the hazard analysis critical control point (HACCP) system was developed by NASA, and it has now been adopted by the food industry globally. This system paves the way for a very secure and high-quality food system that keeps the microbiological content of food very low. Preservation of food for spaceflight is mainly done by thermostabilization or freeze drying. Therefore, food is mainly packed in cans or pouches as illustrated in Fig. 2.1.

Regardless of the kind or source of food, our daily diet provides us with all the macro- and micronutrients that we need for the functioning of our bodies. While not considered nutrients in the purest sense, fluid and dietary fiber are also important nutritional components.

Inadequate nutrient supply can imply either too low or too high levels of intake of nutrients, and either can affect our body and may in the long run even induce

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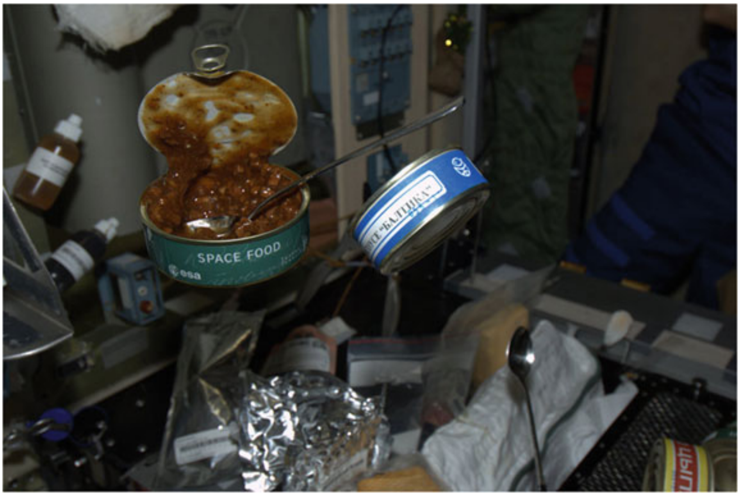

Fig. 2.1 Space food preserved in cans. The small bottles on the *left* are salt and pepper solutions. ©ESA

diseases. As often seen in the Western world, excess intake of energy leads to positive energy balance, which increases fat mass and can lead to metabolic diseases such as glucose intolerance. Although astronauts rarely have positive energy balances and therefore usually do not gain fat mass (Smith et al. 2009), results from Apollo, Skylab, and Space Shuttle missions show that they nevertheless develop glucose intolerance (Leach and Alexander 1975; Leach and Rambaut 1977) and insulin resistance (Stein et al. 1994).

Usually a difficulty one faces with space missions is the small number of crewmembers available to participate in research. One way to overcome that is to examine further aspects of physiological adaptation of astronauts to microgravity in analog models, situations on Earth that reflect aspects of space travel. Kakurin et al. (1976) demonstrated that in bed rest an angle of −6-degree head-down tilt best mimics the hypokinesia and microgravity-induced blood redistribution characteristic of spaceflight.

However, even in these analog studies, it is very difficult to achieve an adequate sample size for sound scientific experimentation. Unfortunately, there are many situations where a small sample size is hard to avoid, and yet the research is still important to perform. These situations include clinical trials of unique study populations such as astronauts, as mentioned, but also individually tailored therapies, isolated environments, emergencies, public health urgency, restricted or limited resources coupled with an important need, or rare diseases. Although various trial designs and certain statistical analysis techniques improve the quality of trials with small sample sizes, these studies are still prone to variability and are at risk of failing to demonstrate the effectiveness of an intervention. Generation of data from larger sample sizes achieved by combining single, smaller data sets can therefore improve the interpretation of data, but only if the experiments are adequately standardized (Institute of Medicine 2001).

We describe in the following report how metabolic research is carried out in microgravity and in analog models. We also present a summary of the nutrient supply in space missions, which might be deficient in certain nutrients. In addition, we provide evidence that during space missions, inadequate nutrient supply may exacerbate and optimized nutrient supply may ameliorate the physiological adaptation processes in microgravity.

2.2 Ground-Based Research

Data pertaining to details of the effects of the space environment on human physiology are limited and difficult to generate. Flying in space is very expensive, and most space agencies and institutes currently have severely limited space life sciences budgets. In addition, space experiments are often technically difficult to devise and perform, as the original researcher is remote from the test subject and the absence of gravity can make the design of experiments quite challenging. Additionally, the number of astronauts and cosmonauts flown each year is small, and the number of experiments each crewmember can participate in is subject to time and other resource constraints. Thus, conclusions must often be drawn from small numbers of data points. Performing a flight analog experiment with human test subjects, such as head-down-tilt bed rest, is also expensive and time consuming; therefore, obtaining a large number of test subjects is difficult in analog studies, although access to test subjects, hardware, and testing is indeed easier than it is in space.

One way to design experiments with small numbers of subjects and still receive statistically sound and reliable results is to standardize study conditions in such a way that the studied effect is not influenced. The European Space Agency (ESA) has developed a standardization plan that will be applied to every study ESA is sponsoring. The same is true for the bed rest studies that were carried out at NASA's Flight Analog Research Unit at the University of Texas Medical Branch at Galveston. The prescribed standards are in particular applied to environmental aspects of the facility in which the trials are taking place and to the constraints on subjects (e.g., sleep, hygiene) as well as to the dietary aspects of the studies. By using this approach and applying the appropriate statistical analyses, researchers can draw conclusions from a set of experiments carried out over several years. This is not only important for gathering sufficient data but also allows researchers to draw conclusions from a sufficient sample size and to publish the data to make them accessible to the public.

2.2.1 Food Selection in Spaceflight and Analog Studies

To avoid any impact of inadequate macro- and micronutrient supply on the human body, standards for nutrient intake are defined by respective nutrition experts or expert committees, taking into account particular circumstances in spaceflight and analog studies. These levels of nutrient intake have to be met on either a weekly basis or, depending on experiment requirements, on a daily basis to avoid any effect of dietary intake on experiment results. Ensuring the prescribed standardized and controlled nutrient intake in a lab is quite cumbersome and requires the appropriate expertise of a registered dietitian as well as a metabolic kitchen.

2.2.2 Spaceflight

Performing metabolic experiments on board a space station requires standardized nutrient intake. The meals are planned some time in advance by a registered dietitian together with the principal investigator of the experiment. The dietitian will match the preferences of each participant with the experiment requirements. As an example, the 5-day menu of space food for an experiment to investigate the effects of sodium intake on body fluid regulation and bone turnover is shown in Fig. 2.2. The food for the prescribed meals is packed into containers for the experiment, and the containers are labeled accordingly. The astronaut, as planned, will consume the food on the appropriate experiment days (Table 2.1).

2.2.3 Analog Studies: Head-Down Tilt Bed Rest

In analog studies such as bed rest, the procedure is different. The food and beverages used are standard commercially available food items. For nutrient intake analysis, data are obtained from the manufacturer's information, from tables of nutrient content, or from direct chemical analysis. The test subjects are asked which kind of food and beverages they are allergic to or very much dislike. This needs to be taken into account since one prerequisite of a metabolic experiment is to have a standardized, day-by-day, relatively constant nutrient intake. To guarantee the appropriate intake, the test subjects need to be able to consume the food and beverages provided. The certified dietitian must therefore define test subjects' diets according to the predefined nutrient needs as well as their respective preferences. The meal plan of each individual test subject has then to be prepared in the metabolic kitchen (Figs. 2.3 and 2.4).

Meal	DAY L_1	DAY L_2	DAY L_3	DAY L_4	DAY L_5
Breakfast	Vanilla Breakfast Drink (B) FB62	Chocolate Breakfast Drink (B) FB61	Chocolate Breakfast Drink (B) FB61	Chocolate Breakfast Drink (B) FB61	Chocolate Breakfast Drink (B) FB61
	Orange Drink (B) FB14	Lemonade (B) FB13	Orange Drink (B) FB14	Lemonade (B) FB13	Orange Juice (B) FB55
	Granola (R) FR15	Granola (R) FR15	Granola (R) FR15	Berry Medley ® FR64	Oatmeal w/ Brown Sugar FR25
	Blueberry Raspberry Yoghurt (T) FT77	Fruit Cocktail P (T) FT14	Fruit Cocktail P (T) FT14	Blueberry Raspberry Yoghurt (T) FT77	Fruit Cocktail P (T) FT14
				Granola Bar (NF) FS09	
Lunch	Lemonade (B) FB13	Lemonade (B) FB13	Apple Cider (B) FB52	Apple Cider (B) FB52	Strawberry Drink (B) FB17
	Chicken w/ Corn and Black Beans (T) FT81	Orange Pineapple Drink (B) FB16	Beef Stew (T) FT01	Chicken Fajitas (T) FT44	Lemonade (B) FB13
	Potato Medley (T) FT87	Beef Fajitas (I) FT22	Brown Rice FT83	Brown Rice FT83	Beef Steak (I) FW03
	Rhubarb Applesauce (T) FT88	Brown Rice FT83	Berry Medley ® FR64	Peach Ambrosia ® FR27	Homestyle Potatoes FT86
	Strawberries ® FR38	Macadamia Nuts (NF) FS25	Waffles (NF) FE05	Macadamia Nuts (NF) FS25	Strawberries ® FR38
	Macadamia Nuts (NF) FS25		Macadamia Nuts (NF) FS25		
Dinner	Peach Apricot Drink (B) FB41	Orange Mango Drink (B) FB30	Lemonade (B) FB13	Orange Juice (B) FB55	Lemonade (B) FB13
	Tuna (T) FK01	Beef Tips w/ Mushrooms (I) FT60	Apple Cider (B) FB52	Tuna (T) FK01	Beef Tips w/ Mushrooms (I) FT60
	Beef Steak (I) FW03	Red Beans & Rice FT56	Chicken Pineapple Salad ® FR63	Red Beans & Rice FT56	Brown Rice FT83
	Green Beans & Potatoes (T) FT71	Brownie (NF) FS22	Barbecued Beff Brisket (I) FT24	Brownie (NF) FS22	Vegetable Quiche ® FR59
	Tapoica Pudding P (T) FT69				Macadamia Nuts (NF) FS25
	Crackers (NF) FS26				Brownie (NF) FS25
	Candy Coated Chocolates (NF) FS19				
Snack	Lemonade (B) FB13	Orange Grapefruit Drink (B) FB15	Lemonade (B) FB13	Lemonade (B) FB13	Grape Drink (B) FB07
	Macadamia Nuts (NF) FS25	Macadamia Nuts (NF) FS25	Granola (R) FR15	Bread Pudding (T) FT52	Crackers (NF) FS26
	Strawberries ® FR38	Strawberries ® FR38	Macadamia Nuts (NF) FS25	Cranapple Dessert (T) FT65	Candy Coated Chocolates (NF) FS19
	Cranapple Dessert (T) FT65	Berry Medley ® FR64	Orange Juice (B) FB55	Macadamia Nuts (NF) FS25	

Fig. 2.2 Menu for an astronaut on a diet with lower sodium intake than the average in-flight diet

Table 2.1 Content of energy, macronutrients, selected minerals, and fluid of the menu in Fig. 2.2 (day labels include L for low sodium)

	Day L1	Day L2	Day L3	Day L4	Day L5	Mean
Energy (kcal)	3004	2902	2999	2938	2829	2934
Protein (g)	104	109	107	105	109	107
Fat (g)	93	87	98	94	89	92
Carbohydrate (g)	437	429	422	418	396	420
Sodium (mg)	1851	1986	1882	1911	1938	1914
Potassium (mg)	3179	3083	3166	3598	3247	3255
Calcium (mg)	1100	947	1036	1014	1220	1063
Water (ml)	2268	2166	2103	2161	2123	2164

Fig. 2.3 Metabolic kitchen in the Institute of Aerospace Medicine at the German Aerospace Center, Cologne, Germany, Copyright DLR

2.2.4 *Facility and Environment*

Environmental conditions such as day and night lighting and sleep cycle; time shifts because of docking of rockets or other reasons; and kind, level, and duration of exercise may affect experiment results in space missions. Similar requirements apply to analog studies in ground-based labs. In the latter, even conditions such as temperature and humidity or gurney use for showering might be predefined and controlled. Adherence to the predefined conditions of experiments with a small n is of utmost importance to be able to conclude that differences are caused only by the effects of microgravity, bed rest, or other stimuli and to avoid an impact of any other factor.

Fig. 2.4 Weighing of apple juice on a lab scale in a metabolic kitchen, Copyright DLR

2.3 Space Food on Space Missions

Crewmembers preparing for spaceflights test the space food and beverages planned for consumption during flight several months before their mission. Usually their final selections of food and beverages during flight depend on availability and certain rules for their food consumption for their respective meals.

At the outset of human spaceflight, it was obvious that food and beverages needed to be provided for the space travelers. The food developed for the early missions in the 1960s was mainly pureed food in squeeze tubes, small cubed food items coated with an edible film to prevent crumbs from escaping, or freeze-dried powdered food (Perchonok and Bourland 2002).

Most of the space food on early ISS missions was of American or Russian origin, reflecting the respective food culture. However, with more and more international participation in spaceflight, other space agencies are supporting space food development. Today we also find European, Japanese, and Canadian food on board the ISS, made with recipes mainly reflecting their food culture. This multicultural menu leads to an increase in food variety and supports a balanced nutrient supply too (Bourland et al. 2000; Smith et al. 1971).

2.4 Physiological Changes in Spaceflight

After space travelers launch from a space port, they very rapidly experience microgravity. The musculoskeletal system undergoes dramatic adaptation processes, as do many other systems including the fluid and electrolyte system (Adams et al. 2003; Buckey et al. 1996; Cintron et al. 1990; Convertino 1996; Drummer et al. 2000; Fritsch-Yelle et al. 1996; Leblanc et al. 2007).

With the gravity vector gone, the fluid in the body starts to equally distribute along the body axis, which lead to a fluid shift from the lower part of the body to the upper. Leg volume is lower, and relative blood volume in the upper part of the body increases (Moore and Thornton 1987; Smith et al. 1997b). As an adaptation process, blood volume starts to decrease during the first days in microgravity.

Loss of gravity also influences the mechanical loading of the lower parts of the body. As time goes by, this leads to a reduction in muscle mass and strength, as is observed when a leg is put in a cast after a fracture. Reduction of muscular contraction because of greater mechanical loading also leads to adaptation processes in bone mass (LeBlanc et al. 2000). The bone-resorbing cells, the osteoclasts, are activated by unloading and induce a degradation of bone mass until the strength mandatory in the microgravity environment is reached. Concomitantly, the activity of the bone-forming cells, the osteoblasts, is either reduced or unchanged (Smith et al. 2005a).

Microgravity, however, also seems to affect appetite and as a result nutrient consumption. Although scientific evidence for any change in appetite is missing, anecdotal descriptions from space travelers tell us that they seem to experience fewer smell and taste sensations while they are in microgravity. Smell and taste sensations, however, are very important for eating, and decreases in those might be one reason why most of the space travelers in past missions reduced their food intake.

Another observation mentioned anecdotally is that stomach fullness is experienced much more rapidly in microgravity and can block a space traveler from continuing to eat. This might also play an important role in reduced food intake during spaceflight.

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