A Food and Nutrition Plan for Space Flight to Mars:

A Balanced, Plant-Rich, and Time-Restricted Diet to Minimize Health Risks from Space and Improve Metabolic Health

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Abstract:

After decades of advancement, we are once again on the verge of human deep space exploration, with upcoming planned missions to the Moon and Mars. This food and nutrition plan considers macronutrients, micronutrients, and meal timing (i.e. intermittent fasting) to address human health risks in space and minimize the impact of space hazards. The proposed diet is designed to improve biomarkers of metabolic syndrome while also considering and accommodating the unique nutritional needs imposed by space exploration. This plan can be used pre-flight to improve metabolic health and can also be maintained over the course of a long-duration space mission.

Introduction:

The Role of Nutrition in Space

Spaceflight presents environmental exposures that are unique from what we experience on earth. This imposes new and different risks to human health that must be considered and managed when planning a mission of any duration, especially long missions. Nutrition has an unrecognized capacity to optimize health and minimize disease risk. By creating dietary and behavioral recommendations that improve health enough for survival on Mars, we will certainly be able to improve the health of those who remain on Earth.

In the age of social and popular media, dietary fads are often over-represented. While it is exciting to stimulate public interest in nutrition, many times these trends are unsupported by controlled human studies and/or have undesirable side effects. Fresh scientific perspectives are always needed; however, a long-duration spaceflight trip is not only financially expensive but also costly to astronaut health. It is imperative to use research-based evidence when formulating dietary plans and eating schedules for Mars-bound crew members.

Health Risks Associated with Space Exploration

The two central human health hazards encountered in space are space radiation and microgravity (Figure 1). Apart from Apollo, all previously crewed missions have been within low Earth orbit (LEO), where Earth’s magnetosphere provides added radiation protection[1]. Long-term exploration missions to the Moon, Mars, and beyond will not have this additional protection and must endure increased ionizing radiation exposure. The main sources of space radiation are solar particle events (SPEs) and galactic cosmic rays (GCRs). Chronic GCR exposure is a predominant health concern as GCRs contain heavy ions (HZE) which are difficult to

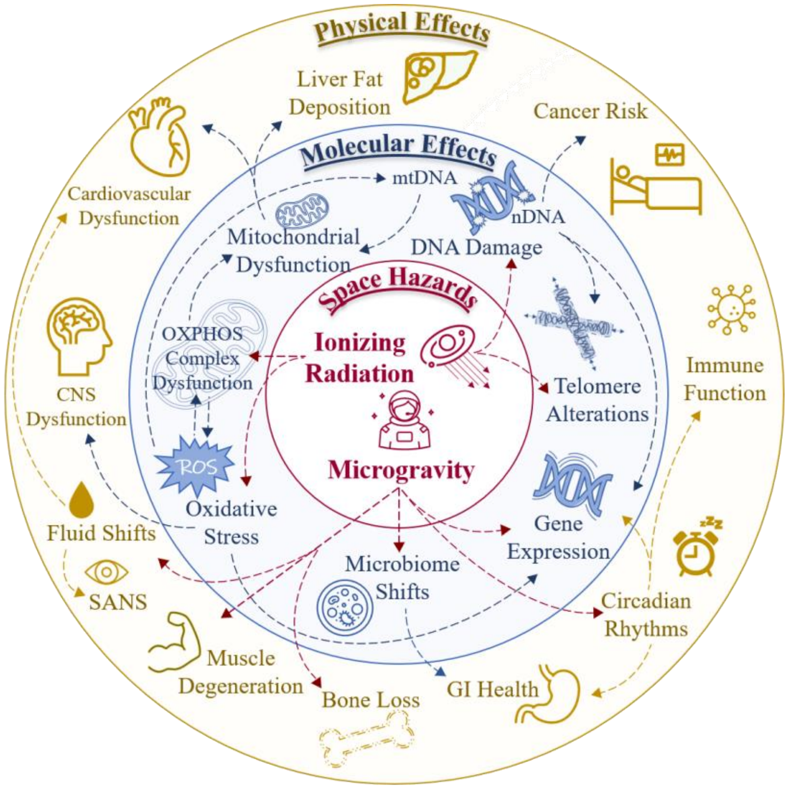

Figure 1. Diagram of Space Hazards. Illustration of the complex relationship between space hazards and the associated molecular and physical effects[8]. Abbreviations: OXPHOS; oxidative phosphorylation, ROS; reactive oxygen species, SANS; spaceflight associated neuro-ocular syndrome, GI; gastrointestinal, CNS; central nervous system, mtDNA; mitochondrial DNA, nDNA; nuclear DNA.

shield against due to their high energy and penetrability[2]. The effects of chronic GCR exposure are undefined, however, HZE are known to cause difficult-to-repair clustered DNA double strand breaks[3].

Microgravity also imparts cellular changes which contribute to a host of disease pathologies and may even compound the adverse effects of radiation[4]. On a physical level, microgravity facilitates muscle and bone loss due to reduced gravitational loading and causes fluid shifts which lead to unfavorable cardiovascular responses[5] (Figure 1). Space radiation and microgravity each contribute to a range of adverse molecular changes which can compound upon one another and lead to tissue/physiologic changes (Figure 1). It is crucial for the proposed food and nutrition plan (FNP) to consider and address each of the spaceflight-associated effects.

Proposed Dietary Approach

Evidence demonstrates astronaut total energy expenditure (TEE) is either maintained or increased while in space as compared to on earth[6,7]. The ideal diet for long-term space flight is a balanced, sufficiently caloric diet. Many current popular nutrition fads are extremely shifted in their macronutrient distribution, such as ketogenic (mostly fat) and carnivore (mostly protein) diets. Given the specific space hazards and their associated molecular and physical risks, the diet best suited to long term spaceflight includes a balance of protein, fat, and carbohydrates.

Apart from what we eat, when we eat can also impart a significant influence on our health. There is evidence that intermittent fasting can induce positive changes in glucose metabolism and cardiovascular health[8–10]. The two most well-studied intermittent fasting regimens in humans are alternate day fasting and daily time-restricted feeding. Many astronauts fail to meet energy intake requirements, which may further contribute to muscle degeneration and body mass loss during the mission[11]. For this reason, it would be unwise to conduct any caloric restriction as part of the FNP. There is some evidence that time-restricted eating, which does not require any caloric restriction, can offer some of the same positive metabolic effects as those seen with caloric restriction[10,12]. The proposed FNP employs 10-hr time-restricted eating window with 14-hr fasting interval each day.

At the 2020 Space Education and Strategic Applications Conference, Dr. Susan Jewell of Mars-Moon Astronautics Academy and Research Science (MMAARS, Inc.) noted that there are 3 P’s to worry about when it comes to the challenges facing astronauts: Physical, Physiological, and Psychological. While the physical and physiological effects of nutrition are established, we must also consider the psychological effects of a nutrition plan, as restrictive diets can take a toll on participant mood and hinder diet adherence. Food variety and palatability are crucial to keep astronauts from skipping meals which would increase risk of bone and muscle loss[13]. In addition to numerous health benefits (as discussed in later sections), a macronutrient-balanced diet best allows for accommodating palatability and astronaut food preference to optimize dietary adherence.

Body:

Protein

Amounts and Timing

Astronauts engage in high intensity resistance training to mimic gravitational loading and minimize bone and muscle loss. Despite these exercise countermeasures, crewmembers still tend to lose muscle mass and bone mass during spaceflight[14]. Where exercise countermeasures come up short, nutrition may be able to fill in the gap.

Sufficient dietary protein is required to meet astronaut energy expenditures and support muscle repair. Energy requirements for astronauts include moderate to high protein (1.2-1.8 g/kg) consumption based on the DRI guidelines for a moderately active to active individuals[15]. The proposed FNP includes 20% (1.6g/kg) of total energy from protein. This in line with what is currently being consumed on the ISS and is a realistic and attainable amount[16,17].

Timing and distribution of protein consumption throughout the day can also have significant impacts. Consuming protein within 1-3 hours post-exercise augments muscle repair and protein synthesis[18]. For protein consumption after the immediate post-exercise period, evidence supports evenly distributing protein portions in moderate amounts. A randomized-control trial in healthy males demonstrated consumption of an intermediate amount of protein (20g) every 6 hours during the 12-hr post exercise period significantly increased muscle protein synthesis compared to consumption of more frequent smaller protein doses or a less frequent large dose[19]. Similarly, a 7-day feeding study in healthy adults demonstrated significantly higher muscle protein synthesis rates when protein intake was spread out evenly over the course of the day compared to mostly being consumed in the evening meal[20]. Thus, for optimal muscle maintenance and growth, it is best to spread out protein intake evenly across the course of the day in moderate amounts (~30g/meal).

Amino Acid Supplementation

Protein and amino acid supplementation have been well studied for any potential ability to reduce muscle loss associated with spaceflight. However, the evidence is inconclusive as to whether such supplementation is effective. Some literature supports leucine supplementation to boost muscle protein synthesis[21–23]. However, a leucine-enriched high protein diet failed to prevent muscle loss induced by bed rest[24]. Results that may seem promising on the ground, such as excess protein diets reversing nitrogen and muscle losses during bed rest, can prove ineffective in space[25,26]. Currently, evidence does not support amino acid supplementation to mitigate spaceflight-induced muscle and bone loss.

Protein Sources

Protein source is also an important consideration given the difference in amounts of iron and sulfur in animal products compared to vegetable-based protein. Current ISS mission menus provide over double (23 ± 5 mg/d) the required amount of iron (10 mg/d) because of the use of fortified foods and the majority of protein coming from animal sources[16]. Iron is one of the more hazardous micronutrients to consume in excess because our bodies have no regulated method for iron excretion. Excess iron is associated with increased oxidative stress and increased risk of cardiovascular disease[27]. Even when inflight iron intake is lower than preflight intake, serum markers of iron status still increase during flight because of hematologic changes that increase destruction of nascent red blood cells and lead to iron release[28–30]. Future menus should keep spaceflight dietary iron close to the specified requirement and minimize risk of excess iron intake, which may exert potentially harmful effects especially during long-duration missions. This includes limiting fortified foods and decreasing the amount of protein from animal sources.

Furthermore, animal protein has higher sulfur content than vegetable protein and is associated with increased acid load and bone loss[31,32]. Diets with predominantly vegetable-derived protein may have better outcomes for bone loss as they reduce urinary calcium excretion and increase urinary pH compared to animal-protein diets[33,34]. To address the potential hazards of excess iron and sulfur from animal products, the proposed diet sources its protein primarily from plants. Numerous meta-analyses conclude that there is not a notable difference between animal and plant-derived protein in supporting lean muscle mass retention and muscle strength[35,36]. Deriving most of the dietary protein from plant sources will also be more friendly to on-board food production as discussed in a later section.

Carbohydrates

Amounts

The proposed FNP derives 45% of total energy from carbohydrates. On ISS missions, carbohydrates have typically composed ~50% of energy intake and there have not been any noted adverse effects of carbohydrate consumption in this range[16,17]. However, there are concerns over spaceflight-induced insulin resistance, as shown during bedrest and spaceflight studies[37,38]. The central drivers of insulin resistance are obesity and sedentary behavior, but it is also influenced by other factors such as inflammation, lipid metabolism, and the gut microbiome[39]. Because “obese” and “sedentary” are not adjectives that can be accurately applied to the typical astronaut, the insulin resistance observed inflight is likely originating elsewhere. The proposed nutrition plan includes measures to improve other known factors of insulin resistance including inflammation (Carbohydrate and Fat Sections), lipid metabolism (Fat Section), and gut health (Carbohydrate and Micronutrient Sections).

Types of Carbs

Taking advantage of the types of carbohydrates included in the FNP will further aid in addressing critical space health risks. Inflammation is a prevalent spaceflight health concern, as bedrest and spaceflight studies exhibit increased inflammatory biomarkers[40,41]. Several spaceflight-induced cellular stresses such as increased oxidative damage, mitochondrial dysfunction, and physiological stresses such as fluid shifts, poor gastro-intestinal (GI) health, and immune responses all drive inflammatory responses in the body (Figure 1). GI health has become increasingly linked to inflammation, and intestinal permeability has been proposed as a new target for prevention and therapy of inflammatory disease[42]. Intestinal permeability refers to the ability of the intestinal barrier to shield against invasion from bacteria or toxins while also regulating and maintaining electrolyte and water absorption[42]. Beyond compromising intestinal function and homeostasis, increased intestinal permeability also increases inflammation in tissues such as liver and adipose, and can lead to insulin resistance[42].

Nutritional approaches to strengthen the intestinal barrier and reduce permeability include increased dietary fiber intake (especially soluble fiber), decreased intake of simple sugars (ex. fructose), and probiotics[42,43]. Following consumption, soluble fiber becomes undigested carbohydrate that the microbiome ferments into small organic molecules such as short-chain fatty acids (SCFA) which possess anti-inflammatory functions[44,45]. Diets high in fructose and other simple sugars increase intestinal permeability, the risk of bacterial invasion, and can lead to low-grade liver inflammation which facilitates increased liver fat deposition and insulin resistance[42]. Thus, dietary fiber and simple sugar consumption have significant health implications for GI permeability and downstream inflammation and metabolic dysfunction. The diet plan minimizes simple sugars and includes a healthy portion of fiber (40 g/d) which is slightly more than current ISS menu offerings (~33 g/d) (Table 1)[16]. In healthy individuals, high levels of fiber intake are not associated with any adverse effects or toxicity. Increased fiber intake may also help address the potentially adverse increase in inflight iron status by decreasing iron absorption and improving iron homeostasis[28].

Fat

Keto is a No-Go

One of the latest nutrition fads is the ketogenic diet, which consists of high fat, modest protein, and minimal carbohydrate composition. It has been praised for its potential benefits in short-term effects of weight loss, decreased cardiovascular disease risk, and improved glucose metabolism[46]. However, the restrictiveness of the diet and the lack of evidence defining long-term effects make it a less desirable option for a spaceflight nutrition plan. Further, there is conflicting evidence for the relationship between the ketogenic diet and lipid profiles, with potential concern for dyslipidemia[46–49]. This is particularly relevant as one of the physiologic consequences of spaceflight is increased blood cholesterol and liver fat deposition[50].

Furthermore, increased risk of renal stones is a noted consequence of the ketogenic diet due to reduced urinary pH, and astronauts are already at an elevated risk of renal stones due to increased bone resorption[51–54]. On a similar note, there is also evidence that a short-term ketogenic diet impairs markers of bone modeling and remodeling[55]. Thus, the ketogenic diet may potentially exacerbate astronaut health challenges on multiple fronts including bone loss, dyslipidemia, renal stone risk, and dietary adherence given the restrictive nature.

A moderate amount of dietary fat is favorable given the needs for adequate dietary protein and carbohydrates. Also, evidence demonstrates increased gut permeability with high fat and Western (high fat/high carb) diets[42]. Thus, a balanced diet appears to be the best fit to sustain crewmember energy needs and support gut health.

Types of Fats

It is also important to optimize the types of fats in the diet to reduce disease risk. For example, evidence supports increased omega-3 fatty acid consumption lowers inflammation, blood pressure, and plasma triglycerides[56–58]. These omega-3 benefits are significant and particularly applicable given the observed adverse effects of spaceflight on cardiovascular health, blood lipids, and liver lipid deposition[11,59]. Omega-3 consumption also has implications for bone health, as a bedrest study observed a negative correlation between NTX (a urinary marker of bone resorption) and omega-3 FA intake (Figure 2, Left)[60]. Though no specific studies on inflight omega-3 FA consumption have been conducted, there is a significant correlation between inflight fish intake and whole body bone mineral density (Figure 2, Right)[60]. Thus, there is evidence to support higher intake of omega-3-rich foods in flight, which will likely have positive

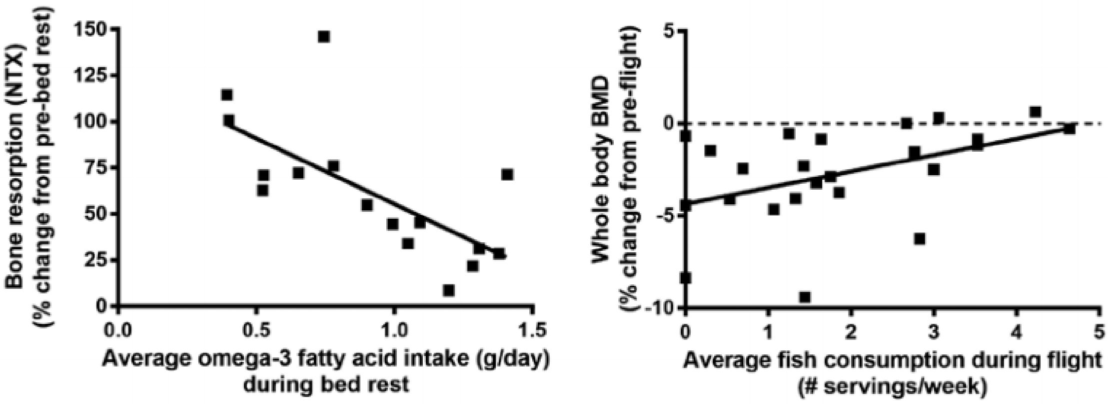

Figure 2. Omega-3 Fatty Acids and Bone Health. The association between omega-3 FA consumption and bone resorption in bed rest (left, n = 16, Pearson r = 0.46, p < .05) and the relationship between inflight fish consumption and whole-body bone mineral density (BMD) upon landing (right, n = 24, Pearson r = -0.62, p < .01). Figures adapted from Zwart 2010 (51).

implications for bone health, inflammation, and cardiovascular health. The three main forms of omega 3 FA are alpha-linolenic acid (ALA) (common in plant seeds and oils), docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) (common in fish and other seafood). Because fish can also contain notable levels of heavy metals, the proposed FNP will include ALA-rich food sources and DHA and EPA from supplements to minimize toxin exposure[61].

Recent concern has been raised over consumption of seed oils, a common source of omega-6 FA, as an underlying cause and contributor of disease development. The basis for this concern likely stems from the ratio of omega 6 to omega 3 FA intake, as a higher ratio is associated with obesity and cardiovascular disease[62,63]. The proposed FNP includes increased omega 3 FA intake (3g/d vs. 1g/d current RDA) to decrease the ratio of omega 6 to omega 3 and hopefully minimize these observed risks. Because olive oil is associated with more health benefits than most seed oils, the FNP will include olive oil as the main cooking oil for prepared foods.

Micronutrients with Major Benefits

Careful Considerations

Vitamin and mineral intake influence overall health and can address some spaceflight-associated disease risks. However, when it comes to micronutrients and dietary supplements, there can sometimes be “too much of a good thing”. For example, vitamin A supplementation (at 2x the RDA) was investigated to potentially address flight-induced decreases in serum retinol levels, however, vitamin A intake at this level was found to increase bone resorption and fracture risk[64–66]. Thus, we must be mindful of effects of high intake when proposing supplementation and only include supplements that have been extensively tested, are well-tolerated, and produce consistent outcomes in human trials. Micronutrient intake levels and rationale for the proposed FNP are extensively outlined in Table 2.

Tackling Oxidative Stress

When considering space radiation and resultant oxidative stress, one of the first nutritional countermeasures that come to mind is antioxidants. Mitochondria are particularly vulnerable to damage and dysfunction associated with space hazards (Figure 1). Mitochondrial DNA is more sensitive to oxidative damage than nuclear DNA and reactive oxygen species damage mitochondrial oxidative phosphorylation complexes, which in turn gives rise to more oxidative stress (Figure 1)[11,67]. CoQ10, also known as ubiquinol, is a less well-known nutrient that has gained attention in recent years. It is an antioxidant and a necessary component of the electron transport chain complex which supports mitochondrial function and energy production. Circulating

CoQ10 levels rapidly deplete after intense exercise, but CoQ10 supplementation minimized exercise-induced depletion and decreased cytosolic reactive oxygen species (ROS) following intense exercise in young adults[68]. Clinical trials of CoQ10 supplementation have also shown beneficial effects on glucose metabolism, lipid profiles, and inflammation[69–72]. There is ample evidence to support CoQ10 as highly safe well-tolerated supplement[73–75]. CoQ10 supplementation (200mg/d) is included in the proposed FNP to support mitochondrial health, reduce oxidative stress, and perhaps benefit astronaut glucose metabolism, blood lipids, and inflammation.

In addition to CoQ10, curcumin (an antioxidant found in turmeric) is associated with reduced inflammation, improved muscle function, reduced muscle damage, and reduced muscle pain after exercise[76]. Numerous randomized controlled trials have demonstrated the safety and effectiveness of curcumin supplementation in improving liver function, blood lipid profiles, and markers of metabolic syndrome[77]. Participants were found to tolerate high levels without notable side effects[76]. Supplemental curcumin (200mg/d) is included in the proposed diet plan for its potential to address concerns for inflight inflammation, muscle health, and insulin resistance. The dosage of 200mg/d was chosen because it is on the lower end of the effective range of clinical trial doses[76,77]. The amounts of curcumin and CoQ10 supplementation are well below doses associated with adverse effects. Food sources of curcumin (ex. turmeric) and CoQ10 (ex. liver) are less common in the average diet and it may be hard to consume enough of these foods to reach doses associated with beneficial effects. Thus, the proposed FNP includes curcumin and CoQ10 as supplements.

Notably, animal research supports the use of an antioxidant cocktail to reduce cellular damage from HZE space radiation[78–80]. However, current evidence in human trials is inconclusive as to whether antioxidant cocktails improve oxidative stress, muscle damage, and exercise performance outcomes[81,82]. More work is needed to investigate specific micronutrient mixtures and identify safe doses that elicit consistent observed benefits and minimize adverse effects in humans. Because the micronutrients that typically comprise antioxidant supplements (vit. A, C, E) are common in food sources, the proposed FNP does not include a specific antioxidant mixture supplement but maximizes consumption of antioxidant-rich foods.

Prebiotics and Probiotics

Nutrition plays a large role in gut health and facilitates changes in intestinal health and microbial diversity[42,83]. Prebiotics refers to the foods that feed the gut microbiome, such as soluble fiber. By increasing fiber intake (especially soluble fibers such as oats, flax seeds, nuts, etc.), there is more undigested fiber that passes to the colon to support the microbiome. By consuming less simple-sugars and carbohydrates with more fiber, we are also decreasing intestinal permeability and supporting gut health[42].

Apart from prebiotic carbohydrate intake, probiotics can also support intestinal permeability[42,84,85]. Probiotics refers to the bacterial species that we consume to support a diverse range of healthy, beneficial bacteria. Spaceflight has been shown to reduce gut microbe diversity. The proposed FNP includes a once daily probiotic supplement with numerous bacterial strains to improve microbiome diversity and function.

Time-Restricted Feeding

Recent social media pushes and studies have shed light onto the potential benefits of intermittent fasting. Intermittent fasting stimulates the “metabolic switch” to get the body to regularly mobilize fuel stores (oxidize more fats, but without going to ketotic state, which may impose risks for astronauts as previously mentioned). A few different eating schedules fall under the umbrella of intermittent fasting including intermittent energy restriction (IER) and time-restricted feeding (TRF). In TRF, all food for the day is consumed in a certain time window which is then followed by a fasting period (ex. 8 hrs/16 hrs, 12 hrs/12 hrs). One of the advertised benefits of TRF is that caloric restriction is not necessary to see similar metabolic benefits as with IER.

There is human evidence that the benefits of intermittent fasting are not entirely from caloric restriction or weight loss and TRF can improve markers of cardiometabolic health[12]. There is evidence for positive effects on the cardiovascular system such as lower blood pressure, decreasing atherosclerosis progression, benefits for T2D, as well as lipid profiles and inflammation[9]. Most of these positive effects are observed with an early TRF schedule (8am-2pm eating, 2pm-8am fasting)[12,86]. Notably, a randomized control trial of TRF in resistance-trained young males concluded that TRF does not reduce lean body mass or muscular improvements with resistance training[87]. This is important when considering space-induced challenges of bone and muscle loss.

Proposed FNP includes a 10-hour daytime eating window and 14-hour nighttime fasting window, aimed at getting the benefits of TRF without being too restrictive and ensuring crewmembers have time to consume all their food. Coordinating the fasting period to be mostly overnight may also help regulate crewmember circadian schedules, which are commonly altered in spaceflight[11]. The diet and eating schedule to be kept onboard during the mission should be made familiar pre-flight so astronauts are accustomed to the schedule and food types prior to the mission.

Addressing Food Production and Nutritional Stability

Given the proposed diet is mainly composed of vegetable-based protein and fats, this bodes well for sustainable food production to support nutritional needs with reduced dependence on resupply missions. The Vegetable Production System (VEGGIE) is a plant growth system currently aboard the ISS, which cultivates high quality produce. The volume of food output from the current VEGGIE system makes a minimal contribution to inflight food supply, as almost all food comes packaged in frequent resupply missions. For the proposed FNP, most of the food would also be prepackaged, however, a long-duration spaceflight journey to Mars would need to expand VEGGIE's capacity for regular food production.

Ideal crops would have low space and water needs and high nutrient density. A larger variety of plants would also translate to increased dietary variety, which is associated with increased probability of nutritional adequacy[88]. Food that is not produced on board will be cooked and prepared pre-flight and should only require heating and/or hydration prior to consumption. The food prepared on earth should ideally be made using organic foods to minimize pesticides and toxins exposure. Food will be dried, freeze-dried, cooked, packaged, and vacuum sealed to preserve the food, maximize space, and minimize load weight.

Conclusion

Given the current evidence on spaceflight biology and health changes, as well as the molecular and physiologic effects of space hazards, there are multiple angles by which nutrition can address these changes. The proposed FNP includes time-restricted diet of balanced macronutrient composition with 45% of energy from carbohydrates, 35% of energy from fat, and 20% of energy from protein. Most of the dietary protein will come from plant sources to reduce excess iron and sulfur consumption and support expanding on board food production to contribute more regularly to diet. Protein intake will also be evenly spread across the feeding window to best support muscle synthesis and prevent muscle loss. Dietary fats will be predominantly mono- and polyunsaturated, with an abundance of omega-3 FA from food and supplements. Carbohydrate sources will be rich in fiber and poor in simple sugars such as fructose.

On the micronutrient front, the proposed FNP includes daily supplementation with Vitamin D, Omega-3 FA, CoQ10, Curcumin, and pro-biotics to support bone health, inflammation, oxidative stress, and gut health. This diet can be used before or during a long duration spaceflight mission or analog mission to improve metabolic markers while also addressing the nutritional requirements that space hazards impose. A metabolic study (n = 1) of the proposed FNP was conducted for two weeks where the participant followed the FNP description for their personal calorie needs (~2,200 kcal/d). Participant’s fasting blood glucose and blood pressure were taken one day prior to initiating the diet, and one day after the two-week diet period (Table 3). An example menu for one week of the study is included in Table 4. After following the FNP for two weeks, the participant’s fasting blood sugar decreased by 5 mg/dL, systolic blood pressure decreased by 6mm Hg, and diastolic blood pressure decreased by 9 mm Hg.

The results of this metabolic study suggest that the proposed FNP can maintain or improve metabolic markers while still managing the prominent health risks associated with spaceflight.

Appendix

Space Food and Nutrition Plan Summary	
Percentage Protein	**(20%)**
Percentage Fat	**(35%)**
Percentage Carbohydrates	**(45%)**
Dietary Fiber	**40 g/d**
Carbohydrates Classified by Glycemic Index High (≥ 70) (Ex. Sugars/Starches) Medium (56-69) (Ex. Potatoes/Corn/White Rice) Low (≤55) (Ex. Fruits/Veg/Nuts/Beans)	 **15% Total Carbs** **25% Total Carbs** **60% Total Carbs**
Micronutrient Supplementation: ▪ Vitamin D (800 IU/d) ▪ CoQ10 (200 mg/d) ▪ Curcumin (200 mg/d) ▪ Omega 3 (EPA/DHA) (1,800 mg/d) Pro-biotics: ▪ Daily Probiotic Supplement Mixture	
Food Intake Intervals ▪ Eating (8am-6pm) (10 hrs) ▪ Fasting (6pm-8am) (14 hrs)	

Table 1. Nutrition Plan Summary. Proposed Food and Nutrition Plan (FNP) during long-term spaceflight including a Mars mission.

Macronutrients				
	Earth DRI (% energy)	FNP (% energy)	FNP (total kcal, grams) (for a 2,200 kcal/d diet)	Rationale
Protein	10-35%	20%	440 kcal (110 g)	▪ Adequate protein to support lean mass retention and increased exercise[15–17].
Fat	20-35%	35%	770 kcal (86 g)	▪ High fat diet not good for gut health[42]. ▪ HFD may potentially worsen already increased inflight blood lipids[46–50].

Total Carbohydrates	45-65%	45%	990 kcal (248 g)	▪ High carb diet (western) and simple sugars are not good for gut health[42]. ▪ Inclusion of fiber rich carbs could as prebiotic for gut health[42].

Micronutrients

	Earth DRI	UL	FNP	Rationale
Vitamin A	700♀/900♂ ug/d	3,000 ug/d	800 ug/d	▪ Serum retinol markers decrease from pre- to post-flight[66]. ▪ 2X the DRI was associated with higher bone loss in bed rest studies[65]. ▪ Good for gut health[42].
Vitamin B1 (Thiamin)	1.1♀/1.2♂ mg/d	None	1.5 mg/d	▪ Same as current NASA spaceflight requirement[16].
Vitamin B2 (Riboflavin)	1.1♀/1.3♂ mg/d	None	2.0 mg/d	▪ Same as current NASA spaceflight requirement[16].
Vitamin B3 (Niacin)	14♀/16♂ mg/d	35 mg/d	20mg NE/d	▪ Same as current NASA spaceflight requirement[16].
Vitamin B5 (Pantothenic Acid)	5 mg/d	None	5 mg/d	▪ Same as earth DRI and current NASA spaceflight requirement[16]
Vitamin B6	1.3 mg/d	100 mg/d	2.0 mg/d	▪ Same as current NASA spaceflight requirement[16]. ▪ Stored in muscle, muscle loss increases B6 excretion in bed rest[89]. ▪ No current evidence for inflight B6 status changes[17].
Vitamin B9 (Folate)	400 DFE/d	1,000 DFE/d	400 DFE/d	▪ Same as earth DRI and current NASA spaceflight requirement[16]. ▪ Decreased RBC folate over long-term ISS mission, likely related to decreased folate intake during flight[66].
Vitamin B12	2.4 ug/d	None	2.4 ug/d	▪ Same as earth DRI and current NASA spaceflight requirement[16].
Vitamin C	75♀/90♂ mg/d	2,000 mg/d	100 mg/d	▪ Same as earth DRI and current NASA spaceflight requirement[16].
Calcium (mg/d)	1,000 mg/d	2,500 mg/d	1,000 mg/d	▪ Inflight negative calcium balance is common- increased urinary and fecal calcium from bone loss[17]. ▪ Excess dietary calcium (2,000mg/d) will not reduce bone loss[90].
Copper (ug/d)	900 ug/d	10,000 ug/d	1.5-3.0 mg/d	▪ Same as current NASA spaceflight requirement[16].
Vitamin D	600 IU/d (15ug)	4,000 IU/d (100ug)	1200 IU/d (400 IU/d Food) (800 IU/d Supplement)	▪ Same dietary food requirement as NASA (10ug or 400 IU/d) excluding supplementation[16]. ▪ 800 IU/d supplementation shown to sustain vitamin D status in long duration spaceflight[91].
Vitamin E	15 mg/d	1,000 mg/d	20 mg/d	▪ Same as current NASA spaceflight requirement[16].
Iodine (ug/d)	150 ug/d	1,100 ug/d	150 ug/d	▪ Same as earth DRI and current NASA spaceflight requirement[16].

Iron	18♀/8♂ mg/d	45 mg/d	10 mg/d	▪ Same as current NASA spaceflight requirement[16]. ▪ Excess iron may worsen oxidative stress[27]. ▪ Iron status is already elevated during spaceflight from hematologic changes[28–30].
Vitamin K	90♀/120♂ ug/d	None	100 ug/d	▪ Same as current NASA spaceflight requirement[16].
Magnesium (mg/d)	320♀/420♂ mg/d	None	350 mg/d	▪ Same as current NASA spaceflight requirement[16].
Phosphorus (mg/d)	700 mg/d	4,000 mg/d	1,000 mg/d	▪ Same as current NASA spaceflight requirement[16].
Potassium (mg/d)	2,600♀/3,400♂ mg/d		3,500 mg/d	▪ Same as current NASA spaceflight requirement[16].
Selenium (ug/d)	55 ug/d		70 ug/d	▪ Same as current NASA spaceflight requirement[16]. ▪ Serum selenium decreases about 10% after long-term ISS mission[66] ▪ No observed functional effects of decrease in serum selenium.
Sodium (mg/d)	1,500 mg/d		2,000 mg/d	▪ NASA reduced ISS menu sodium content from 5,300 mg/d to 3,000 mg/d as high sodium exacerbates bone loss and may worsen vision changes by increasing intracranial pressure[92]. ▪ Bringing sodium closer to the earth DRI may better address inflight bone loss, vision changes, and high blood pressure.
Zinc (mg/d)	8♀/11♂ mg/d	40 mg/d	15 mg/d	▪ Same as current NASA spaceflight requirement[16]. ▪ Trend for decreased serum zinc after flight than before flight of a long-term ISS mission[66].

Table 2. Spaceflight FNP Micronutrient Levels and Rationale. Earth Dietary Reference Intakes (DRI) taken from National Institute of Health (NIH) DRI Reports and Tables for adult men and women ages 31-50[93–96]. Proposed Food and Nutrition Plan (FNP) intake values for long-term spaceflight consider current NASA spaceflight requirements, observed inflight physiologic changes, and address physical and molecular health concerns of spaceflight. Data and rationale for biotin, choline, chloride, chromium, fluoride, manganese, and molybdenum have not been included as there is low concern for deficiency with a typical diet and NASA has no current dietary requirement. ♀Recommended daily intake for adult female. ♂Recommended daily intake for adult male.

Marker	**Pre-FNP Trial**	**Post-FNP Trial**
Fasting Blood Glucose	98 mg/dL	93 mg/dL
Blood Pressure	134/82 mm Hg	128/73 mm Hg

Table 3. Metabolic Study Trial Results. Metabolic markers of fasting blood glucose and blood pressure were measured one day prior to the two-week FNP trial and one day following the completion of the FNP trial.

Monday

	Calories	**Carbs**	**Fat**	**Protein**	**Cholest**	**Sodium**	**Sugars**	**Fiber**
Breakfast – *8am*								
Wegmans - Roasted Tomato Salsa, 2 Tbsp	10	2g	0g	0g	--mg	220mg	1g	--g
Monterey Mushrooms - Whole Mushrooms, 3 oz	20	2g	0g	3g	0mg	15mg	--g	1g
Olive Oil, 0.25 tbsp	30	0g	3g	0g	0mg	0mg	0g	0g
Wegmans - Whole Wheat Multigrain Tortillas, 1 wrap	190	35g	5g	6g	0mg	370mg	0g	5g
Bell Pepper - Red Bell Pepper Chopped, 0.25 cup chopped	10	2g	0g	0g	0mg	1mg	1g	0g
Wegmans - Cheese, Sharp Cheddar, 1 oz (about inch cube)	110	0g	9g	7g	30mg	180mg	0g	0g
Large Egg - One Large Egg, 1.5 each	105	0g	8g	9g	0mg	98mg	0g	0g
Skim Milk - Skim Milk, 1 cup	80	11g	0g	8g	5mg	110mg	11g	0g
Lunch – *12pm*								
Sauce - Wegmans Teriyaki, 1 tbsp	20	5g	--g	1g	--mg	255mg	4g	--g
Wegmans - Steamables Whole Grain Brown Rice, Quinoa & Lentils, 1 cup	240	46g	4g	7g	0mg	420mg	--g	4g
Edamame - Shelled Soybeans (Frozen), 0.5 Cup (75g)	100	9g	3g	8g	--mg	30mg	1g	4g
Stew Beef - Stew Beef, 0.3 lb(s)	204	0g	8g	29g	78mg	84mg	0g	0g
Dinner – *5pm*								
Fillippo Berrio - Grilled Vegetable Pesto, 0.38 cup	255	6g	26g	2g	0mg	510mg	5g	2g
Explore Cuisine - Green Lentil Penne (Organic), 112 g	400	70g	2g	24g	0mg	0mg	2g	6g
Snacks								
Mott's - Mixed Berry Applesauce - Snack & Go, 1 Pouch (*2 pm*)	40	10g	0g	0g	--mg	5mg	8g	1g
Mamma Chia - Chia Squeeze Vitality Snack - Wild Raspberry, 1 pouch (*10 am*)	70	10g	3g	2g	0mg	0mg	7g	3g
Veggie Caesar Salad, 1 serving(s) (*2 pm*)	199	10g	16g	5g	0mg	137mg	1g	4g
TOTAL:	**2,083**	**218g**	**87g**	**111g**	**113mg**	**2,435mg**	**41g**	**30g**

Tuesday

	Calories	**Carbs**	**Fat**	**Protein**	**Cholest**	**Sodium**	**Sugars**	**Fiber**
Breakfast – *8am*								
Spectrum - Cold Milled Organic Premium Ground Flaxseed, 2 Tbsp. (14g)	70	4g	6g	3g	0mg	5mg	0g	3g
Trader Joe's - Freeze Dried Banana Slices, Unsweetened, 35 gram	130	31g	0g	2g	--mg	--mg	27g	2g
Trader Joe's - Organic Gluten Free Oatmeal Classic, 2 container (57g)	440	76g	8g	16g	0mg	400mg	2g	12g
Skim Milk - Skim Milk, 1 cup	80	11g	0g	8g	5mg	110mg	11g	0g
Lunch – *12pm*								
Chicken Breast Tenderloins - Tenderloins, 4 oz	110	1g	1g	26g	55mg	40mg	1g	0g
Trader Joe's - Quinoa Cowboy Veggie Burger, 2 Burger	360	44g	16g	10g	0mg	560mg	4g	12g

Dinner – *5 pm*								
Wegmans - Sesame Garlic Sauce, 2 tbsp.	40	9g	0g	1g	0mg	320mg	8g	1g
Trader Joes - Organic Dry Roasted & Unsalted Cashews, 0.2 cup, 30 g	152	8g	11g	4g	0mg	76mg	2g	1g
Olive oil - Organic Olive Oil, 0.5 tbsp	60	0g	7g	0g	0mg	0mg	0g	0g
Trader Joe's - Jasmine Brown Rice, 3/4 cup cooked	180	37g	0g	2g	0mg	10mg	0g	3g
Trader Joes - Organic Broccoli Florets, 85 g	25	4g	0g	2g	0mg	20mg	1g	3g
Wegmans - Extra Firm Tofu - Organic, 1/2 of pkg	200	5g	10g	20g	0mg	0mg	0g	3g
Snacks								
Trader Joes - Cashew Butter Unsalted, 2 Tbsp (*10 am*)	210	9g	16g	6g	0mg	0mg	2g	1g
Veggie Caesar Salad, 1 serving(s) (*2 pm*)	199	10g	16g	5g	0mg	137mg	1g	4g
Trader Joes - Roasted, Unsalted Almonds, 0.25 cup (*2 pm*)	170	5g	15g	7g	0mg	0mg	1g	4g
TOTAL:	**2,426**	**254g**	**106g**	**112g**	**60mg**	**1,678mg**	**60g**	**49g**

Wednesday

	Calories	Carbs	Fat	Protein	Cholest	Sodium	Sugars	Fiber
Breakfast – *8am*								
Olive Oil, 0.25 tbsp	30	0g	3g	0g	0mg	0mg	0g	0g
Wegmans - Whole Wheat Multigrain Tortillas, 1 wrap	190	35g	5g	6g	0mg	370mg	0g	5g
Bell Pepper - Red Bell Pepper Chopped, 0.33 cup chopped	13	3g	0g	0g	0mg	1mg	1g	0g
Wegmans - Sharp Cheddar, 1.2 oz	132	1g	11g	8g	36mg	216mg	0g	0g
Sprouts - Organic Refried Beans (Pinto), 0.5 cup (130g)	110	20g	0g	7g	0mg	360mg	0g	7g
Skim Milk - Skim Milk, 1 cup	80	11g	0g	8g	5mg	110mg	11g	0g
Lunch – *12 pm*								
Olive oil - Organic Olive Oil, 1 tbsp	120	0g	14g	0g	0mg	0mg	0g	0g
Trader Joe's - Cashews, Roasted & Unsalted, 1 oz	170	8g	14g	5g	0mg	5mg	2g	1g
Wegmans Organic - Garbanzo Beans, 1.2 cup (130g)	264	48g	2g	17g	0mg	312mg	0g	17g
Raw - Cauliflower Head, Large, 0.33 large head	48	10g	0g	4g	0mg	57mg	4g	4g
Dinner – *5 pm*								
Wegmans - Organic Cannellini Beans*, 0.75 cup (130g)	150	27g	0g	11g	0mg	195mg	0g	6g
Wegman's - Pasta Small Shells, 1 cup dry	400	82g	2g	14g	--mg	0mg	4g	4g
Dave's Gourmet - Butternut Squash Pasta Sauce, 0.75 cup	150	26g	6g	2g	15mg	537mg	14g	5g
Snacks								
Trader Joes - Roasted, Unsalted Almonds, 0.5 cup (*2 pm*)	340	10g	30g	14g	0mg	0mg	2g	8g
TOTAL:	**2,197**	**281g**	**87g**	**96g**	**56mg**	**2,163mg**	**38g**	**57g**

Thursday

	Calories	Carbs	Fat	Protein	Cholest	Sodium	Sugars	Fiber
Breakfast – *8 am*								
Trader Joes - Freeze dried berry medley, 0.5 bag (34g)	60	15g	1g	1g	--mg	--mg	8g	5g
Trader Joe's - Organic Gluten Free Oatmeal Classic, 2 container (57g)	440	76g	8g	16g	0mg	400mg	2g	12g
Spectrum - Cold Milled Organic Premium Ground Flaxseed, 2 Tbsp. (14g)	70	4g	6g	3g	0mg	5mg	0g	3g
Lunch – *12 pm*								
Sauce - Wegmans Teriyaki, 1 tbsp	20	5g	--g	1g	--mg	255mg	4g	--g
Stew Beef - Stew Beef, 0.3 lb(s)	204	0g	8g	29g	78mg	84mg	0g	0g
Edamame - Shelled Soybeans (Frozen), 0.5 Cup (75g)	100	9g	3g	8g	--mg	30mg	1g	4g
Wegmans - Steamables Whole Grain Brown Rice, Quinoa & Lentils, 1 cup	240	46g	4g	7g	0mg	420mg	--g	4g
Dinner – *5 pm*								
Wegmans - Extra Firm Tofu - Organic, 1/2 of pkg	200	5g	10g	20g	0mg	0mg	0g	3g
Trader Joes - Organic Broccoli Florets, 85 g	25	4g	0g	2g	0mg	20mg	1g	3g
Trader Joe's - Jasmine Brown Rice, 3/4 cup cooked	180	37g	0g	2g	0mg	10mg	0g	3g
Olive oil - Organic Olive Oil, 0.5 tbsp	60	0g	7g	0g	0mg	0mg	0g	0g
Trader Joes - Organic Dry Roasted & Unsalted Cashews, 0.2 cup, 30 g	152	8g	11g	4g	0mg	76mg	2g	1g
Wegmans - Sesame Garlic Sauce, 2 tbsp.	40	9g	0g	1g	0mg	320mg	8g	1g
Snacks								
Mamma Chia - Chia Squeeze Blackberry Bliss, 1 pouch (*2 pm*)	70	10g	3g	2g	0mg	5mg	5g	3g
Trader Joes - Roasted, Unsalted Almonds, 0.25 cup (*2 pm*)	170	5g	15g	7g	0mg	0mg	1g	4g
Trader Joes - Cashew Butter Unsalted, 2 Tbsp (*10 am*)	210	9g	16g	6g	0mg	0mg	2g	1g
TOTAL:	**2,241**	**242g**	**92g**	**109g**	**78mg**	**1,625mg**	**34g**	**47g**

Friday

	Calories	Carbs	Fat	Protein	Cholest	Sodium	Sugars	Fiber
Breakfast – *8 am*								
Wegmans - Roasted Tomato Salsa, 2 Tbsp	10	2g	0g	0g	--mg	220mg	1g	--g
Large Egg - One Large Egg, 1.5 each	105	0g	8g	9g	0mg	98mg	0g	0g
Monterey Mushrooms - Whole Mushrooms, 3 oz	20	2g	0g	3g	0mg	15mg	--g	1g
Wegmans - Sharp Cheddar, 1.2 oz	132	1g	11g	8g	36mg	216mg	0g	0g
Bell Pepper - Red Bell Pepper Chopped, 0.33 cup chopped	13	3g	0g	0g	0mg	1mg	1g	0g
Wegmans - Whole Wheat Multigrain Tortillas, 1 wrap	190	35g	5g	6g	0mg	370mg	0g	5g
Olive Oil, 0.25 tbsp	30	0g	3g	0g	0mg	0mg	0g	0g
Lunch – *12 pm*								
Raw - Cauliflower Head, Large, 0.33 large head	48	10g	0g	4g	0mg	57mg	4g	4g

Wegmans Organic - Garbanzo Beans, 1.2 cup (130g)	264	48g	2g	17g	0mg	312mg	0g	17g
Trader Joe's - Cashews, Roasted & Unsalted, 1 oz	170	8g	14g	5g	0mg	5mg	2g	1g
Olive oil - Organic Olive Oil, 1 tbsp	120	0g	14g	0g	0mg	0mg	0g	0g
Dinner – *5 pm*								
Dave's Gourmet - Butternut Squash Pasta Sauce, 0.75 cup	150	26g	6g	2g	15mg	537mg	14g	5g
Wegman's - Pasta Small Shells, 1 cup dry	400	82g	2g	14g	--mg	0mg	4g	4g
Wegmans - Organic Cannellini Beans*, 0.75 cup (130g)	150	27g	0g	11g	0mg	195mg	0g	6g
Snacks								
Trader Joes - Organic Raw Almonds, 0.25 cup (30g) (*2 pm*)	170	6g	15g	6g	0mg	0mg	1g	4g
Trader Joe's - Freeze Dried Banana Slices, Unsweetened, 35 gram (*10 am*)	130	31g	0g	2g	--mg	--mg	27g	2g
Trader Joes - Cashew Butter Unsalted, 2 Tbsp (*10 am*)	210	9g	16g	6g	0mg	0mg	2g	1g
TOTAL:	**2,312**	**290g**	**96g**	**93g**	**51mg**	**2,026mg**	**56g**	**50g**

Saturday

	Calories	**Carbs**	**Fat**	**Protein**	**Cholest**	**Sodium**	**Sugars**	**Fiber**
Breakfast – *8 am*								
Skim Milk - Skim Milk, 1 cup	80	11g	0g	8g	5mg	110mg	11g	0g
Sprouts - Organic Refried Beans (Pinto), 0.5 cup (130g)	110	20g	0g	7g	0mg	360mg	0g	7g
Olive Oil, 0.25 tbsp	30	0g	3g	0g	0mg	0mg	0g	0g
Wegmans - Whole Wheat Multigrain Tortillas, 1 wrap	190	35g	5g	6g	0mg	370mg	0g	5g
Bell Pepper - Red Bell Pepper Chopped, 0.33 cup chopped	13	3g	0g	0g	0mg	1mg	1g	0g
Wegmans - Sharp Cheddar, 1.2 oz	132	1g	11g	8g	36mg	216mg	0g	0g
Lunch – *12 pm*								
Fillippo Berrio - Grilled Vegetable Pesto, 0.38 cup	255	6g	26g	2g	0mg	510mg	5g	2g
Explore Cuisine - Green Lentil Penne (Organic), 112 g	400	70g	2g	24g	0mg	0mg	2g	6g
Dinner – *5 pm*								
Trader Joes - Organic Broccoli Florets, 85 g	25	4g	0g	2g	0mg	20mg	1g	3g
Trader Joes - Organic Dry Roasted & Unsalted Cashews, 0.2 cup, 30 g	152	8g	11g	4g	0mg	76mg	2g	1g
Trader Joe's - Brown Jasmine Rice, 45 grams	160	35g	1g	3g	0mg	0mg	0g	2g
Frozen Peas - Peas, 0.25 cup	25	6g	0g	2g	0mg	30mg	2g	3g
Brown Sugar - Brown Sugar, Dark, Organic, 1.5 tsp	27	8g	0g	0g	--mg	2mg	8g	--g
Coconut oil, 2 tsp	80	0g	9g	0g	0mg	0mg	0g	0g
Thai Kitchen - Red - Curry Paste, 1.5 tsp	8	2g	0g	0g	0mg	143mg	0g	0g
Thrive Market - Coconut Milk Lite, 0.25 container (360 gs ea.)	60	2g	6g	--g	--mg	--mg	--g	--g
Chicken tenderloin - Chicken breast tenderloin, 4 oz	100	0g	1g	25g	--mg	--mg	--g	--g

Snacks								
Trader Joe's - Freeze Dried Banana Slices, Unsweetened, 35 gram (*10 am*)	130	31g	0g	2g	--mg	--mg	27g	2g
Trader Joes - Organic Raw Almonds, 0.25 cup (30g) (*10 am*)	170	6g	15g	6g	0mg	0mg	1g	4g
Mamma Chia - Chia Squeeze Vitality Snack - Wild Raspberry, 1 pouch (*2 pm*)	70	10g	3g	2g	0mg	0mg	7g	3g
Mamma Chia - Chia Squeeze Blackberry Bliss, 1 pouch (*2 pm*)	70	10g	3g	2g	0mg	5mg	5g	3g
TOTAL:	**2,287**	**268g**	**96g**	**103g**	**41mg**	**1,843mg**	**72g**	**41g**

Sunday

	Calories	**Carbs**	**Fat**	**Protein**	**Cholest**	**Sodium**	**Sugars**	**Fiber**
Breakfast – *8 am*								
Skim Milk - Skim Milk, 1 cup	80	11g	0g	8g	5mg	110mg	11g	0g
Trader Joe's - Freeze Dried Banana Slices, Unsweetened, 35 gram	130	31g	0g	2g	--mg	--mg	27g	2g
Spectrum - Cold Milled Organic Premium Ground Flaxseed, 2 Tbsp. (14g)	70	4g	6g	3g	0mg	5mg	0g	3g
Trader Joe's - Organic Gluten Free Oatmeal Classic, 2 container (57g)	440	76g	8g	16g	0mg	400mg	2g	12g
Lunch – *12 pm*								
Trader Joe's - Paneer Tikka Masala (Updated), 1 container	410	39g	23g	15g	30mg	760mg	6g	6g
Dinner – *5 pm*								
Chicken tenderloin - Chicken breast tenderloin, 4 oz	100	0g	1g	25g	--mg	--mg	--g	--g
Thrive Market - Coconut Milk Lite, 0.25 container (360 gs ea.)	60	2g	6g	--g	--mg	--mg	--g	--g
Thai Kitchen - Red - Curry Paste, 1.5 tsp	8	2g	0g	0g	0mg	143mg	0g	0g
Coconut oil, 2 tsp	80	0g	9g	0g	0mg	0mg	0g	0g
Brown Sugar - Brown Sugar, Dark, Organic, 1.5 tsp	27	8g	0g	0g	--mg	2mg	8g	--g
Frozen Peas - Peas, 0.25 cup	25	6g	0g	2g	0mg	30mg	2g	3g
Trader Joe's - Brown Jasmine Rice, 45 grams	160	35g	1g	3g	0mg	0mg	0g	2g
Trader Joes - Organic Dry Roasted & Unsalted Cashews, 0.2 cup, 30 g	152	8g	11g	4g	0mg	76mg	2g	1g
Trader Joes - Organic Broccoli Florets, 85 g	25	4g	0g	2g	0mg	20mg	1g	3g
Snacks								
Trader Joes - Organic Raw Almonds, 0.25 cup (30g) (*10 am*)	170	6g	15g	6g	0mg	0mg	1g	4g
Justin's - Vanilla Almond Butter, 32 g (*2 pm*)	200	10g	16g	5g	0mg	65mg	7g	2g
Mamma Chia - Chia Squeeze Vitality Snack - Wild Raspberry, 1 pouch (*2 pm*)	70	10g	3g	2g	0mg	0mg	7g	3g
TOTAL:	**2,207**	**252g**	**99g**	**93g**	**35mg**	**1,611mg**	**74g**	**41g**

Table 4. 1-Week FNP Diet Menu. Diet log for the first week of the metabolic study. Foods were recorded and computed in MyFitnessPal and formatted in Word.

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