Development of a Preflight and Inflight Diet for Long-Duration Spaceflight

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1.1 Abstract

There are several issues with spaceflight such as radiation exposure, muscle atrophy, and bone demineralization that need to be addressed before long-duration missions are undertaken. One possible countermeasure that could target these issues is nutrition. This papers aims to assess nutritional countermeasures to tackle these issues and, from this, develop an appropriate diet plan for long-duration spaceflight. It was found that there are several antioxidant supplements that could mitigate radiation damage. Manipulation of other supplements and macronutrients may influence muscle and bone loss. The proposed diet shows promise, although research into dosages is needed before it is put into practice.

1.2 Introduction

Long-duration spaceflight is quickly becoming a reality. More astronauts are staying for longer periods on the International Space Station (ISS), with one astronaut recently breaking the record for the longest spaceflight by a woman. There are plans to return to the moon and also move on to Mars. The flight time to Mars alone is estimated to take 162 – 189 days (Lewandowski et al.) [1], with total mission time being much longer. It is the responsibility of space agencies to ensure the health of their astronauts on such long-duration missions, not only for crew safety but also so that the astronauts can carry out mission-critical tasks. This will be a challenge given the many changes that the body faces during long-duration spaceflight.

There is a decrease in muscle size and power with spaceflight (Trappe et al.) [2], which occurs despite the current countermeasures, indicating that the exercise hardware may not be adequate (Hargens et al.) [3]. Bone mass is also lost, with weight-bearing bones such as the spine, femur and pelvis losing as much as 1.0 – 1.6% per month (Iwamoto et al.) [4]. It has previously been found that astronauts eat approximately 80% of their recommended energy intake and there may also be issues with vitamin and mineral intake (Smith, Zwart, Block, et al.) [5].

Perhaps one of the biggest issues with long-duration spaceflight is radiation exposure. Dan Masys, an independent expert for the National Aeronautics and Space Administration (NASA) Human Research Programme has been quoted saying “Now, 20 or more years into advances in space technology and propulsion and systems and vehicles, radiation is still the deal breaker. It has never changed” (pbs.org) [6]. All of these issues need to be addressed to ensure astronaut health for long-duration missions.

An intervention that may be able to target some of these issues is nutrition. It is known that on Earth nutrition can play an important role in skeletal muscle protein synthesis and remodelling (van Vliet et al.) [7]. Nutritional interventions can also be used to assist people with bone issues such as osteoporosis (Sahni et al.) [8]. Therefore, designing a nutrition plan for astronauts which would maximize their muscle protein synthesis, as well as potentially assist in preserving muscle mass would be of benefit. The current report aims to assess the nutritional and dietary strategies that may be of most benefit to astronauts and make a recommendation for a seven-day diet plan for long-duration spaceflight.

1.3 Diet Considerations

1.3.1 Ketogenic Diet and Fat

A current diet that has gained a lot of attention is the ketogenic or low-carbohydrate high-fat diet. There are potentials for this to be helpful in astronauts due to its benefits for diabetics, as astronauts may have issues with insulin resistance (Hughson et al.) [9]. Most of the energy in this diet is derived from fat, which has a higher caloric density than carbohydrate or protein. This could be useful as it has previously been found that astronauts only eat approximately 80% of their recommended energy intake (Smith, Zwart, Block, et al.) [5], and getting energy from fat may mean that consuming more calories is easier. However, some concerns remain with recommending this diet. Protein intake is generally low to ensure that the body remains in ketosis (< 15% of calories coming from protein). This could have implications for muscle protein synthesis stimulation which would be important for limiting muscle atrophy. There have also been recent findings which indicate that athletes on a ketogenic diet have impaired markers of bone remodelling (Heikura et al.) [10]. This would be undesirable in astronauts who experience loss of bone mineral density simply from being in microgravity. However, this study was on a short duration ketogenic diet so whether or not this would occur long term is unknown. But, given the risk of this occurring in astronauts if they were on a ketogenic diet, it would be unwise to suggest such a diet for them at the current time until this issue has been researched further. This is particularly true as no studies could be found investigating the effect of a ketogenic diet during bed rest or similarly reduced physical activity levels. More research is required to determine the safety of using such a diet before it is applied to astronauts during exploration class missions.

1.3.2 Protein

While the ketogenic diet is not currently advisable for astronauts there may be other dietary recommendations which could influence some of the issues that are associated with spaceflight. It is known that total dietary protein intake is important for maintaining skeletal muscle mass, particularly a diet with sufficient leucine (Gorissen and Witard) [11]. It is recommended that for optimal hypertrophy dietary protein is spread evenly across all meals (Macnaughton and Witard) [12]. It has been found that 30g of protein supplied at breakfast, lunch, and dinner provided a more effective stimulus of muscle protein synthesis compared to a typical feeding pattern where most protein is eaten at the evening meal (Mamerow et al.) [13].

As well as intaking correct protein amounts, protein quality is important. The protein should contain sufficient amounts of all essential amino acids as all essential amino acids are needed for maximal and sustained muscle protein synthesis (Witard, Wardle, et al.) [14]. A particularly important amino acid is leucine and it is suggested that 1-3g of leucine per 20-40g of protein provides a stimulus for muscle protein synthesis and promotes a positive nitrogen balance (Jäger et al.) [15]. This may be beneficial for astronauts, if they can evenly space their protein intake throughout the day and intake enough protein and leucine per meal to promote muscle protein synthesis. It may also be beneficial to implement a dietary plan that is coordinated with the exercise plan provided. It is generally recommended that protein should be taken between 1 and 3 hours after exercise to maximize the response of muscle hypertrophy (Rasmussen et al.) [16]. For leg only exercise 20g of protein appears to be sufficient, but for whole-body exercise 40g is recommended (Witard, Jackman, et al.; Macnaughton et al.) [17, 18]. This should be taken into account in the dietary plan to maximize adaptation to exercise training as well as to maximize muscle protein synthesis, therefore minimizing skeletal muscle atrophy. Another potential benefit of protein intake is in regards to radiation exposure. A review by Turner et al. [19] concluded that sufficient dietary protein intake may help to prevent neural damage that can occur in astronauts due to radiation exposure.

An issue with high protein intake, however, is the associated low-grade metabolic acidosis (Carnauba et al.) [20]. This has implications for bone, as metabolic acidosis stimulates physicochemical mineral dissolution and increases the activity of bone-resorbing osteoclasts (Bushinsky and Frick) [21]. Is it, therefore, not advised that protein intake during flight is excessively high. It has been noted that a high protein intake of 1.8 grams per kilogram of body weight per day (g/kgBW/day) during bed rest combined with potassium bicarbonate (90 mmol/day) consumption can counteract the effect of this low-grade acidosis (Buehlmeier et al.) [22]. This could be used to ensure that bone resorption does not take place with a slightly increased protein intake.

1.3.3 Carbohydrates and Fibre

Current inflight intake of carbohydrates in astronauts comprise 50% of the diet (Smith, Zwart, Kloeris, et al.) [23]. Thus far the current carbohydrate intake during flight does not seem to be causing any issues. Carbohydrate intake is important for maintaining muscle mass. Co-ingestion of carbohydrates along with a suboptimal amount of amino acids can potentially rescue the muscle protein synthesis response (Witard, Wardle, et al.) [14]. It was mentioned previously that there is increased insulin resistance with spaceflight, which may indicate that there is some change in carbohydrate metabolism. However, more research in this area needs to be conducted before changes in carbohydrate intake are recommended.

In terms of dietary fibre, the current intake on the ISS is reported to be 33 ± 4 g/day, with NASA recommendations for exploration class missions being 10 – 14 g/1000kcal per day (Smith, Zwart, Kloeris, et al.) [23]. Dietary fibre intake is important to mitigate bowel issues, an issue which would not be advisable on long-duration spaceflight.

1.3.4 Vitamin Supplementation

Bone health is also a concern for astronauts. There may be little that diet can do to minimize bone loss since it is mainly due to a lack of mechanical loading. This can be seen as weight-bearing bones have more bone loss than the upper arm bones (Collet et al.) [24]. However, it has been reported that astronauts have compromised vitamin D status after long-duration spaceflight (Smith, Zwart, Block, et al.) [5]. This may be due to their lack of exposure to sunlight and the fact that they intake less than their required amount of energy during the flight (Smith, Zwart, Block, et al.) [5]. In order to mitigate this issue, it may be advisable for vitamin D supplements to be taken by astronauts. Since there have been recommendations stating that the optimal serum 25(OH)-D3 level is around 80 nmol/L (Trivedi et al.) [25], and the astronauts had an average post-flight level of 47.7 nmol/L (Smith, Zwart, Block, et al.) [5], it would be recommended that a dose of 100 000 IU dose of vitamin D be taken every four months as this is safe and effective in reducing incidents of fractures in men and women over the age of 65 (Trivedi et al.) [25]. This type of supplementation would also be beneficial for spaceflight as it would limit astronauts needing to supplement every day and reduce mass requirements for vitamin D supplements. Other deficiencies do not appear to occur during flight so other supplementation does not appear to be necessary. However, all data so far is based off the current spaceflight lengths and ISS menu. It is unknown whether or not deficiencies in other vitamins and minerals could occur during much longer duration flights, such as those to Mars.

1.3.5 Iron

The current iron intake on the ISS is 22.7 ± 4.5 mg/day (Smith, Zwart, Kloeris, et al.) [23], which is likely due to the high meat content of the menu. This is much higher than the recommended intake for those on the ISS of 10 mg/day (Smith, Zwart, Kloeris, et al.) [23]. It has been suggested that high iron levels can increase oxidative stress and, therefore, lead to an increased risk of cell transformation (Stevens and Kalkwarf) [26]. Excess iron levels could also cause increased susceptibility to radiation-induced cancer (Stevens and Kalkwarf) [26].

1.3.6 Conclusion

It would appear that, at the current time, there is too little data on the ketogenic diet to recommend its use, particularly given its low protein profile and risk of bone demineralization. A high protein intake of 1.2 – 1.8 g/kgBW/day would be recommended, with protein spaced evenly across meals and after exercise in order to maximize muscle protein synthesis throughout the day. It may also be beneficial to take 90 mmol/day of potassium bicarbonate to try and minimize any bone-resorbing activity that the high protein intake may induce. The current carbohydrate intake during spaceflight seems sufficient and there is no data to indicate that it should be altered. A dose of 100 000 IU/4-months of vitamin D supplementation could be recommended to try and counter the effects of this deficiency that has been noted in astronauts. Currently, the iron intake is too high, and thus should be lowered for future missions to 10 mg/day as is currently recommended. This could be achieved by reducing the number of meat products on the menu.

1.4 Radiation

There are two main types of radiation that astronauts are exposed to in deep space, Galactic Cosmic Radiation (GCR) and solar energetic particles (SEPs) (Zeitlin et al.) [27]. GCR particles are highly penetrative and highly energetic and are not stopped by the shielding on a typical spaceship (Zeitlin et al.) [27]. SEPs are spontaneously ejected close to the Sun by solar flares and coronal mass ejection, and shielding is much more effective against these particles (Zeitlin et al.) [27]. The European Space Agency has proposed radiation dose limits for astronauts on a mission to Mars of between 800 and 1000 mSv (Cougnet et al.) [28]. Data has indicated that an estimated dose equivalent from GCR for the total travel period to and from Mars, assuming a 180-day outbound and return trip, would be 662 ± 108 mSv, as measured by the Mars Science Laboratory (Zeitlin et al.) [27]. This does not take into account the radiation exposure that astronauts will experience on the Martian surface, which may add to this dose. Exposure to space radiation presents three different risks; cancer and cellular effects from exposure to heavy ions, immune and hematopoietic failure from high doses of protons, and possible neurological effects from single tracks of cosmic-ray heavy nuclei (Rabin et al.) [29]. NASA has indicated that alternative approaches to protect against GCR should be sought out as it is not feasible to provide adequate shielding due to mass limitations (Bradford et al.) [30]. Nutrition may be one such alternative countermeasure.

It has been found that, in rats, a diet rich in multiple antioxidants started 24 hours after exposure to a lethal dose of radiation mitigated death (Brown et al.) [31]. The antioxidants used in this study were L-selenomethionine, sodium ascorbate, N-acetyl cysteine, α-lipoic acid, α-tocopherol succinate, and co-enzyme Q10 (Brown et al.) [31]. It was noted that it may be beneficial to use a combination of antioxidants as different antioxidants function under different mechanisms and affect different free radicals (Brown et al.) [31]. A review by Rabin et al. [29] indicated that diets high in strawberry and blueberry extracts may protect against the negative effects of GCR by reducing oxidative stress and the generation of reactive oxygen species. Similarly, mice fed a diet rich in dried plums, another polyphenol-rich fruit, ameliorated cancellous bone loss caused by simulated space radiation exposure (Schreurs et al.) [32]. These findings indicate that diets rich in antioxidants may be beneficial in limiting radiation-induced damage. However, these studies were all conducted in animals and so extrapolation to astronauts may be limited and dosages remain unknown. It is also important to note that excess levels of some nutrients and antioxidants can have deleterious effects (Fang et al.) [33].

In terms of the antioxidants mentioned above, these may be beneficial in humans and could be recommended in different dosages to assess their efficacy. Excess ascorbic acid (vitamin C) or ascorbic acid in conjunction with excess iron levels can have toxic effects in humans (Duarte and Lunec) [34]. A review by Levine et al. [35] concluded that there is no benefit in taking greater than 400mg of vitamin C supplements per day and the recommended daily intake should be increased to 200mg. L-selenomethionine supplementation provides the amino acid selenium and it is recommended that a total dietary intake of 350 µg/day be taken in healthy adults, which would include a supplement of 200 µg/day, with the remainder being obtained from the diet (G. N. Schrauzer; Gerhard N. Schrauzer) [36, 37]. Co-enzyme Q10 is synthesised in the human body, however, under conditions of oxidative stress, production may not meet demands (Bhagavan and Chopra) [38]. It has been noted that doses ranging from 600 – 3000 mg/day are safe in patients with a variety of diseases (Bhagavan and Chopra) [38]. It could, therefore, be recommended that at least 600 mg/day be taken by astronauts to make use of the beneficial effects of this supplement. In terms of N-acetyl cysteine, a review by Dodd et al. [39] indicated that there may be adverse effects of doses greater than 3 g/day and in doses taken intravenously. There appear to be too few studies regarding its use in humans, and it has been suggested that it may be harmful in cancer cases and premalignancy (Šalamon et al.) [40]. It has also been found that N-acetyl cysteine can cause damage to isolated DNA and could have carcinogenic effects as well as anti-carcinogenic effects (Oikawa et al.) [41]. Due to these findings, it may not be advisable to supplement with this in astronauts until further research is conducted. A review on α-lipoic acid concluded that moderate doses have few adverse effects, whereas higher doses on this supplement may increase oxidative damage (Shay et al.) [42]. Optimal doses still need to be determined, but this review covered studies that had doses ranging from 200 – 600 mg/day with no evidence of adverse side effects (Shay et al.) [42]. α-Lipoic acid could, therefore, be supplemented in this range in astronauts, and a middle dose of 400 mg/day may be the best starting place for a trail with this supplement. α-Tocopherol Succinate is a form of vitamin E supplementation. A systematic review found that α-tocopherol supplementation may play a protective role against radiation-induced oxygen free radical toxicity (Yasueda et al.) [43]. The current recommended daily intake of vitamin E for the general population, as well as for astronauts, is 15 mg/day and there seems to be no evidence to increase this dose for exploration class missions (Smith, Zwart, Kloeris, et al.) [23].

Omega-3 fatty acids may be another beneficial supplement in regards to preventing radiation-induced damage to astronauts. Findings indicate that they mitigate the promotion of tumorigenesis in rats after injection with the carcinogen azoxymethane and have chemoprotective effects (Davidson et al.) [44]. A review by Turner et al. [19] also concluded that fish oil supplementation, in combination with pectin supplementation, could help in the removal of damaged colon epithelial cells that are no longer able to repair due to DNA damage. Apart from their benefit in potentially reducing radiation-induced damage, omega-3 fatty acids could play a role in mitigating bone loss. Zwart et al. [45] found that the mean intake of omega-3 fatty acids during bed rest was negatively correlated with bone resorption markers. This study also found that astronauts who had higher fish intake during spaceflight had higher whole-body bone mineral density (Zwart et al.) [45]. It has been found in patients with chronic heart failure that there is a dose-dependent effect of omega-3 supplementation, with 4g/day of the supplement being safe and effective in this population (Moertl et al.) [46].

Another potential concern for astronauts are pesticides on the foods brought from Earth. Exposure to pesticides can induce genotoxic damage and oxidative stress (Bolognesi; Teodoro et al.) [47, 48]. However, the effects depend on the degree of exposure and tend to be a concern in farmers or workers exposed to very high levels (Bolognesi; Teodoro et al.) [47, 48], so this does not appear to be an area of concern for astronauts.

1.4.1 Conclusion

From these data, it would seem that taking multiple different antioxidants is beneficial in mitigating some of the detrimental effects of space radiation. Specifically, the antioxidants that should be trialled in humans include; strawberry and blueberry extracts, dried plums, L-selenomethionine, sodium ascorbate, α-lipoic acid, α-tocopherol succinate, and co-enzyme Q10. In terms of the doses of these supplements that could be recommended in humans, L-selenomethionine or selenium should be supplemented in a dose of 200 µg/day, sodium ascorbate or vitamin C at 200 mg/day, co-enzyme Q10 at 600 mg/day, α-lipoic acid at 400 mg/day, and vitamin E at 15 mg/day. These antioxidants could be trialled in individuals on Earth to determine safe and effective doses before they are supplemented in astronauts. It would appear that supplementation with omega-3 fatty acids is beneficial for mitigating radiation-induced damage as well as for bone health. Up to 4g/day of omega-3 supplementation is safe in heart failure patients, so this dose may be appropriate in an astronaut population.

1.5 Proposed Inflight Diet

The breakdown for the proposed diet is outlined in table II (appendix I). The energy requirement is based on the current energy intake for ISS missions (Smith, Zwart, Kloeris, et al.) [23], as there are no data indicating energy requirements will change for exploration class missions. For simplicity of calculations, data on percentages and calories are based off an 80kg individual. All vitamin and mineral requirements not discussed above are based on the current NASA guidelines for long-duration missions (Smith, Zwart, Kloeris, et al.) [23].

Based on the fact that muscle protein synthesis and hypertrophy are optimised when protein is spaced evenly across all meals, it is advised that meal intervals are spaced evenly throughout the day. Ideally, there would be four meals, each containing between 20 – 30 g of protein and 1 – 3g of leucine. One meal should be as soon as possible after the daily exercise to promote recovery and protein synthesis. If the exercise is whole-body exercise, then the protein intake in the post-exercise meal should be increased to 40g.

The current food system on the ISS is made up of prepacked foods. All foods are packaged in individual portions so those menu items can easily be exchanged and customised. However, if this current system were to be used to provide food for a crew of six on a full Mars mission, it is estimated that 9660kg of packaged food would be required (Perchonok et al.) [49]. Given the mass and space limitations on spacecraft, this does not seem like a feasible means of providing all of the food for a Mars mission. However, it has been noted that there would be little means of producing and processing food during the flight to Mars, and as such the food for this portion of the mission would need to be pre-packaged sources (Teixeira et al.) [50].

In terms of the inflight diet then, it seems that the current ISS system of pre-packaged foods still provides the best option. This food system involves freeze-dried and rehydratable foods, that are rehydrated via a water dispenser system (Perchonok et al.) [49]. Many of the food items are irradiated and thermostabilized so that they are suitably sterile for consumption (Perchonok et al.) [49]. There are some natural forms of foods such as nuts and dried fruits that are vacuum sealed for transport (Perchonok et al.) [49]. Given that this system has been used successfully for the entire ISS lifespan, it seems appropriate for future missions until better alternatives have been researched and proven sustainable.

Table I outlines the proposed inflight and pre-flight meal plan. All portions have been calculated to cover the nutritional requirements outlined in table II for an 80kg male astronaut. The portions are based off foods as prepared on Earth, calculated in MyFitnessPal, and would have to be converted to dehydrated weight for flight unless otherwise specified. The micronutrients per day were estimated and if they did not meet the values outlined in table II then supplementation is indicated in column 6 of table I to make up the required amounts. For ease of use, the supplements could be combined into a single tablet for each day of the week so astronauts would only have to take one tablet each day. This could be expanded to be tailored towards each astronaut’s diet plan, for example, different supplements might be needed in different amounts by women on different days of their menstrual cycle and this could then be accommodated for in such a tablet. Some supplements must always be supplemented, as determined from the review above; 4g Omega-3, 600mg Co-Enzyme Q10, 100000IU/4-months Vitamin D, 200µg Selenium, 90mmol Potassium Bicarbonate, and 400mg α-Lipoic Acid. Most, but not all, of the food items are based on those offered on the ISS menu so it is known that these sorts of foods can be altered to be suitable for flight. The pre-flight plan is proposed to be the same as inflight to acclimatise astronauts to the new diet and ensure they are getting adequate nutrients before the mission begins. Since the diet is fairly similar to a standard diet it may not need to be adopted too long pre-flight as it would not be a drastic change. However, this may need to be assessed on an individual basis to determine if there are any nutrient deficiencies that need to be addressed in individual astronauts. For example, if an astronaut has some form of vitamin C deficiency they may need to implement the diet for 1 month prior to the flight as this is typically the length of time vitamin C replacement takes (Maxfield and Crane) [51].

Table I. Proposed seven day, inflight and pre-flight meal plan for long-duration missions.

	Meal 1	**Meal 2**	**Meal 3 (Post Exercise)**	**Meal 4**	**Supplements**
Day 1	Tea/Coffee, 225g Yogurt, 50g Granola, 60g Dried Plums	70g Hash Browns (dehydrated), Scrambled Eggs (3 Eggs), 25g Cashew Nuts, 250ml Orange Juice	140g Salmon, 200g Steamed Broccoli, 200g Steamed Carrots, 100g Mashed Potatoes, 1 Cup Chocolate Pudding	400g Vegetarian Black Bean Chili, 210g Boiled Rice, 50g Blueberries (+1g Leucine Supplementation)	4g Omega-3, 600mg Co-Enzyme Q10, 100000IU Vitamin D, 200µg Selenium, 90mmol Potassium Bicarbonate, 400mg α-Lipoic Acid, 1700mg Potassium, 35µg Chromium, 0.15mg Iodine, 10mg Zinc, 170mg Magnesium, 30µg Biotin, 25mg Pantothenic Acid, 10mg Vitamin E
Day 2	Tea/Coffee, 3 Egg Omelette with Cheese, 28g Dried Strawberries	200g Vegetarian Bolognese, 100g Cooked Whole-Wheat Pasta (+1g Leucine Supplementation)	170 g Chicken Breast, 200g Stir Fry Vegetables, 200g Boiled Egg Noodles	200g Quiche Lorraine, 60g Dried Plums	4g Omega-3, 600mg Co-Enzyme Q10, 200µg Selenium, 90mmol Potassium Bicarbonate, 400mg α-Lipoic Acid, 80mg Vitamin C, 160mg Vitamin A, 3400mg Potassium, 670mg Calcium, 90µg Vitamin K, 10mg Vitamin E, 30mg Pantothenic Acid, 125µg Folate, 30µg Biotin, 260mg Magnesium, 5mg Zinc, 0.15mg Iodine, 35µg Chromium
Day 3	Tea/Coffee 100g Porridge Oats, 200g Milk, 25g Dried Blueberries, 60g Dried Plums	300g Vegetarian Enchilada, 200g Boiled Brown Rice, 250ml Cranberry Juice (+1g Leucine Supplementation)	200g Tuna Salad, 250ml Orange Juice	4 Buttermilk Pancakes, 3 Slices Bacon, 40g Maple Syrup	4g Omega-3, 600mg Co-Enzyme Q10, 200µg Selenium, 90mmol Potassium Bicarbonate, 400mg α-Lipoic Acid, 100mg Vitamin C, 200mg Vitamin A, 3000mg Potassium, 100µg Vitamin K, 25mg Pantothenic Acid, 230µg Folate, 1.5µg Vitamin B_{12}, 30µg Biotin, 15mg Vitamin E, 0.15mg Iodine, 35µg Chromium
Day 4	Tea/Coffee, 225g Yogurt, 60g Dried Plums, 25g Dried Strawberries	Cheese Pizza	150g Beef Steak, 200g Mashed Sweet Potatoes, 200g Steamed Carrots, 100g Peas	Salad: 30 Mixed Leaves, 28g Pine Nuts, 60g Feta Cheese, 2 tbsp Ranch Dressing, 100g	4g Omega-3, 600mg Co-Enzyme Q10, 200µg Selenium, 90mmol Potassium Bicarbonate, 400 mg α-Lipoic Acid, 3000mg Potassium, 140mg Vitamin C, 6mg Vitamin E, 30µg Vitamin K, 25mg Pantothenic Acid, 240µg

				Butternut Squash Chunks, Cashew Nuts, (+1g Leucine Supplementation)	Folate, 30µg Biotin, 0.15mg Iodine, 35µg Chromium
Day 5	Tea/Coffee, 2 Slices French Toast, 40g Maple Syrup, 2 Slices Bacon, 250ml Apple Juice	150g Tofu, 200g Boiled Egg Noodles. 100g Stir Fry Vegetables, 60g Dried Plums,	170g Chicken Breast, 200g Korma Curry Sauce, 210g Boiled Rice, 100g Peas, 28g Cashews	Scrambled Eggs (3 Large Eggs), 50g Fried Mushrooms, 200g Sautéed Green Beans, 250ml Orange Juice	4g Omega-3, 600mg Co-Enzyme Q10, 200µg Selenium, 90mmol Potassium Bicarbonate, 400mg α-Lipoic Acid, 30µg Biotin, 0.15mg Iodine, 35µg Chromium, 2000mg Potassium, 10mg Vitamin E, 35µg Vitamin K, 20mg Pantothenic Acid
Day 6	Tea/Coffee, 225g Yogurt, 100g Granola, 25g Dried Blueberries	400g Cream of Chicken Soup, 1 Dinner Roll, 30g Cheese, 60g Dried Plums	400g Vegetarian Lasagne, 250ml Cranberry Juice (+1g Leucine Supplementation)	140g Salmon, 1 tbsp Tartar Sauce, 100g Cauliflower Gratin, 100g Peas, 200g Low Fat Chocolate Milk	4g Omega-3, 600mg Co-Enzyme Q10, 200µg Selenium, 90mmol Potassium Bicarbonate, 400 mg α-Lipoic Acid, 180mg Vitamin C, 3600 Potassium, 12mg Vitamin E, 25µg Vitamin K, 25mg Pantothenic Acid, 230µg Folate, 30µg Biotin, 0.15mg Iodine, 35µg Chromium, 270mg Magnesium, 6mg Zinc
Day 7	Tea/Coffee, 3 Egg Omelette with Cheese, 100g Sautéed Mushrooms, 50g Sautéed Peppers, 250ml Apple Juice	200g Vegetarian Bolognese, 100g Cooked Whole-Wheat Pasta, 1 Granola Bar (+1g Leucine Supplementation)	170g Chicken Breast, 1 Wheat Tortilla, 210g Boiled Rice, 50g Sautéed Peppers, 250ml Orange Juice	140g Vegetarian Quiche, 50g Dried Apples, 60g Dried Plums, 250g Low Fat Milk	4g Omega-3, 600mg Co-Enzyme Q10, 200µg Selenium, 90mmol Potassium Bicarbonate, 400 mg α-Lipoic Acid, 1800mg Potassium, 10mg Vitamin E, 30µg Biotin, 0.15mg Iodine, 35µg Chromium, 90µg Vitamin K, 25mg Pantothenic Acid, 180µg Folate, 300mg Magnesium, 6mg Zinc

1.6 Conclusion

From reviewing the literature it seems that the most appropriate diet for astronauts is one with slightly higher than normal protein intake of 1.2 – 1.8 g/kgBW/day along with potassium bicarbonate supplementation. Some supplementation within the diet is required, specifically omega-3 supplementation for bone health and to mitigate radiation-induced damage, and supplementation with a cocktail of antioxidants to also mitigate radiation induced damage. Vitamin D supplementation is also advised for optimal bone health.

The diet plan provided may be able to mitigate some of the detrimental effects of long-duration spaceflight. However, it should be noted that accurately calculating micronutrients for such a diet is difficult given that access to the actual foods that will be used is not feasible. Similarly, micronutrient calculations for all foods in table II could not be completed, particularly for pre-prepared meal items e.g. vegetarian Bolognese, vegetarian chili, pancakes etc. The recommended micronutrient supplementation, therefore, is an estimate based on available information, and this should be taken into consideration when using this diet.

Many of the recommendations herein have not been assessed inflight and as such research into dosages needs to be conducted. This could be achieved during an Earth-based analogue mission to determine its safety and efficacy in humans before it is used by astronauts. This could be achieved by monitoring for nutrient deficiencies/toxicity while using the diet, as well as assessing changes in muscle mass and bone mineralization during the analogue mission. However, assessing the radiation protective effects of the diet in humans would be challenging. This could be achieved by assessing markers of cellular damage and oxidative stress in the body during the use of the diet to see if they decrease below basal levels. The proposed diet seems promising in mitigating many of the adverse issues associated with long-duration spaceflight.

1.7 Appendices

1.7.1 Appendix I

Table II. Nutrient description and ranges

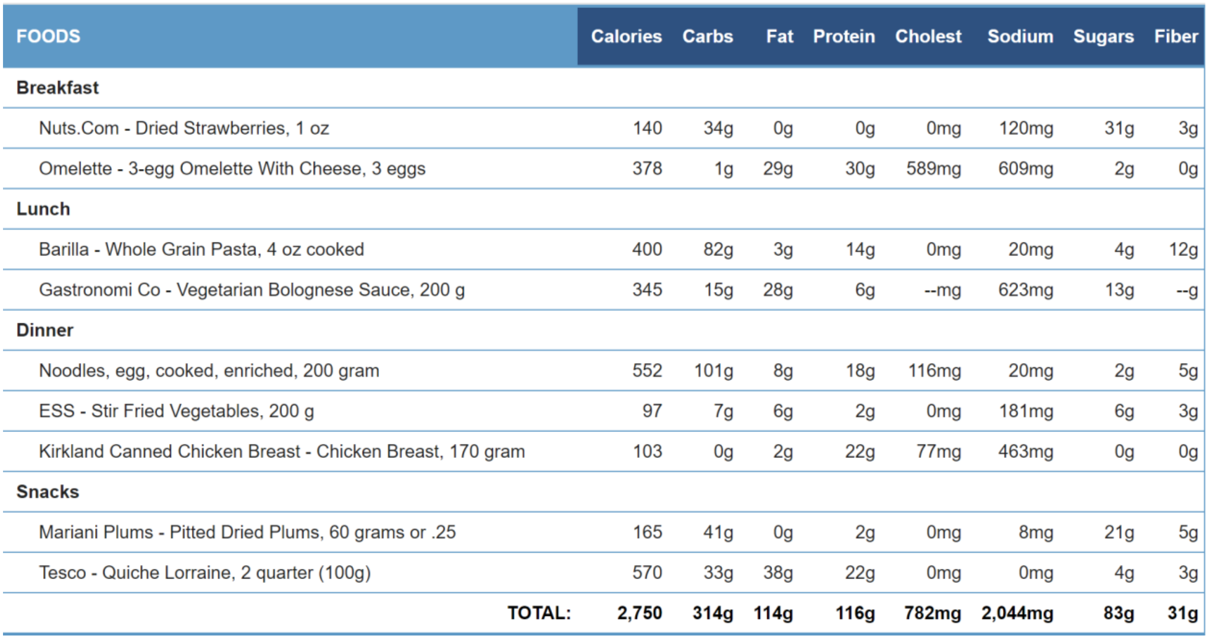
	Nutrient Requirements	**Calories and Percentage of Total Caloric Intakes**
Energy	2800 kcal/day	N/A
Carbohydrates	4.4 – 4.8 g/kgBW/day	1400 – 1540 kcal/day (50 – 55%)
Fibre	28 – 39.2 g/day	10 – 14 g/1000kcal/day
Fats	0.9 – 1.4 g/kgBW/day	672 – 1008 kcal/day (24 – 36%)
Protein	1.2 – 1.8 g/kgBW/day	384 – 576 kcal/day (14 – 21%)
Iron	10 mg/day	N/A
Vitamin D	100 000 IU/4-months	N/A
Omega-3 Fatty Acids	4 g/day	N/A
Potassium Bicarbonate	90 mmol/day	N/A
L-Selenomethionine/ Selenium	350 µg/day	N/A
Sodium Ascorbate/ Vitamin C	200 mg/day	N/A
α-Lipoic Acid	400 mg/day	N/A
α-Tocopherol Succinate	15 mg/day	N/A
Co-Enzyme Q10	600 mg/day	N/A
Retinol/Vitamin A	700 – 800 µg/day	N/A
Thiamine	1.1 – 1.2 mg/day	N/A
Vitamin K	90 µg/day (women) 120 µg/day (men)	N/A
Riboflavin	1.3 mg/day	N/A
Niacin	16 mg/day	N/A
Pantothenic Acid	30 mg/day	N/A
Vitamin B_6	1.7 mg/day	N/A
Folate	400 µg/day	N/A
Vitamin B_{12}	2.4 µg/day	N/A
Biotin	30 µg/day	N/A
Calcium	1200 – 2000 mg/day	N/A
Phosphorous	700 mg/day	N/A
Magnesium	320 mg/day (women) 420 mg/day (men)	N/A
Copper	0.5 – 9.0 mg/day	N/A
Zinc	11 mg/day	N/A
Manganese	1.8 mg/day (women) 2.3 mg/day (men)	N/A
Iodine	0.15 mg/day	N/A
Fluoride	3.0 mg/day (women) 4.0 mg/day (men)	N/A

Chromium	35 µg/day	N/A
Sodium	1500 – 2300 mg/day	N/A
Potassium	4700 mg/day	N/A
Water	≥ 2 L/day	N/A

1.7.2 Appendix II. Meal Plan Day 1

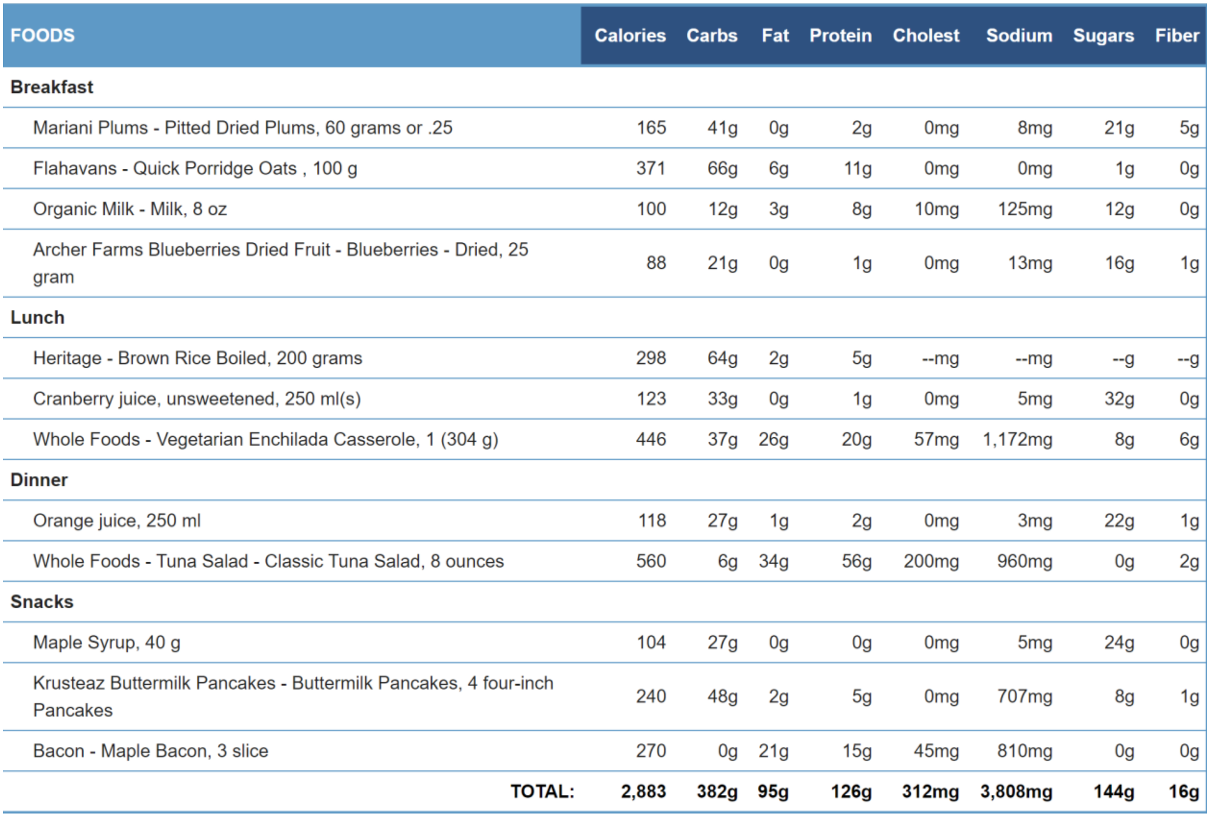
FOODS	Calories	Carbs	Fat	Protein	Cholest	Sodium	Sugars	Fiber
Breakfast								
Mariani Plums - Pitted Dried Plums, 60 grams or .25	165	41g	0g	2g	0mg	8mg	21g	5g
Marks and Spencer - 4 Nut and Flame Raisin Granola, 50 g	230	30g	9g	5g	--mg	15mg	12g	3g
Fage Greek - Yogurt, 227 gram	220	9g	11g	20g	30mg	65mg	--g	--g
Lunch								
Orange juice, 250 ml	118	27g	1g	2g	0mg	3mg	22g	1g
Hash Browns - Hash Browns Dehydrated, 70 grams	180	15g	11g	2g	0mg	330mg	0g	2g
Scrambled egg, 3 large	273	3g	20g	18g	507mg	265mg	3g	0g
Nuts - Cashew nuts, raw, 25 gram	138	8g	11g	5g	0mg	3mg	1g	1g
Dinner								
Potatoes - Mashed Potatoes, 100 g	122	12g	2g	2g	3mg	30mg	2g	1g
chocolate pudding - pudding, 1 cup	300	56g	5g	8g	20mg	380mg	44g	0g
Carrots - Steamed Carrots, 200 grams	69	15g	0g	3g	0mg	115mg	7g	5g
Steamed broccoli, 200 g	68	13g	1g	6g	0mg	66mg	3g	5g
Salmon in Foil - Baked Salmon, 142 gram	301	5g	18g	29g	78mg	213mg	3g	2g
Snacks								
Aladdin - Vegetarian Black Bean Chili, 400 gram	355	59g	6g	16g	0mg	1,070mg	11g	18g
Blueberries, 50 g	29	7g	0g	0g	0mg	1mg	5g	1g
Rice - Boiled Rice, 210 g	157	34g	1g	0g	0mg	0mg	0g	1g
TOTAL:	**2,725**	**334g**	**96g**	**118g**	**638mg**	**2,564mg**	**134g**	**45g**

1.7.3 Appendix III. Meal Plan Day 2



FOODS	Calories	Carbs	Fat	Protein	Cholest	Sodium	Sugars	Fiber
Breakfast								
Nuts.Com - Dried Strawberries, 1 oz	140	34g	0g	0g	0mg	120mg	31g	3g
Omelette - 3-egg Omelette With Cheese, 3 eggs	378	1g	29g	30g	589mg	609mg	2g	0g
Lunch								
Barilla - Whole Grain Pasta, 4 oz cooked	400	82g	3g	14g	0mg	20mg	4g	12g
Gastronomi Co - Vegetarian Bolognese Sauce, 200 g	345	15g	28g	6g	--mg	623mg	13g	--g
Dinner								
Noodles, egg, cooked, enriched, 200 gram	552	101g	8g	18g	116mg	20mg	2g	5g
ESS - Stir Fried Vegetables, 200 g	97	7g	6g	2g	0mg	181mg	6g	3g
Kirkland Canned Chicken Breast - Chicken Breast, 170 gram	103	0g	2g	22g	77mg	463mg	0g	0g
Snacks								
Mariani Plums - Pitted Dried Plums, 60 grams or .25	165	41g	0g	2g	0mg	8mg	21g	5g
Tesco - Quiche Lorraine, 2 quarter (100g)	570	33g	38g	22g	0mg	0mg	4g	3g
TOTAL:	**2,750**	**314g**	**114g**	**116g**	**782mg**	**2,044mg**	**83g**	**31g**

1.7.4 Appendix IV. Meal Plan Day 3

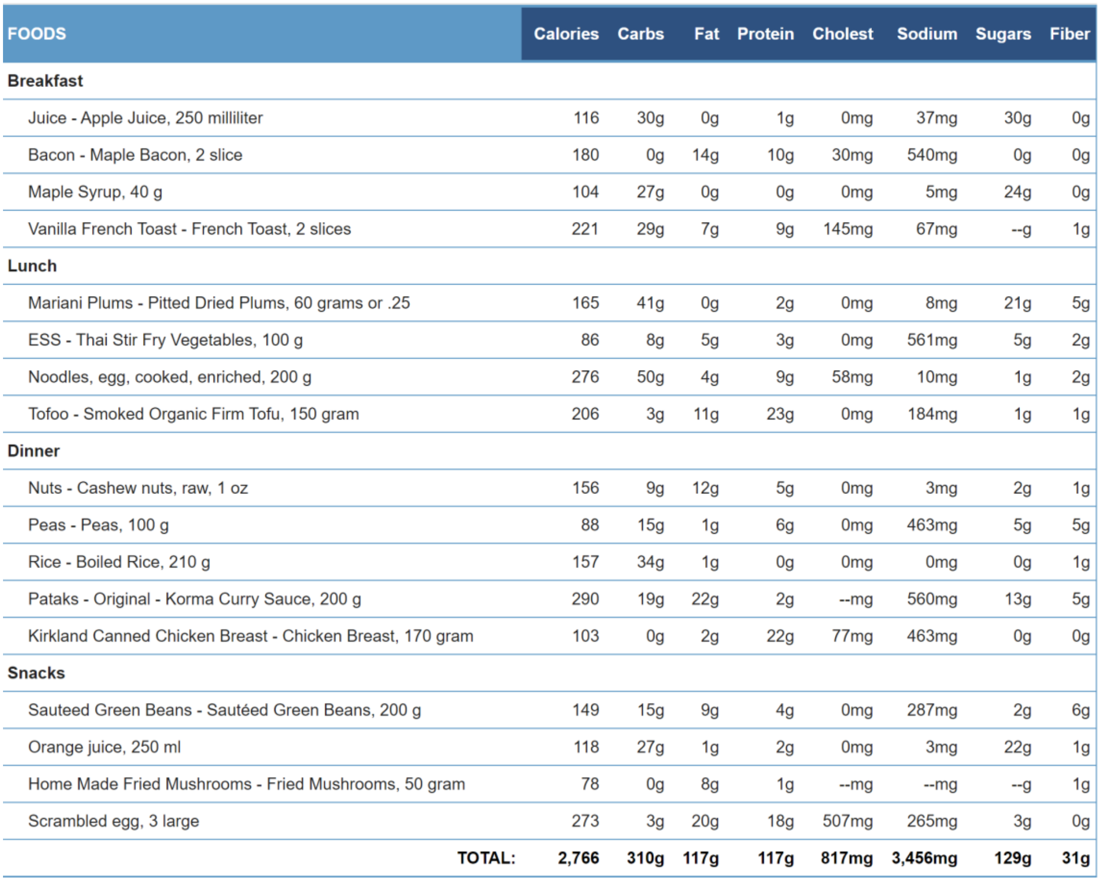


FOODS	Calories	Carbs	Fat	Protein	Cholest	Sodium	Sugars	Fiber
Breakfast								
Mariani Plums - Pitted Dried Plums, 60 grams or .25	165	41g	0g	2g	0mg	8mg	21g	5g
Flahavans - Quick Porridge Oats , 100 g	371	66g	6g	11g	0mg	0mg	1g	0g
Organic Milk - Milk, 8 oz	100	12g	3g	8g	10mg	125mg	12g	0g
Archer Farms Blueberries Dried Fruit - Blueberries - Dried, 25 gram	88	21g	0g	1g	0mg	13mg	16g	1g
Lunch								
Heritage - Brown Rice Boiled, 200 grams	298	64g	2g	5g	--mg	--mg	--g	--g
Cranberry juice, unsweetened, 250 ml(s)	123	33g	0g	1g	0mg	5mg	32g	0g
Whole Foods - Vegetarian Enchilada Casserole, 1 (304 g)	446	37g	26g	20g	57mg	1,172mg	8g	6g
Dinner								
Orange juice, 250 ml	118	27g	1g	2g	0mg	3mg	22g	1g
Whole Foods - Tuna Salad - Classic Tuna Salad, 8 ounces	560	6g	34g	56g	200mg	960mg	0g	2g
Snacks								
Maple Syrup, 40 g	104	27g	0g	0g	0mg	5mg	24g	0g
Krusteaz Buttermilk Pancakes - Buttermilk Pancakes, 4 four-inch Pancakes	240	48g	2g	5g	0mg	707mg	8g	1g
Bacon - Maple Bacon, 3 slice	270	0g	21g	15g	45mg	810mg	0g	0g
TOTAL:	**2,883**	**382g**	**95g**	**126g**	**312mg**	**3,808mg**	**144g**	**16g**

1.7.5 Appendix V. Meal Plan Day 4

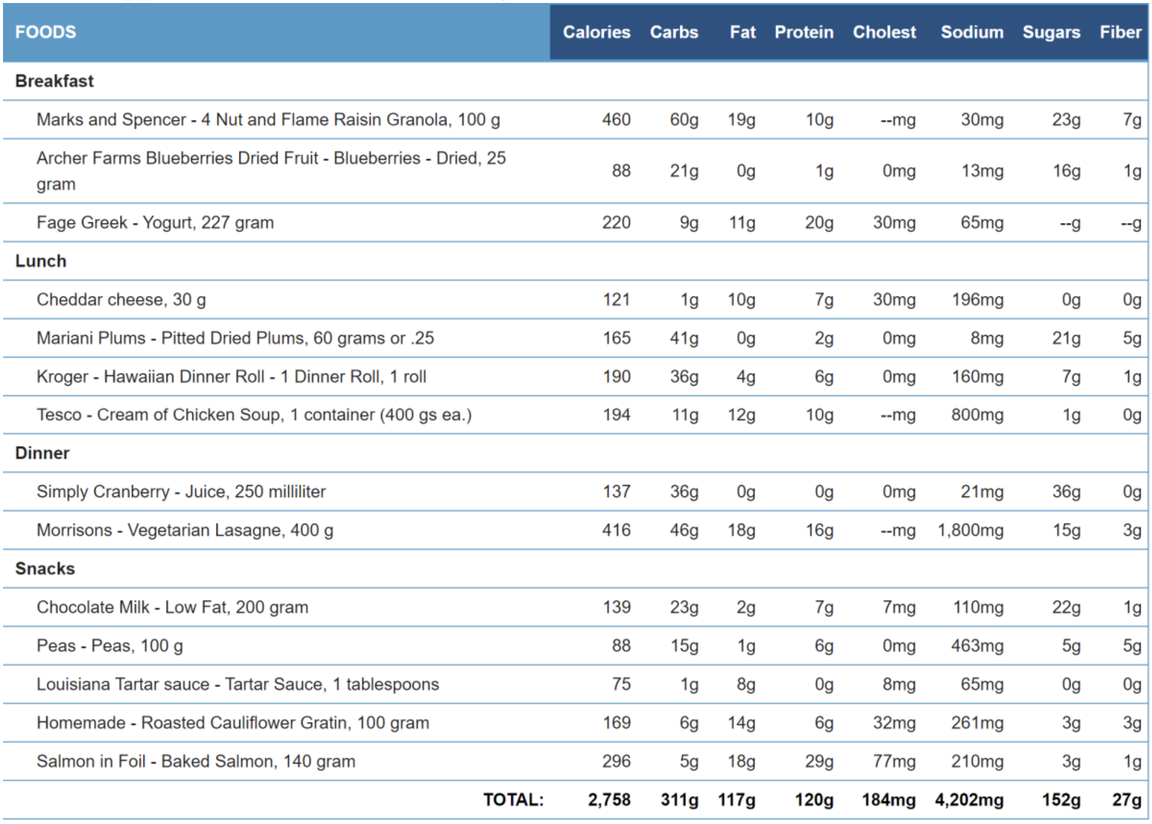
FOODS	Calories	Carbs	Fat	Protein	Cholest	Sodium	Sugars	Fiber
Breakfast								
Nuts.Com - Dried Strawberries, 1 oz	140	34g	0g	0g	0mg	120mg	31g	3g
Mariani Plums - Pitted Dried Plums, 60 grams or .25	165	41g	0g	2g	0mg	8mg	21g	5g
Fage Greek - Yogurt, 227 gram	220	9g	11g	20g	30mg	65mg	--g	--g
Lunch								
Pizza Pizza - Small Cheese Pizza, 1 container (6 slice)	1,080	156g	30g	54g	90mg	2,460mg	6g	6g
Dinner								
Peas - Peas, 100 g	88	15g	1g	6g	0mg	463mg	5g	5g
Carrots - Steamed Carrots, 200 grams	69	15g	0g	3g	0mg	115mg	7g	5g
Simply Potatoes - Sweet Potatoes, Mashed, 200 gram	194	39g	2g	4g	0mg	282mg	23g	4g
Angus Beef Steak - Steak, 6 oz	225	0g	8g	36g	113mg	140mg	0g	0g
Snacks								
Nuts - Cashew nuts, raw, 20 gram	110	6g	9g	4g	0mg	2mg	1g	1g
Odyssey Feta Cheese - Feta Cheese, 60 gram	148	4g	8g	13g	32mg	720mg	2g	0g
Generic - Home Cooked Butternut Squash, 100 g	45	12g	0g	1g	0mg	4mg	2g	2g
ranch dressing - Dressing, 2 tbsp	140	2g	14g	1g	10mg	260mg	1g	0g
Sincerely Nuts Pine Nuts - Pine Nuts, 1 oz.	188	4g	19g	4g	0mg	1mg	1g	1g
Tesco - Mixed Leaves, 30 g	5	1g	0g	0g	0mg	1mg	1g	0g
TOTAL:	**2,817**	**338g**	**102g**	**148g**	**275mg**	**4,641mg**	**101g**	**32g**

1.7.6 Appendix VI. Meal Plan Day 5



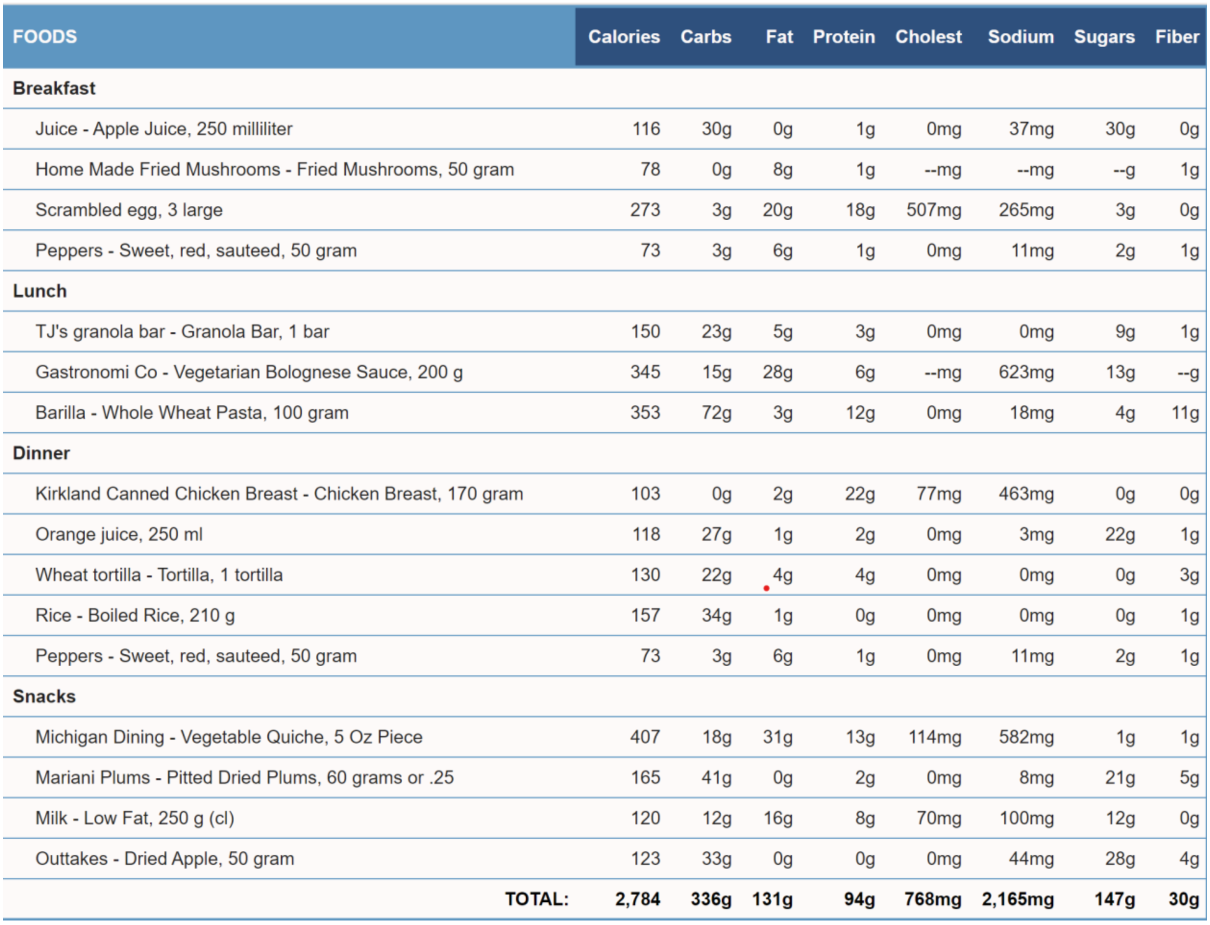
FOODS	Calories	Carbs	Fat	Protein	Cholest	Sodium	Sugars	Fiber
Breakfast								
Juice - Apple Juice, 250 milliliter	116	30g	0g	1g	0mg	37mg	30g	0g
Bacon - Maple Bacon, 2 slice	180	0g	14g	10g	30mg	540mg	0g	0g
Maple Syrup, 40 g	104	27g	0g	0g	0mg	5mg	24g	0g
Vanilla French Toast - French Toast, 2 slices	221	29g	7g	9g	145mg	67mg	--g	1g
Lunch								
Mariani Plums - Pitted Dried Plums, 60 grams or .25	165	41g	0g	2g	0mg	8mg	21g	5g
ESS - Thai Stir Fry Vegetables, 100 g	86	8g	5g	3g	0mg	561mg	5g	2g
Noodles, egg, cooked, enriched, 200 g	276	50g	4g	9g	58mg	10mg	1g	2g
Tofoo - Smoked Organic Firm Tofu, 150 gram	206	3g	11g	23g	0mg	184mg	1g	1g
Dinner								
Nuts - Cashew nuts, raw, 1 oz	156	9g	12g	5g	0mg	3mg	2g	1g
Peas - Peas, 100 g	88	15g	1g	6g	0mg	463mg	5g	5g
Rice - Boiled Rice, 210 g	157	34g	1g	0g	0mg	0mg	0g	1g
Pataks - Original - Korma Curry Sauce, 200 g	290	19g	22g	2g	--mg	560mg	13g	5g
Kirkland Canned Chicken Breast - Chicken Breast, 170 gram	103	0g	2g	22g	77mg	463mg	0g	0g
Snacks								
Sauteed Green Beans - Sautéed Green Beans, 200 g	149	15g	9g	4g	0mg	287mg	2g	6g
Orange juice, 250 ml	118	27g	1g	2g	0mg	3mg	22g	1g
Home Made Fried Mushrooms - Fried Mushrooms, 50 gram	78	0g	8g	1g	--mg	--mg	--g	1g
Scrambled egg, 3 large	273	3g	20g	18g	507mg	265mg	3g	0g
TOTAL:	**2,766**	**310g**	**117g**	**117g**	**817mg**	**3,456mg**	**129g**	**31g**

1.7.7 Appendix VII. Meal Plan Day 6



FOODS	Calories	Carbs	Fat	Protein	Cholest	Sodium	Sugars	Fiber
Breakfast								
Marks and Spencer - 4 Nut and Flame Raisin Granola, 100 g	460	60g	19g	10g	--mg	30mg	23g	7g
Archer Farms Blueberries Dried Fruit - Blueberries - Dried, 25 gram	88	21g	0g	1g	0mg	13mg	16g	1g
Fage Greek - Yogurt, 227 gram	220	9g	11g	20g	30mg	65mg	--g	--g
Lunch								
Cheddar cheese, 30 g	121	1g	10g	7g	30mg	196mg	0g	0g
Mariani Plums - Pitted Dried Plums, 60 grams or .25	165	41g	0g	2g	0mg	8mg	21g	5g
Kroger - Hawaiian Dinner Roll - 1 Dinner Roll, 1 roll	190	36g	4g	6g	0mg	160mg	7g	1g
Tesco - Cream of Chicken Soup, 1 container (400 gs ea.)	194	11g	12g	10g	--mg	800mg	1g	0g
Dinner								
Simply Cranberry - Juice, 250 milliliter	137	36g	0g	0g	0mg	21mg	36g	0g
Morrisons - Vegetarian Lasagne, 400 g	416	46g	18g	16g	--mg	1,800mg	15g	3g
Snacks								
Chocolate Milk - Low Fat, 200 gram	139	23g	2g	7g	7mg	110mg	22g	1g
Peas - Peas, 100 g	88	15g	1g	6g	0mg	463mg	5g	5g
Louisiana Tartar sauce - Tartar Sauce, 1 tablespoons	75	1g	8g	0g	8mg	65mg	0g	0g
Homemade - Roasted Cauliflower Gratin, 100 gram	169	6g	14g	6g	32mg	261mg	3g	3g
Salmon in Foil - Baked Salmon, 140 gram	296	5g	18g	29g	77mg	210mg	3g	1g
TOTAL:	**2,758**	**311g**	**117g**	**120g**	**184mg**	**4,202mg**	**152g**	**27g**

1.7.8 Appendix VIII. Meal Plan Day 7



FOODS	Calories	Carbs	Fat	Protein	Cholest	Sodium	Sugars	Fiber
Breakfast								
Juice - Apple Juice, 250 milliliter	116	30g	0g	1g	0mg	37mg	30g	0g
Home Made Fried Mushrooms - Fried Mushrooms, 50 gram	78	0g	8g	1g	--mg	--mg	--g	1g
Scrambled egg, 3 large	273	3g	20g	18g	507mg	265mg	3g	0g
Peppers - Sweet, red, sauteed, 50 gram	73	3g	6g	1g	0mg	11mg	2g	1g
Lunch								
TJ's granola bar - Granola Bar, 1 bar	150	23g	5g	3g	0mg	0mg	9g	1g
Gastronomi Co - Vegetarian Bolognese Sauce, 200 g	345	15g	28g	6g	--mg	623mg	13g	--g
Barilla - Whole Wheat Pasta, 100 gram	353	72g	3g	12g	0mg	18mg	4g	11g
Dinner								
Kirkland Canned Chicken Breast - Chicken Breast, 170 gram	103	0g	2g	22g	77mg	463mg	0g	0g
Orange juice, 250 ml	118	27g	1g	2g	0mg	3mg	22g	1g
Wheat tortilla - Tortilla, 1 tortilla	130	22g	4g	4g	0mg	0mg	0g	3g
Rice - Boiled Rice, 210 g	157	34g	1g	0g	0mg	0mg	0g	1g
Peppers - Sweet, red, sauteed, 50 gram	73	3g	6g	1g	0mg	11mg	2g	1g
Snacks								
Michigan Dining - Vegetable Quiche, 5 Oz Piece	407	18g	31g	13g	114mg	582mg	1g	1g
Mariani Plums - Pitted Dried Plums, 60 grams or .25	165	41g	0g	2g	0mg	8mg	21g	5g
Milk - Low Fat, 250 g (cl)	120	12g	16g	8g	70mg	100mg	12g	0g
Outtakes - Dried Apple, 50 gram	123	33g	0g	0g	0mg	44mg	28g	4g
TOTAL:	**2,784**	**336g**	**131g**	**94g**	**768mg**	**2,165mg**	**147g**	**30g**

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