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Formulating Nutritionally Adequate Low-Carbohydrate Diets: An Analysis of the Australian Food Composition Database

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Abbreviations: LC: Low-Carbohydrate; VLC: Very Low-Carbohydrate; ADGs: Australian Dietary Guidelines; AGHE: Australian Guide to Healthy Eating; TEI: Total Energy Intake; NRVs: Nutrient Reference Values; RDI: Recommended Dietary Intakes; AI: Adequate Intakes; FSANZ: Food Standards Australia New Zealand; SDT: Suggested Dietary Target

ABSTRACT

Background: There is a lack of evidence-based resources available to guide the formulation of nutritionally adequate low-carbohydrate (LC) diets.

Methods: We searched the FSANZ Australian Food Composition Database to identify the top 10 LC food sources for each of the 27 essential micronutrients (vitamins, minerals, and fatty acids). To be included, foods had to contain ≤5.0g total digestible carbohydrates per serve (serving), contain at least 20% of the highest available Nutrient Reference Value (NRV) per serve, and be classified as a minimally processed food. We then categorized the foods into practical food groups and developed a sample meal plan suitable for a very LC diet (<30g/day) using these resources.

Results: Twelve (12/27) nutrients had 10 LC foods containing ≥20% NRV of that nutrient per serve for both men and women. Nine (9/27) nutrients had 10 LC foods containing ≥20% NRV for women but not for men, and six (6/27) nutrients had <10LC food sources for both women and men. Vitamin A, vitamin B12 and zinc had entirely animal food sources, and 16/27 nutrients had >80% animal food sources. Vitamin C had entirely plant food sources, and two additional nutrients (vitamin B7 and magnesium) had more than 80% plant food sources. The top 10 LC foods across all 27 nutrients were categorised into 18LC food groups. The group representing the highest number of nutrients was oily fish followed by seafood, offal, white fish, nuts, legumes, seeds, eggs, poultry, non-cruciferous vegetables, pork, ruminant animals, game meat, cruciferous vegetables, dairy, fruit, fungi, then grains. The sample meal plan met or exceeded the highest NRVs by ≥90% for 24/27 and 25/27 nutrients, for men and women respectively.

Conclusion: This study presents practical information to support healthcare practitioners and future researchers in formulating nutritionally adequate LC dietary plans.

Introduction

Low-carbohydrate (LC) diets include dietary approaches containing less than 130 grams (g) of digestible carbohydrates daily, with very low-carbohydrate (VLC) diets typically containing less than 50 g/day. LC diets have become increasingly popular over recent years, and their health benefits have been demonstrated in numerous clinical populations, including type 2 diabetes [1,2],

polycystic ovarian syndrome (PCOS) [3-5], type 1 diabetes [6,7], the metabolic syndrome [8,9], overweight and obesity [10], and epilepsy [11-13]. However, a 2019 systematic review analysed changes in micronutrient intakes for various LC diets investigated in clinical trials and found that intakes of certain nutrients decreased significantly, raising concern about the potential increased risk of nutritional deficiencies [14].

LC diets are not currently included as a recommended dietary pattern in national dietary guidelines, including the Australian Dietary Guidelines (ADGs) [15,16]. The Australian Guide to Healthy Eating (AGHE) [17] is a nationally recognised resource developed from the ADGs [16] to guide the formulation of high-carbohydrate diets (45-65% total energy intake [TEI]) using specific proportions of various food groups to meet the Nutrient Reference Values (NRVs) for key nutrients [18]. It encourages Australians to base their diets on grain and cereal products that have been fortified with key nutrients, such as thiamine, folic acid and iodine [15]. Adults aged 19-50 years are recommended to consume six daily serves of bread, rice, pasta, porridge, cereal, muesli, crumpets and scones [16]. Given that grain and cereal products are high in carbohydrates (starches and/or sugars), they cannot be included in LC diets in the quantities recommended by national authorities. This presents a practical challenge for researchers and healthcare practitioners attempting to formulate LC dietary plans that meet the NRVs, and there is an urgent need for evidence-based information and practical resources on this topic to minimize the risk of nutritional deficiencies.

Previous research demonstrates that LC diets can in fact meet nutritional requirements for adults [19] and adolescents [20], despite macronutrient proportions not aligning with national dietary guidelines. Zinn et al. 2018 showed that two LC meal plans (61-69g/day of carbohydrates) exceeded NRVs, including Recommended Dietary Intakes (RDI) and Adequate Intakes (AI), for all nutrients except iron for females [19]. However, the study provided no practical guidance on how to construct nutritionally adequate LC dietary plans. Similarly, Jebeile et al. 2020 assessed the nutritional adequacy of different VLC and LC meal plans with <30g, <50g and <130g/day of carbohydrates [20]. The results suggest that it is particularly challenging to meet nutritional requirements on a VLC diet. The <30g/day meal plan was below the RDIs for calcium, iodine and magnesium, in addition to being below the female RDI for iron [20]. The authors concluded that to maximize nutrient values, carbohydrates should be increased to 120g/day [20]. There appears to be a gap in the knowledge and understanding of how to source essential nutrients when dietary carbohydrates are restricted.

To our knowledge, no study has taken a nutrient-centered approach to identify specific foods and/or food groups that can assist researchers and healthcare practitioners in formulating LC dietary plans to be nutritionally adequate. Therefore, the aim of this study was to present practical information on meeting the NRVs for essential vitamins, minerals, and fatty acids using a LC dietary approach. Specific objectives of this study were to identify the top 10 LC food sources for each of the essential vitamins, minerals, and fatty acids, and categorise these foods into practical LC food groups. We then used these resources to develop a sample meal plan suitable for a VLC diet.

Materials and Methods

Data Collection

We searched the Food Standards Australia New Zealand (FSANZ) Australian Food Composition Database [21] between March 2020 and February 2021 to identify the top 10 LC food sources for 27 essential micronutrients. The nutrients assessed were vitamin A, vitamin D, vitamin E, thiamine (vitamin B1), riboflavin (vitamin B2), niacin (vitamin B3), pantothenic acid (vitamin B5), vitamin B6, biotin (vitamin B7), folate (vitamin B9), vitamin B12, vitamin C, calcium, iodine, chromium, magnesium, iron, fluoride, sodium, potassium, selenium, copper, zinc, molybdenum, manganese, phosphorous, and total long-chain omega-3 fats. Where data for multiple forms of a single nutrient were available (e.g., natural folate and folic acid), we used the preformed or most biologically active versions of the nutrients for analysis, which included: folate (natural), niacin (preformed B3), vitamin D3 equivalents, retinol (vitamin A), vitamin E (total vitamin E activity of a food) and total long-chain omega-3 fatty acids (DHA + EPA + DPA). Choline and vitamin K are essential nutrients that were not available in the Australian Food Composition Database [21], so these nutrients could not be assessed. In addition, linoleic acid (total omega-6 fats) could not be assessed because the database only presented data according to each individual omega-6 fatty acid, and it was not possible for us to analyse this data in the same way as the other nutrients.

Data Synthesis and Analysis

i) Identifying the Top LC Sources of Essential Micronutrients

The Australian Food Composition Database (searchable online database) [21] was searched according to each essential nutrient. For each nutrient, foods were ranked from highest to lowest (nutrient content per 100g) and individually assessed, in order, against pre-specified eligibility criteria by two independent researchers (JT, RF or NS). For each food, the following data items were extracted from the database for assessment: food description, nutrient content per 100g, nutrient content per serve (serving), and total (digestible) carbohydrates per serve. To be included in the top 10 food list for a nutrient, foods had to: contain ≤5.0g of total digestible carbohydrates per serve, ≥20% of the NRV per serve

(based on meeting 100% of the NRV with five eating occasions daily), and be classified as whole or minimally processed food according to the NOVA classification system (NOVA 1-3) (Supplementary Table 1: NOVA Classifications [22]). The database was searched until 10 different foods for each nutrient were deemed eligible and included. Two independent researchers compared their results for any discrepancies (JT, RF or NS) and if consensus could not be reached, a third researcher (KR) made the decision.

Food serve sizes were taken from the ADGs, where possible [16]. For foods that were not specified in the ADGs, a registered dietitian (JT) designated a serve size based on average serve sizes provided by food manufacturers and/or what was considered to be a practical amount of the food (Supplementary Table 2). The highest available NRVs for adults aged 19-50 years were used to assess the eligibility of foods. In order of preference, we used the Suggested Dietary Target (SDT), RDI or AI [18]. If there were ≤10 foods containing ≥20% of the highest NRV per serve for a nutrient (e.g., potassium), the database search continued until 10 different foods were identified and the %NRV values of all included foods were reported in the results for transparency. Foods were excluded from the top 10 list for a nutrient if they: contained >5.0g total digestible carbohydrates per serve, were classified as NOVA 4 foods (ultra-processed foods) [22], were herbs, spices, salts, or leavening agents (e.g., yeast or baking powder), or were synthetically fortified with the nutrient of interest (e.g., tofu fortified with B12). Additional coding items describing how we dealt with similar foods, raw and cooked foods, different foods with the same nutrient value, and foods with non-edible components are included in the Supplementary Files (Supplementary Table 3), as well as a list of all excluded foods (Supplementary Excel File 1).

ii) Categorising Foods into Practical LC Food Groups

We used an iterative process to categorise the identified LC foods into practical LC food groups. The top 10 food sources for each nutrient were merged in Excel and automatically sorted according to food type. Two researchers (JT and RF) manually sorted individual foods into groups of similar food types until all foods were grouped. The smallest number of food groups that allowed for variable dietary preferences and food availability was used.

iii) Developing a Sample Meal Plan for a VLC Diet

A 3-day meal plan was developed by a registered dietitian (JT) to be suitable for a VLC diet containing ~30g/day of digestible carbohydrates. The LC food groups were used to construct individual meals, and only foods from the top 10 LC food lists were included in the meal plan, with the exception of some minimally processed added fats (i.e., butter, olive oil and coconut cream) included to help meet energy requirements. The energy target for the meal plan was set at 9,088kJ/day (2,172kcal/day) which reflects minimum energy requirements for most adults to maintain a healthy weight (BMI = 22kg/m^2) [18]. The meal plan was designed to meet the upper end of the AMDR for protein (15-25% energy) [18], with remaining energy to be made up of dietary fats. The 3-day meal plan was inputted into FoodWorks (Xyris software, version 10) with foods selected from the Australian Food Composition Database [21]. The nutrient adequacy of the meal plan was assessed to calculate the average amount per day of all essential nutrients analysed. The total daily amounts of dietary energy, digestible carbohydrates, fibres (non-digestible carbohydrates), proteins, and fats in the meal plan were also assessed and reported.

Results

Table 1 presents the top 10 LC food sources of 27 essential micronutrients. Twelve (12/27) nutrients had all 10 LC food sources containing ≥20% NRV of that nutrient per serve for both men and women (Table 1). These nutrients were vitamin D, vitamin B2, vitamin B6, vitamin B7, vitamin B12, copper, iodine, molybdenum, phosphorus, selenium, sodium, and total long-chain omega-3 fats (Table 1). Of the remaining nutrients, nine (9/27) had all 10 LC foods that contained ≥20% NRV for women but not for men, and six (6/27) nutrients had <10 LC food sources for both women and men (Table 1). Vitamin A, potassium, and fluoride had the lowest number of LC food sources containing ≥20% NRV of that nutrient per serve with each having five or less for both men and women (Table 1). Three (3/27) nutrients (vitamin A, vitamin B12 and zinc) had 100% animal food sources, and 16 nutrients (16/27) had >80% animal food sources (Table 1). One nutrient (vitamin C) had 100% plant food sources, and two additional nutrients (vitamin B7 and magnesium) had >80% plant food sources (Table 1). Eighteen LC food groups were identified and are presented in Table 2 with the individual foods included in each group. The LC food group representing the highest number of nutrients was oily fish (20 different nutrients, n=20), followed by seafood (n=16), offal (n=14), white fish (n=11), nuts (n=11), legumes (n=11), seeds (n=11), eggs (n=10), poultry (n=9), non-cruciferous vegetables (n=9), pork (n=7), ruminant animals (n=7), game meat (n=7), cruciferous vegetables (n=7), dairy (n=6), fruit (n=5), fungi (n=5), then grains (n=3) (Table 2). The 3-day sample meal plan is presented in Table 3, and its nutrient analysis is presented in Supplementary Table 4. The total energy provided in the meal plan is 9,017kJ/day (2,155kcal/day) with 29g/day of carbohydrates (5% TEI), 128 g/day of proteins (24% TEI), and 163 g/day of fats (67% TEI) (Supplementary Table 4). The meal plan

met or exceeded the highest NRVs by ≥90% for 24/27 and 25/27 nutrients, for men and women respectively. The male NRVs that were <90% met were chromium (>50% AI), potassium (83% SDT), and total long-chain omega-3 fats (85% SDT). The female NRVs that were <90% met were chromium (>70% AI) and potassium (83% SDT) (Supplementary Table 4). Nutrient data in the FoodWorks database was incomplete for vitamin B5, vitamin B7, chromium, copper, fluoride, manganese, and molybdenum, so values are likely underestimates.

Table 1: Top 10 low-carbohydrate food sources of essential micronutrients available from the Australian Food Composition Database.

Nutrient	Food	NOVA	Serve size (g)	Nutrient / serve	%NRV (M)	%NRV (W)	Nutrient / 100g
Vitamin A (retinol) (ug) | SDT men: 1500ug/day | SDT women 1220ug/day	Liver, lamb	1	65*	20150	1343	1652	31000
	Liver, chicken	1	65*	6967.4	464	571	10719
	Eel	1	115	899.3	60	74	782
	Whole egg, chicken	1	105	452.6	30	37	431
	Gemfish	1	100*	206	14	17	206
	Camembert	3	40	200	13	16	500
	Cream cheese	3	40	156	10	13	390
	Cheddar	3	40	124	8	10	310
	Chicken, with skin	1	80*	104	7	9	130
	Sardines	1	100*	91	6	7	91
Vitamin D (D3 equivalents) (ug) | AI men and women: 5ug/day	Mushrooms (vitamin D enhanced)	1	75	18.1	363	363	24.18
	Barramundi	1	100*	13.2	264	264	13.2
	Salmon	3	100*	10.6	212	212	10.6
	Anchovies / sprat	3	100*	6.4	127	127	6.35
	Whole egg, chicken	1	105 (2 med)	6.3	127	127	6.03
	Chicken	1	80*	6.1	122	122	7.6
	Sardines	1	100*	5.7	113	113	5.65
	Quail	1	80*	5.4	109	109	6.8
	Duck	1	80*	5.4	107	107	6.7
	Turkey	1	80*	4.8	96	96	6
Vitamin E (total vitamin E activity of food) (mg) | SDT men: 19mg | SDT women: 14mg	Tahini	2	30 (2 tbs)	63.3	333	452	211
	Whole egg, chicken	1	105 (2 med)	14.7	77	105	14
	Sunflower seeds	1	30	11.7	62	84	39
	Almonds / almond meal	1 / 2	30	9.5	50	68	31.5
	Salmon	1	100*	4.9	26	35	4.9
	Hazelnuts	1	30	4.8	25	34	16
	Kingfish / Eel	1	100* / 115	4.5	24	32	4.5
	Pine nuts	1	30	3.9	21	28	13
	Trout	1	100*	3.6	19	26	3.6
	Barramundi	1	100*	3.6	19	26	3.6

Vitamin B1 (thiamine) (mg) | RDI men: 1.2mg/day | RDI women: 1.1mg/day	Pork	1	65*	0.98	81	89	1.5
	Tuna	1	100*	0.56	47	51	0.56
	Sunflower seeds	1	30 (4 tbs)	0.51	43	46	1.7
	Linseeds	1	30	0.5	41	45	1.65
	Salmon, smoked	2	100	0.42	35	38	0.42
	Soy, flour	2	30 (1/4 cup)	0.33	28	30	1.1
	Lupin, flakes	1	50 (1/2 cup, dry)	0.32	27	29	0.64
	Tahini	1	30 (2 tbs)	0.29	24	26	0.95
	Peanuts	1	30	0.24	20	22	0.79
	Wheat germ	2	15 (3 tbs)	0.23	19	20	1.5
Vitamin B2 (riboflavin) (mg) | RDI men: 1.3mg/day | RDI women: 1.1mg/day	Liver, lamb	1	65*	5.2	400	473	8
	Liver, chicken	1	65*	1.24	95	112	1.9
	Whole egg, chicken	1	105 (2 med)	0.57	44	52	0.54
	Quail	1	80*	0.5	38	45	0.62
	Kangaroo	1	65*	0.45	35	41	0.69
	Abalone	1	115	0.43	33	39	0.37
	Oysters	1	115 (8 oysters)	0.43	33	39	0.37
	Anchovies	3	100*	0.4	31	36	0.4
	Chicken, with skin	3	80*	0.36	28	33	0.45
	Almond meal	2	30	0.27	21	25	0.9
Vitamin B3 (niacin) (mg) | RDI men: 16mg/day | RDI women: 14mg/day	Chicken	1	80*	13.6	85	97	17
	Tuna	1	100*	13.4	84	96	13.4
	Salmon, smoked	3	100*	10	63	71	10
	Liver, lamb	1	65*	9.4	59	67	14.5
	Pork	1	65*	8.6	54	62	13.3
	Crocodile	1	80*	8.4	53	60	10.5
	Veal	1	65*	5.9	37	42	9
	Peanuts	1	30	5.4	34	39	18
	Sunflower seeds	1	30	4.4	27	31	14.5
	Wheat bran	2	15 (1/4 cup)	2.9	18	20	19
Vitamin B5 (pantothenic acid) (mg) | AI men: 6mg/day | AI women: 4mg/day	Liver, lamb	1	65*	4.6	76	114	7
	Liver, chicken	1	65*	3.9	65	98	6
	Salmon	1	100*	2.8	47	70	2.8
	Crab	1	100*	2	33	50	2
	Whole egg, chicken	1	105 (2 med)	1.8	30	45	1.7
	Mushrooms	1	75	1.6	27	40	2.1
	Chicken	1	80*	1.6	27	40	2
	Pork	1	65*	1.2	21	31	1.9
	Brie / camembert	3	40	1.2	20	30	3
	Peanuts	1	30	1.1	18	26	3.5

Vitamin B6 (mg) | RDI men and women: 1.3mg/day	Eggplant	1	75*	1.37	105	105	1.82
	Cucumber	1	75	1.35	104	104	1.8
	Veal	1	65*	0.65	50	50	1
	Chicken	1	80*	0.55	42	42	0.69
	Bok choi	1	75*	0.54	42	42	0.72
	Silverbeet	1	75*	0.54	42	42	0.72
	Kangaroo	1	65*	0.52	40	40	0.8
	Pork	1	65*	0.49	38	38	0.75
	Liver, chicken	1	65*	0.48	37	37	0.74
	Pistachio	1	30	0.45	35	35	1.5
Vitamin B7 (biotin) (ug) | AI men: 30ug/day | AI women: 25ug/day	Peanuts	1	30	36	120	144	120
	Hazelnuts	1	30	23.7	79	95	79
	Whole egg, chicken	1	105 (2 med)	18.6	62	74	17.7
	Almond meal	2	30	16.8	56	67	56
	Mushrooms	1	75	11.3	38	45	15
	Pistachio nuts	1	30	9	30	36	30
	Bream (fish)	1	100*	8.8	29	35	8.8
	Broccoli	1	75	8.7	29	35	11.6
	Sunflower seeds	1	30	8.7	29	35	29
	Pecans	1	30	6.9	23	28	23
Vitamin B9 (natural folate) (ug) | SDT men and women: 600ug/day	Liver, chicken	1	65*	952	159	159	1464
	Liver, lamb	1	65*	442	74	74	680
	Choy sum	1	75	319	53	53	425
	Lime	1	65	226	38	38	347
	Cabbage	1	75	209	35	35	278
	Lupin, flakes	2	50 (4 tbs, raw)	175	29	29	350
	Broccoli	1	75	119	20	20	158
	Kangaroo	1	65*	111	18	18	170
	Spinach	1	45 (1 cup)	101	17	17	225
	Watercress	1	35 (1 cup)	98	16	16	280
Vitamin B12 (ug) | RDI men and women: 2.4ug/day	Liver, lamb	1	65*	49.7	2072	2072	76.5
	Mussels	1	100*	20	833	833	20
	Octopus	1	100*	17.8	742	742	17.8
	Oysters	1	115	17.3	719	719	15
	Abalone	1	115	17.3	719	719	15
	Liver, chicken	1	65*	10.3	428	428	15.8
	Sardines	1	100*	7	292	292	7
	Mullet (fish)	1	100*	6	250	250	6
	Rabbit / Ostrich	1	65* / 100	5.2	217	217	8
	Whole egg, chicken	1	105 (2 med)	4.2	175	175	4

Vitamin C (mg) | SDT men: 220mg/day | SDT women: 190mg/day	Lime	1	65	225.6	237	274	347
	Capsicum	1	75	129	59	68	172
	Kale	1	75	90	41	47	120
	Broccoli	1	75*	82.5	38	43	110
	Cabbage	1	75	75	34	39	100
	Seaweed	1	75*	75	34	39	39
	Kohlrabi / Melon, hairy	1	75	53.3	24	28	71
	Brussel sprouts	1	75*	47.3	21	25	63
	Watercress	1	45	45.5	21	24	101
	Rocket	1	45	37.4	17	20	83
Calcium (mg) | RDI men and women: 1000mg/day	Sardines / sprat	1	100*	873	87	87	873
	Cheese, tasty / Cheese, Colby / Parmesan	3	40	398	40	40	995
	Yoghurt, natural	3	200 (small tub)	364	36	36	182
	Oysters	1	115 (8 oysters)	263.4	26	26	229
	Mozzarella / Halloumi / Cheddar	3	40	240	24	24	600
	Prawns	1	100*	239	24	24	239
	Poppy seeds	1	15 (1 tbs)	215.7	22	22	1438
	Shrimp paste	3	15 (1 tbs)	207	21	21	1380
	Cheese, Blue vein / Brie / Camembert	3	40	196	20	20	490
	Salmon, canned	3	100	191	19	19	191
Chromium (ug) | AI men: 35 ug/day | AI women: 25 ug/day	Abalone	1	115	450.8	1288	1803	392
	Trout	1	100*	162	463	648	162
	Milkfish / Herring	1	100*	25.3	72	101	25.3
	Salmon	1	100*	19.8	57	79	19.8
	Basa dory / Silver perch / Kingfish	1	100*	12.6	36	50	12.6
	Chicken	1	80*	11.2	32	45	14
	Spinach	1	45	10	29	40	22.3
	Broccoli	1	75	7.8	22	31	10.4
	Tomato	3	75	7.4	21	29	9.8
	Psyllium	2	5	6	17	24	120
Copper (mg) | AI men: 1.7mg/day | AI women: 1.2mg/day	Liver, lamb	1	65*	5.2	306	433	8
	Prawns	1	100*	1.8	106	150	1.8
	Oysters	1	115	1.4	81	115	1.2
	Trout	1	100*	0.8	48	68	0.82
	Crab	1	100*	0.7	40	57	0.68
	Lobster	1	100*	0.7	39	55	0.66
	Sunflower seeds	1	30 (2 tbs)	0.6	35	50	2
	Brazil nuts	1	30	0.6	35	50	2
	Cocoa, powder	2	15 (2 tbs)	0.6	33	46	3.7
	Mushrooms	1	75	0.5	29	41	0.66

Fluoride (ug) | AI men: 4000ug/day | AI women: 3000ug/day	Duck	1	80*	2960	74	99	3700
	Mullet (fish)	1	100*	1365	34	46	1365
	Flathead (fish)	1	100*	890	22	30	890
	Rabbit	1	65*	650	16	22	1000
	Gelatin	1	10 (1 tbs)	650	16	22	6500
	Salmon	3	100*	570	14	19	570
	Snapper / Whiting / Bream	1	100*	479	12	16	479
	Tomato	1	75	195	5	7	260
	Avocado	1	75	172.5	4	6	230
	Pork	1	65*	106.6	3	4	164
Iodine (ug) | RDI men and women: 150ug/day	Mussels	1	100*	267	178	178	267
	Seaweed	1	75*	252.8	169	169	337
	Oysters	1	115	232.3	155	155	202
	Abalone	1	115	231.2	154	154	201
	Scallops	1	100*	178	119	119	178
	Whole egg, chicken	1	105 (2 med)	136.5	91	91	130
	Morwong (fish)	1	100*	130	87	87	130
	Salmon	3	100*	60	40	40	60
	Crab	1	100*	59	39	39	59
	Snapper / Sardines	2	100*	52	35	35	52
Iron (mg) | RDI men: 8 mg/ day | RDI women: 18mg/day	Liver, chicken or lamb	1	65*	7.2	89	40	11
	Sardines	1	100*	6.1	76	34	6.1
	Octopus	1	100*	5.6	70	31	5.6
	Abalone	1	115	5.3	67	30	4.65
	Oysters	1	115	5.1	64	28	4.43
	Whole egg, chicken	1	105 (2 med)	5	63	28	4.8
	Cocoa	2	15 (2 tbs)	4.5	56	25	30
	Mutton / lamb	1	65*	3.7	46	21	5.7
	Goat	1	65*	3.2	40	18	4.9
	Shrimp paste, traditional	3	15	3.1	38	17	20.5
Magnesium (mg) | RDI men: 420mg/day | RDI women: 320mg/day	Pepitas	1	30 (2 tbs)	178	42	56	592
	Linseeds / flax seeds	1	30 (2 tbs)	118	28	37	392
	Sunflower seeds	1	30 (2 tbs)	111	26	35	370
	Brazil nuts	1	30	105	25	33	350
	Tahini	2	30 (2 tbs)	96	23	30	320
	Lupin, flakes	2	50 (1/3 cup, raw)	94	22	29	188
	Oysters	1	115	92	22	29	80
	Cocoa	2	15 (2 tbs)	89	21	28	590
	Soy, flour	2	30 (1/4 cup)	86	20	27	285
	Almonds	1	30	80	19	25	266

Manganese (mg) | AI men: 5.5mg/day | women: 5 mg/day	Abalone	1	115	38.5	700	771	33.5
	Lobster	1	100*	26.5	482	530	26.5
	Trout	1	100*	3.5	64	70	3.5
	Salmon	1	100*	2.9	53	58	2.9
	Wheat germ	2	15 (3 tbs)	2.4	44	48	16
	Flake (fish)	1	100*	2.4	44	48	2.4
	Pine nuts	1	30	2.1	38	42	7
	Macadamias / pecans	1	30	1.5	28	31	5.1
	Silverbeet	1	75*	1.1	19	21	1.4
	Hazelnuts	1	30	1.1	19	21	3.5
Molybdenum (ug) | RDI men and women: 45ug/day	Liver, lamb	1	65*	96.9	215	215	149
	Peanut butter, natural	3	30	37.8	84	84	126
	Green beans	1	75*	22.5	50	50	30
	Abalone	1	115	21.3	47	47	18.5
	Oysters	1	115	15.6	35	35	13.6
	Miso, traditional	3	18	14.9	33	33	83
	Broccolini	1	75	14.9	33	33	19.8
	Almonds	1	30	12	27	27	40
	Seaweed	1	75*	11.5	26	26	15.3
	Celery	1	75	10.7	24	24	14.3
Phosphorus (mg) | RDI men and women: 1000mg/day	Sardines / Sprat / Snapper	1	100*	690	69	69	690
	Dory / Bream / Perch	1	100*	480	48	48	480
	Whole egg, chicken	1	105 (2 med)	422.1	42	42	402
	Pepitas	1	30	369.9	37	37	1233
	Parmesan	3	40	280	28	28	700
	Liver, lamb	1	65*	260	26	26	400
	Cheddar / Mozzarella / Halloumi	3	40	230	23	23	575
	Tahini	3	30 (2 tbs)	219	22	22	730
	Lupin, splits or flakes	2	50 (1/3 cup, raw)	205	21	21	410
	Soy, flour	2	30	202.5	20	20	675
Potassium (mg) | SDT men and women: 4700mg/day	Cocoa, powder	2	15 (2 tbs)	660	14	14	4400
	Soy, flour	2	30	627	13	13	2090
	Snapper / Mackerel / Tuna	1	100*	610	13	13	610
	Flathead / Kingfish / Morwong	1	100*	540	11	11	540
	Mushrooms	1	75	482.3	10	10	643
	Lupin, flakes	2	50 (1/3 cup, raw)	365	8	8	730
	Pork	1	65*	353	8	8	543
	Veal	1	65*	344.5	7	7	530
	Wattle seeds, ground	1	30	292.2	6	6	974
	Pistachio nuts	1	30	285	6	6	950

Selenium (ug) | RDI men: 70ug/day | RDI women: 60ug/day	Brazil nuts	1	30	276	394	460	920
	Mullet (fish)	1	100*	110	157	183	110
	Sardines / Sprat	1	100*	98	140	163	98
	Mussels	1	100*	96	137	160	96
	Whiting / Hoki / Bream / Tuna / Gemfish	1	100*	70	100	117	70
	Oysters	1	115	65.9	94	110	57.3
	Calamari / squid	1	100*	56	80	93	56
	Liver, chicken	1	65*	42.3	60	70	65
	Prawns	1	100*	40	57	67	40
	Egg yolk, chicken	1	32	19.2	27	32	60
Sodium (mg) | SDT men and women: 2000mg/day	Fish sauce, traditional	3	15 (1 tbs)	1511	76	76	10070
	Halloumi	3	40	1160	58	58	2900
	Prawns	1	100*	1077	54	54	1077
	Soy sauce, traditional	3	15 (1 tbs)	1032	52	52	6883
	Salmon, smoked	3	100 (4 slices)	1015	51	51	1015
	Abalone	1	115	911	46	46	792
	Shrimp paste, traditional	3	15 (1 tbs)	900	45	45	6000
	Anchovies, canned	3	15 (6 fish)	822	41	41	5480
	Sardines / Sprat	1	100*	794	40	40	794
	Oyster sauce, traditional	3	15 (1 tbs)	694	35	35	4624
Zinc (mg) | RDI men: 14mg/day | RDI women: 8 mg/day	Oysters	1	115	23.3	166	291	20.25
	Crab	1	100*	6.4	46	80	6.42
	Lamb	1	65*	6.5	46	81	10
	Beef	1	65*	5.2	37	65	8
	Goat	1	65*	5.1	36	63	7.8
	Kangaroo	1	65*	4.4	32	55	6.8
	Turkey	1	80*	3.6	26	45	4.5
	Liver, chicken or lamb	1	65*	3.1	22	38	4.7
	Pork	1	65*	2.9	21	37	4.6
	Parmesan	3	40	2.6	19	33	6.5
Total long-chain omega-3 fats (DHA + EPA + DPA) (mg) | SDT men: 610mg | SDT women: 430mg	Trout	1	100*	4505	739	1048	4505
	Salmon	1	100*	4024	660	936	4024
	Kingfish / Perch / Bream / Morwong	1	100*	2908	477	676	2908
	Mackerel	1	100*	2197	360	511	2197
	Oysters	1	115	662	109	154	576
	Mussel	1	100*	613	100	143	613
	Squid / Calamari	1	100*	416	68	97	416
	Liver, lamb	1	65*	348	57	81	535
	Seaweed	1	75*	240	39	56	320
	Mutton	1	65*	194	32	45	298

Note: *cooked weight. Abbreviations: AI: Adequate Intake; DHA: Docosahexaenoic Acid; DPA: Docosapentaenoic Acid; EPA: Eicosapentaenoic Acid; kJ: Kilojoules; kcal: kilocalories (kcal=kJ/4.184); med: Medium; tbs: Tablespoons; M: Men; W: Women; mg: Milligrams; NRV: Nutrient Reference Value; RDI: Recommended Dietary Intake; SDT: Suggested Dietary Target; ug: micrograms. .

Table 2: Key nutrients provided in low-carbohydrate food groups.

Food group (*n* key nutrients)	Vitamins	Minerals	Fatty acids
Oily fish (20)	Vitamin A (Retinol) Vitamin D Vitamin E Vitamin B1 (Thiamine) Vitamin B2 (Riboflavin) Vitamin B3 (Niacin) Vitamin B5 (Pantothenic acid) Vitamin B12	Calcium Chromium Copper Fluoride Iodine Iron Manganese Phosphorus Potassium Selenium Sodium	Total long-chain omega-3 fats
Seafood (16)	Vitamin A (Retinol) Vitamin B2 (Riboflavin) Vitamin B5 (Pantothenic acid) Vitamin B12	Calcium Chromium Copper Iodine Iron Magnesium Manganese Molybdenum Selenium Sodium Zinc	Total long-chain omega-3 fats
Offal (14)	Vitamin A (Retinol) Vitamin B2 (Riboflavin) Vitamin B3 (Niacin) Vitamin B5 (Pantothenic acid) Vitamin B6 Vitamin B9 (Folate) Vitamin B12	Copper Iron Molybdenum Phosphorus Selenium Zinc	Total long-chain omega-3 fats
White fish (11)	Vitamin D Vitamin E Vitamin B7 (Biotin)	Chromium Fluoride Iodine Manganese Phosphorus Potassium Selenium	Total long-chain omega-3 fats
Nuts (11)	Vitamin E Vitamin B2 (Riboflavin) Vitamin B6 Vitamin B7 (Biotin)	Copper Magnesium Manganese Molybdenum Phosphorus Potassium Selenium	-
Legumes (11)	Vitamin B1 (Thiamine) Vitamin B3 (Niacin) Vitamin B5 (Pantothenic acid) Vitamin B7 (Biotin) Vitamin B9 (Folate)	Magnesium Molybdenum Phosphorus Potassium Selenium Sodium	-

Seeds (11)	Vitamin E Vitamin B1 (Thiamine) Vitamin B3 (Niacin) Vitamin B7 (Biotin)	Calcium Chromium Copper Iron Magnesium Phosphorus Potassium	-
Eggs, chicken (10)	Vitamin D Vitamin E Vitamin B2 (Riboflavin) Vitamin B5 (Pantothenic acid) Vitamin B7 (Biotin) Vitamin B12	Iodine Iron Phosphorus	-
Poultry (9)	Vitamin A (Retinol) Vitamin D Vitamin B2 (Riboflavin) Vitamin B3 (Niacin) Vitamin B5 (Pantothenic acid) Vitamin B6	Chromium Fluoride Zinc	-
Non-cruciferous vegetables (9)	Vitamin B6 Vitamin B9 (Folate) Vitamin C	Chromium Iodine Manganese Molybdenum Potassium	Total long-chain omega-3 fats
Pork (7)	Vitamin B1 (Thiamine) Vitamin B3 (Niacin) Vitamin B5 (Pantothenic acid) Vitamin B6	Fluoride Potassium Zinc	-
Ruminant animals (7)	Vitamin B3 (Niacin) Vitamin B6	Fluoride Iron Potassium Zinc	Total long-chain omega-3 fats
Game meat (7)	Vitamin B2 (Riboflavin) Vitamin B3 (Niacin) Vitamin B6 Vitamin B9 (Folate) Vitamin B12	Fluoride Zinc	-
Cruciferous vegetables (7)	Vitamin B6 Vitamin B7 (Biotin) Vitamin B9 (Folate) Vitamin C	Chromium Molybdenum Potassium	-
Dairy (6)	Vitamin A (Retinol) Vitamin B5 (Pantothenic acid)	Calcium Phosphorus Sodium Zinc	-
Fruit (5)	Vitamin B6 Vitamin B9 (Folate) Vitamin C	Chromium Fluoride	-

Fungi (5)	Vitamin D Vitamin B5 (Pantothenic acid) Vitamin B7 (Biotin)	Copper Potassium	-
Grains (3)	Vitamin B1 (Thiamine) Vitamin B3 (Niacin)	Manganese	-

Table 3: Sample 3-day meal plan for a very low-carbohydrate diet (total digestible carbohydrates: ≤30g/day).

	Day A	Day B	Day C
Breakfast	3 whole eggs (120g, hard-boiled); 50g cheese, cheddar; 30g macadamia nuts; ½ med red capsicum (120g); 1/3 med cucumber (60g).	3 whole eggs (120g, poached); 3 slices of smoked salmon (75g); ½ cup green beans (75g*); ½ cup mushroom (75g*); 1 med tomato (150g); ½ med avocado (80g, flesh); 1 tbs olive oil (18g).	200g natural yoghurt (3% fat); 30g almonds; 3 brazil nuts (15g); 15g sunflower seeds (1 tbs); 1 tb coconut cream (20g); cinnamon.
Lunch	100g* sardines; 40g cheese, haloumi; 15g pine nuts (1 tbs); 1 cup baby spinach (45g, raw); ½ med avocado (80g, flesh); 1 med tomato (150g); 1 tbs olive oil (18g).	200g natural yoghurt (3% fat); 30g almonds; 3 brazil nuts (15g); 1 tbs sunflower seeds (15g); 1 tb coconut cream (20g); cinnamon.	150g* beef (untrimmed); 20 g cheese, parmesan (fresh); 30g pine nuts (2 tbs); 1 cup watercress (40g); 80g silverbeet; 1/3 medium cucumber (60g); 2 tbs lime juice, fresh (40g); 1 tbs olive oil (18g).
Dinner	150g* chicken thighs (1 med thigh with skin on, baked); 40g cheese, fetta; 4 med florets/stalks broccolini (75g*); 5 med brussels sprouts (105g*, boiled); ¼ med eggplant (105g*, grilled); 1 tbs butter (20g).	130g* pork rump steak; 40g cheese, camembert; 30g walnuts; 75g white cabbage; 1 cup rocket (40g); ½ medium red capsicum (120g); 1 tbs olive oil (18g).	Lupin beans (50g uncooked, dehulled, splits); 30g hazelnuts; 1 tbs shrimp paste (15g); ½ cup cabbage (75g*); ½ cup bok choy (75g*); 75g* broccoli; ¼ med red capsicum (70g); 1 tb olive oil (18g); curry spices/salt.
Snacks	40g peanut butter (no added sugar or salt); 120g celery (3 med stalks).	60g chicken liver pate (35g liver fried in butter, 20g extra butter, <5g salt/herbs); 120g celery (3 med stalks, raw).	2 whole eggs (hard-boiled); 25g cream cheese.

Discussion

This research successfully identified the top LC food sources and food groups for 27 essential micronutrients using the FSANZ Australian Food Composition Database. This study is the first of its kind to present practical information on meeting the NRVs for essential vitamins, minerals, and fatty acids using a LC dietary approach based on whole foods. The results of this study can be applied in clinical practice by healthcare practitioners to guide the development of LC dietary plans and educational resources for patients. The results can also be applied in future research studies investigating LC diets wherein nutritional adequacy is important (e.g., diet interventions >2 weeks).

It appears that the prioritisation of animal-based protein foods, including meat, fish, seafood, eggs, and dairy, is a critical consideration for meeting micronutrient requirements on a LC diet. Despite using the serve sizes established in the ADGs which recommend larger serves of plant-based proteins (i.e., 150 g) and smaller serves of animal-based proteins (i.e., 65-80 g) [16], over half of the nutrients assessed had ≥80% animal foods as their top LC dietary sources, and most of the LC food groups identified were animal foods. As such, seven (7/9) meals in the 3-day VLC meal plan contained ≥150 g (cooked weight) of animal-based proteins. This poses practical challenges and safety concerns regarding nutritional deficiencies for individuals choosing to limit or exclude animal foods while following a LC diet. In these cases, inclusion of ultra-processed plant-based meat and dairy alternatives that have been fortified with key nutrients (e.g., potassium, calcium, vitamin B12, iron) and/or targeted nutritional supplementation would need to be considered.

With that said, high intakes of animal protein foods may raise concern for disease risk, especially with consideration of the associations between red meat and colorectal cancer [23]. However, flaws identified in this associational data have led healthcare practitioners to question whether the small absolute risk linking red meat to disease (51 people per 100,000 vs. 43 people per 100,000 [23]) is of any real clinical significance. Additionally, the research did not distinguish between the different types of red meat consumed, such that minimally processed red meats (e.g., beef mince, lamb shoulder, pork chop) and naturally preserved meats (i.e., meat that has been transformed through salting, curing, fermentation, etc.) are categorised the same as ultra-processed red meat products (e.g., party pies, sausage rolls, pizza with meat toppings, etc.) [23]. A 2020 analysis (n = 7411) found that Australians in the highest quintile of ultra-processed food consumption had significantly higher odds of having obesity and abdominal obesity compared with those in the lowest quintile of consumption [24], with obesity established as a major risk factor for colorectal cancer [25]. Given that our analysis excluded ultra-processed foods (NOVA 4) [22], the potentially negative health effects of prioritising animal-based protein foods, including red meat, are likely minimized.

Our research suggests that it may be difficult to meet nutritional adequacy for certain nutrients, including vitamin A, fluoride, and potassium, on a LC diet using single food sources. For example, potassium had zero LC foods containing ≥20% NRV per serve. However, the 3-day meal plan still provided 83% of the SDT for potassium (men and women: 4700mg) since a wide variety of whole foods contain potassium and many single food sources add up to a significant amount across a full day. Similarly, the meal plan provided >100% of the NRV for both men and women for vitamin A and fluoride. It is also of important note that, unlike previous research assessing nutritional adequacy of LC diets [19,20], we used the highest available NRVs, including SDTs. This conservative approach made it less attainable for our 3-day meal plan to meet nutrient targets for nutrients with an SDT, given SDTs are typically set much higher than RDIs or AIs [18]. Nevertheless, our 3-day meal plan met or exceeded the SDTs for vitamin A (retinol), vitamin E, vitamin B9 (folate), vitamin C, sodium, and long-chain omega-3 fats (for women).

There are several strengths of this research. The FSANZ Australian Food Composition database analysed is a validated food database that includes a large variety of foods commonly available and consumed in Australia [21]. The systematic approach used to review this database against pre-specified criteria to identify the top LC food sources of each nutrient minimized the risk of researcher bias. In addition, the decision to merge similar foods allowed for increased variation in the types of LC food sources included, accommodating for individual dietary requirements and food preferences. For example, the current list for long-chain omega-3 fats includes liver, seaweed, and mutton in addition to fish and seafood. If we did not merge similar foods, then the list would have only included different species of oily fish.

Limitations of this research are inherent to the nutrient data that was available in the Australian Food Composition Database [21]. Data for vitamin K, choline and linoleic acid was not available. Nevertheless, the USDA food database [26] shows that good sources of vitamin K and choline include whole eggs, dairy, offal, and ruminant animals, which were practical LC food groups identified in the current study. There were also some known nutrient-dense whole foods that were not available in the database, such as salmon roe and lamb's brain, which would have likely been identified as top sources of one or more essential nutrients in this study. However, it is presumed that these foods are not commonly consumed amongst Australian diets and thus, their lack of inclusion in the database has not largely impacted our results. Finally, The Australian Food Composition database was specific to foods commonly available within Australia and many international foods were not able to be included and assessed. Future research studies assessing nutritional adequacy of LC diets should consider common food items across a variety of countries.

Conclusion

In conclusion, this study successfully identified the top LC food sources and food groups for 27 essential micronutrients using the FSANZ Australian Food Composition Database. Dietitians and other healthcare practitioners can use the results of this research to develop LC dietary plans that meet or exceed the NRVs for vitamins, minerals and fatty acids. The results may also be applied in the design of future experimental studies to guide the formulation of nutritionally adequate LC diet interventions.

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Conflicts of Interest

None

Author Contributions

- **Jessica Turton**: Conceptualization, Methodology, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing
- **Rowena Field**: Conceptualization, Methodology, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing
- **Noor Struik**: Conceptualization, Methodology, Writing - Review & Editing
- **Kieron Rooney**: Writing - Review & Editing, Supervision
- **Helen Parker**: Writing - Review & Editing.

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