Nutritional Epidemiology

The Maximal Amount of Dietary α-Tocopherol Intake in U.S. Adults (NHANES 2001–2002)[1]

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ABSTRACT The current study was designed to determine the maximal amount of α-tocopherol intake obtained from food in the U.S. diet, and to examine the effect of different food group intakes on this amount. Data from 2138 men and 2213 women aged >18 y were obtained from the National Health and Nutrition Examination Survey (NHANES) 2001–2002. Linear programming was used to generate diets with maximal α-tocopherol intake, with the conditions of meeting the recommended daily allowances or adequate intakes for a set of nutrients, sodium and fat recommendations, and energy limits, and that were compatible with the observed dietary patterns in the population. With food use and energy constraints in models, diets formulated by linear programming provided 19.3–24.9 mg α-tocopherol for men and women aged 19–50 or >50 y. These amounts decreased to 15.4–19.9 mg with the addition of the sodium, dietary reference intake, and fat constraints. The relations between maximal α-tocopherol intake and food group intakes were influenced by total fat restrictions. Although meeting current recommendations (15 mg/d) appears feasible for individuals, dramatic dietary changes that include greater intakes of nuts and seeds, and fruit and vegetables, are needed. Careful selection of the highest vitamin E source foods within these groups could further increase the likelihood of meeting the current recommended daily allowance. J. Nutr. 136: 1021–1026, 2006.

KEY WORDS: • *linear programming* • *α-tocopherol* • *Dietary Reference Intakes* • *dietary pattern*

The most recently published U.S. Dietary Reference Intakes (DRI)[3] increased the Recommended Daily Allowance (RDA) for vitamin E from 10 and 8 mg of α-tocopherol equivalents per day for adult men and women, respectively, to 15 mg α-tocopherol for both men and women (1). However, this amount has been criticized as more than can be practically obtained in most American diets (2,3). We previously showed that only 8.0% of men and 2.4% of women met the new Estimated Average Requirement (EAR) for vitamin E (12 mg) from foods alone, in the 1994–1996 Continuing Survey of Food Intakes by Individuals (CSFII) (4). Similar results were observed in the National Health and Nutrition Examination Survey (NHANES) 1999–2000 (5). These studies support the argument that the new DRI for vitamin E may not be a reasonable goal for Americans within the context of habitual dietary patterns, and emphasize the need for more understanding of foods that can contribute to meeting these new vitamin E recommendations.

Linear programming is a mathematical approach that optimizes (minimizes or maximizes) a linear function of decision variables, while respecting multiple linear constraints (6). Solving a problem with linear programming involves building a "model" as a mathematical representation of the problem (7). It is frequently used in economics, management, and engineering (8). Recently, this methodology was used to formulate nutritionally optimal dietary patterns (9–12), to examine the relation between diet cost and dietary quality (6,12), and to develop food-based dietary guidelines in a developing country (13).

Using linear programming, we reported previously that maximal α-tocopherol intake amounts were 20.6, 16.3, 16.0, and 11.5 mg for young (19–50 y) and older men (>50 y) and young and older women, respectively, using the 1994–96 CSFII data with recommended limitations on food intake amount, energy intake, vitamins, minerals, and fats (14). However, because both diets and guidelines have changed over time, it is important to assess whether the new RDA for vitamin E can be met with the latest national dietary intake data.

In the current study, we employed linear programming (14) to formulate diets with maximal intake of α-tocopherol, while also meeting other specified nutritional conditions, in 4 sex and age strata of the NHANES 2001–2002 participants. Constraints included that food intake amounts not exceed certain ranges, that intakes of energy, fat, and sodium not exceed recommended levels, and that a set of nutrient intakes met recommendations. We then compared these α-tocopherol amounts with the current RDA. We also examined the effect of

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[3] Abbreviations: AI, Adequate Intake; CSFII, Continuing Survey of Food Intakes by Individuals; DRI, Dietary Reference Intake; EAR, Estimated Average Requirement; EER, Estimated Energy Requirements; NHANES, National Health and Nutrition Examination Survey; PA, physical activity; RDA, Recommended Daily Allowance.

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different food group intakes on these amounts and identified the most important foods for meeting the RDA for vitamin E in the U.S. diet.

SUBJECTS AND METHODS

Subjects. Subjects were 4994 men and women >18 y old from the 2001–2002 National Health and Nutrition Examination Survey (NHANES). We excluded subjects who were pregnant (n = 309), and who reported energy intake <2.51 MJ/d (600 kcal/d) or >16.72 MJ/d (4000 kcal/d) (n = 334), leaving 4351 subjects (2138 men and 2213 women) in the analysis. These individuals were stratified, by age (19–50 y or >50 y), and sex.

Input data for linear programming models. To obtain the maximal amount of α-tocopherol intake from the current U.S. diet, a linear programming problem was formulated and solved, separately, for the 4 sex-age strata. We then used diet optimization to simulate the effect of variations in different kinds of food consumption on maximal α-tocopherol intake in the full sample.

Dietary data from the NHANES 2001–2002 were available from two data sets: individual food files (15), which provided nutrient data, and Food Guide Pyramid servings data for NHANES (16), which provided standard serving size information. For modeling purposes, we collapsed foods into 61 subgroups based on similarity of nutrient composition (4). These food subgroups were further collapsed into 7 major categories, referred to as food groups (breads and cereals, dairy, fruit, vegetables, meat and eggs, nuts and seeds, and oils and salad dressings). Nutrients from each subgroup were calculated based on the food items in the subgroup, and the average consumption of each item. For example, the citrus fruit category included oranges, grapefruit, and other citrus fruits. Mean nutrient intakes for this category were calculated by weighting the mean reported consumption of these 3 food items by the population. The nutrient profile for each food subgroup was then used in the definition of the objective function and of the constraints introduced in the linear programming models. We calculated nutrient profiles for each sex-age strata separately to obtain the maximal α-tocopherol intake for each. To examine associations between consumption of different food groups and maximal α-tocopherol intake, we calculated nutrient profiles using the dietary data for the total sample. Hence, there were 5 nutrient profiles: 1 for the total sample, and 1 for each of 4 sex-age specific strata.

We used SAS (Release Version 8.02, SAS Institute) to merge and arrange the data, which were then transferred to EXCEL files. Microsoft EXCEL SOLVER (Frontline Systems) was used for linear programming.

Objective function. Linear programming is designed to find the optimal solution to minimize or maximize the objective function, which is dependent on a set of decision variables restricted by various linear constraints (7,12). In this case, the objective function was to maximize dietary α-tocopherol intake. The decision variables were food subgroups. Therefore the linear function can be written as follows:

$$a_1X_1 + a_2X_2 + a_3X_3 + \ldots + a_{61}X_{61}.$$

The variables a_1 through a_{61} were defined as the α-tocopherol values (in mg) per unit weight for the 61 food subgroups, and X_1 through X_{61} were their weights (in g).

Model constraints. To increase the viability of the solution, linear programming includes a number of constraints upon which to optimize the results. The solution selected by a model has to satisfy all of the constraints specified (7). In other words, the diets formulated by the linear programming not only maximized α-tocopherol but also met a set of conditions. **Table 1** lists the constraints we employed in our models.

Food use constraints set upper limits on the amount of each food included so that program model does not select food quantities exceeding amounts eaten in the population. These limits were derived from actual intake distributions. Specifically, dietary intake from each food subgroup was set to not exceed the 75th percentile of the population intake. We also limited dietary intake for each of the food groups within the range from the minimal level to the 90th percentile of the population.

We introduced an energy constraint into each model, to ensure that the energy content of the diets generated by linear programming did not exceed recommended levels. We used estimated energy requirements (EER) as the upper limit for energy, based on sex, age, weight, height, and physical activity (PA) (17). Because obesity is currently a major concern, we assumed PA to be 1, i.e., a sedentary life style. The EER were 11.1, 9.9, 8.4, and 7.5 MJ/d (2655, 2367, 2014, and 1782 kcal/d, respectively) for men aged 19–50 y, >50 y, women aged 19–50 y, and >50 y, respectively (**Table 2**). When we examined the effect of different food group consumption on maximal α- tocopherol intake, we set the energy constraint at 8.368 MJ (2000-kcal) for all models.

To ensure that the diets designed by linear programming were nutrient adequate, we also introduced DRI constraints. The diets were set to meet each age-sex strata's RDA or adequate intakes (AI) for the following 15 essential nutrients: fiber, vitamin A, vitamin C, thiamine, riboflavin, niacin, folate, vitamin B-6, vitamin B-12, calcium, iron, zinc, phosphorus, potassium, and magnesium. In sensitivity analyses, we used the highest level of RDA/AI, which were those for men aged 19–50 y, to ensure that the diets meet nutrient requirements for all subjects.

We used 2 fat constraints, based on the year 2005 Dietary Guidelines for Americans (18). We limited the saturated fat intake to ≤10% of total energy, and total fat intake to ≤35% of total energy. We also limited sodium intake to ≤2300 mg/d.

Sensitivity analysis. Sensitivity analysis allows evaluation of how changes in the condition of the problem might change the optimal solution (19). We used this to examine associations between intake of

TABLE 1

List of constraints to be employed

Food amount constraints	
Consumption of food subgroup, *servings/d*	Number of servings does not exceed 75th percentile of the population
Consumption of food group, *servings/d*	Number of servings does not exceed 90th percentile and is not less than the minimal level in the population
Energy constraints	Total energy does not exceed estimated energy requirements, based on age, sex, weight, height, and physical activity level
DRI constraints	
Fiber, vitamin A, vitamin C, thiamin, riboflavin, niacin, folate, vitamin B-6, vitamin B-12, calcium, iron, zinc, phosphorus, potassium, and magnesium	Intakes are not less than recommended daily allowances or adequate intakes Intakes do not exceed upper limits
Sodium constraint	Intakes do not exceed 2300 mg/d
Fat constraints	
Saturated fat	Intakes do not exceed 10% of total energy
Total fat	Between 20–35% of total energy

TABLE 2

Calculation of Estimated Energy Requirements for different age-sex groups[1]

	n	Age, y	Height, m	Weight, kg	PA	EER[1], kcal[2]
Men						
≤50	1141	35.8	1.77	87.2	1	2655
>50	997	63.1	1.75	86.9	1	2367
Women						
≤50	1196	35.2	1.63	73.4	1	2014
>50	1017	64.4	1.61	74.5	1	1782

[1] Values are means: EER for men ≥ 19 y = 662 − 9.53 × age[y] + PAL × (15.91 × weight[kg] + 539.6 × height[m]); EER for women ≥ 19 y = 354 − 6.91 −× age[y] + PA × (9.36 × weight[kg] + 726 × height[m]).
[2] To convert to kJ, multiply by 4.184.

food groups or macronutrients (protein, fat, and carbohydrate, expressed as % of total energy) and maximal α-tocopherol intake. We varied each food group or macronutrient intake amount within a certain intake range (5 to 95th percentiles for macronutrients, and 0 to 90th percentiles for food groups, except for nuts and seeds, where the 99th percentile was used), and examined variation in the maximal α-tocopherol intake amount. For example, to examine the relation between intake of nuts and seeds and maximal α-tocopherol intake, we gradually increased the intake from 0 to 3 servings/d, in the linear programming models.

RESULTS

Mean α-tocopherol intakes were 7.2, 6.8, 6.1, 6.0 mg/d for men aged 19–50 y, >50 y, women aged 19–50 y, and >50 y, respectively (**Table 3**). Only 5% of men and 4% of women met the vitamin E RDA (15 mg/d), and 10–11% and 7–8%, respectively, met the EAR (12 mg/d). Few foods are rich in α-tocopherol. Foods contributing 1.0 mg or more of naturally occurring α-tocopherol/standard serving include nuts and seeds (2.3 mg/oz), peanut butter (2 mg /serving), oil (2 mg/serving), pizza (1.3 mg/servings), and dark green vegetables (1.2 mg/serving).

With food use and energy constraints in the models (**model 1, Table 4**), diets formulated by linear programming provided 24.9, 24.0, 18.7, and 19.3 mg α-tocopherol, for men aged 19–50 y, >50 y, women aged 19–50 y, and >50 y, respectively. These amounts decreased with the addition of the sodium, DRI, and saturated fat constraints (≤10% of total energy), but still met the RDA of 15 mg α-tocopherol (**model 4,** Table 4). When we further added the total fat constraint (≤35% of total energy), these amounts decreased to 19.9, 19.5, 15.8, and 15.4 mg, respectively (**model 5,** Table 4).

Sensitivity analysis was used to examine the relations between macronutrient intake and maximal α-tocopherol intake (**Fig, 1**). When fat intake increased from 10 to 50% of total energy, maximal α-tocopherol increased from 10 to 20.8

TABLE 3

α-Tocopherol intake status by sex and age in NHANES 2001–2002

	Men		Women	
	19–50 y	>50 y	19–50 y	>50 y
n	1141	997	1196	1017
Intake, *mg/d*	7.2 ± 0.1*	6.8 ± 0.2	6.1 ± 0.1	6.0 ± 0.2
%, ≥RDA (15 mg/d)	5.2	4.9	4.1	4.5
%, ≥EAR (12 mg/d)	11.2	9.9	6.8	7.8

[1] Values are means ± SEM.

TABLE 4

Maximal α-tocopherol intake by sex and age, satisfying sets of constraints

	Men		Women	
Models[1]	19–50 y	>50 y	19–50 y	>50 y
	mg/d			
1	24.9	24.0	18.7	19.3
2	20.5	21.3	17.6	18.3
3	20.1	20.4	16.4	15.7
4	20.1	20.3	16.3	15.7
5	19.9	19.5	15.8	15.4

[1] Model 1, food amount and energy constraints; Model 2, Sodium constraint was added; Model 3, DRI constraint was added; Model 4, saturated fat constraint was added; Model 5, total fat constraint was added.

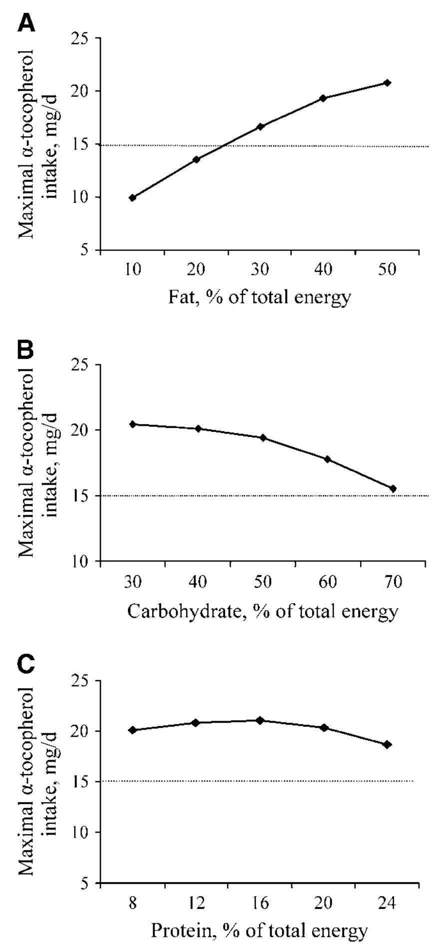

FIGURE 1 The maximal α -tocopherol intake at different percentages of energy from fat (*panel A*), protein (*panel B*), and carbohydrate (*panel C*) when total energy was set at 8.36 MJ. The food amount constraints were employed.

mg/d. To meet the RDA for vitamin E (15 mg/d), at least 25% of total energy must come from fat. An inverse association between carbohydrate and maximal α-tocopherol intake was observed. Variation in protein intake changed maximal α-tocopherol only slightly.

When we employed the food amount, energy, DRI, and saturated fat constraints, the maximal α-tocopherol intake rose with increasing intake of nuts and seeds (**Fig. 2***E*), and oils and salad dressing (Fig. 2*F*). Maximal α-tocopherol increased with greater intake of breads and cereals (Fig. 2*A*), dairy (Fig. 2*B*), and meat and eggs (Fig. 2G), and then fell at 4 servings for breads and cereals, 2.5 servings for dairy and 1.5 ounce equivalents for meat and eggs. For fruit (Fig. 2C) and vegetables (Fig. 2*D*), a positive relation was observed through 5 servings for fruit and 6 servings for vegetables, but then reached a plateau. When the total fat constraint was added, the associations between maximal α-tocopherol intake with breads and cereals, dairy, fruit, vegetables, nuts and seeds, and meat and eggs were the same, but for oils and salad dressing, maximal α-tocopherol increased and then fell at 2 servings. We also repeated the sensitivity analysis for dairy by using fat-free and low-fat forms. With the saturated and total fat constraints in the model, the maximal α-tocopherol changed only slightly with replacement by fat-free and low-fat dairy foods.

When we set total energy intake at 8.36 MJ and used the food amount, energy, DRI, and saturated fat constraints, the maximal α- tocopherol diet, generated by linear programming, contained 3.8 servings of breads and cereals, 4.1 servings of fruit, 6.7 servings of vegetables, 1.3 ounce-equivalents of meat, 2.4 serving of milk and dairy, 3.1 tablespoons of oils, and 0.6 servings of nuts and seeds (**Table 5**). When the total fat constraint was added, consumption of breads and cereals, meat and eggs, milk and dairy, and oil and salad dressings changed to 4.3, 1.5, 2.2 and 2.1 servings, respectively, with no change in other food groups.

DISCUSSION

We observed that the current RDA for vitamin E can be met from foods for all age-sex strata. However, this can be done only with dietary choices that vary considerably from the current practices of most Americans. The relations between maximal α-tocopherol intake and food group intakes were influenced by total fat restrictions. Increased consumption of nuts and seeds (within 2.5 oz-eqs/d) was associated with higher α-tocopherol intake, whereas a low intake of nuts and seeds was related to inadequate α-tocopherol intake. However, from a practical perspective, the general category of nuts and seeds has a wide range of vitamin E content. Almonds, hazelnuts, and sunflower seeds are relatively high (>5 mg/oz) whereas peanuts (2 mg/oz), cashews, and pistachios (both <1 mg/oz) are relatively low. Maximal α-tocopherol intakes in the NHANES 2001–2002 were

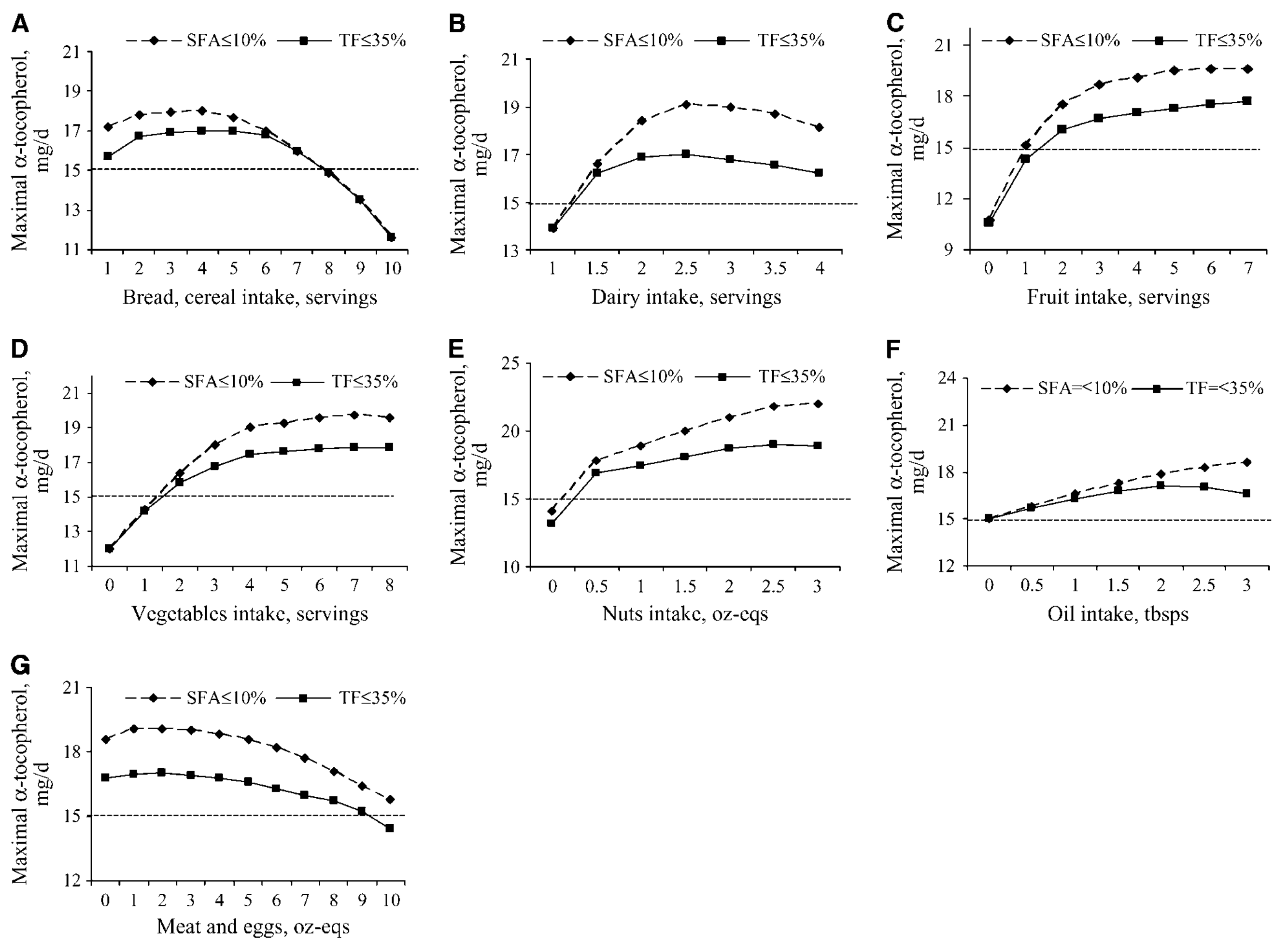

FIGURE 2 Effect of specific food groups on maximal α -tocopherol intake when total energy was set at 8.36 MJ. The food amount, DRI, sodium, and saturated fat constraints were employed. The lower lines (squares) also included total fat constraints (≤35% of total energy). SFA, saturated fat; TF, total fat.

TABLE 5

Linear programming solutions: diets with maximal α-tocopherol intake with different fat constraints

	Saturated fat constraint[1] (≤10% of total energy)	Total fat constraint added[1] (≤35% of total energy)
Breads and cereals, *servings*	3.8	4.3
Fruit, *servings*	4.1	4.1
Vegetables, *servings*	6.7	6.7
Meat and eggs, *oz-eqs*	1.3	1.5
Milk and dairy products, *servings*	2.4	2.2
Oils and salad dressing, *Tbsp*	3.1	2.1
Nuts and seeds, *oz-eqs*	0.6	0.6
α-Tocopherol, *mg*	18.0	17.0

[1] The food amount, sodium, and DRI constraints were also employed. Total energy was set at 8.36 MJ.

slightly higher than those in 1994–96 CSFII population (14), consistent with higher actual α-tocopherol intake (means of 7 mg/d in men and of 6 mg/d in women, vs. 6.7 and 4.7 mg/d, respectively).

The unique contribution of diet optimization by linear programming is that numerous factors (constraints) can be considered simultaneously so that inadvertent negative effects can be avoided (13). This was clearly demonstrated by the behavior of fats and oils under different fat constraints. When only saturated fat was constrained, fats and oils were positively associated with maximal α-tocopherol intake. As a result, the diet generated by linear programming contained as much of these foods as possible. However, when total fat was also constrained, maximizing oil intake was eventually associated with lower maximal α-tocopherol intake, by replacing other foods with higher vitamin E content. For example, with total energy and fat held constant, higher intakes of oils would necessarily lead to lower intake of nuts, which contain relatively high energy and fat as well as α-tocopherol.

In observational studies, high α-tocopherol intake was reported to be associated with lower risk of heart disease (20,21), type 2 diabetes (22–24), hypertension (25), cancer (26–28), cognitive decline, and Alzheimer's disease (29–34). However, randomized, placebo-controlled intervention trials did not support these observations (35–37). Recent studies suggested possible adverse effects of high dose vitamin E supplement use (38,39). To avoid risks associated with high-dose supplement, emphasis on optimal food intake of vitamin E within the range of the DRI is important.

The DRI for vitamin E were established based on the criterion of vitamin E intakes sufficient to prevent hydrogen peroxide-induced hemolysis (1). However, the majority of Americans have α-tocopherol intakes much lower than those recommended (4,5). The Second National Health and Nutrition Examination Survey (NHANES II) reported mean intakes of vitamin E at 9.6 and 7.0 mg/d of α-tocopherol equivalents, for men and women, respectively (40). In the 1994–96 CSFII, dietary α-tocopherol intake medians were only 5.6, and 4.0 mg/d for men and women aged 20 y and older, respectively, and only 8.0% of men and 2.4% of women met the new EAR for vitamin E from foods alone (4). Similarly, a recent study from NHANES 1999–2000 showed that dietary intakes of α-tocopherol in men and women, aged 19 and older, were 7.8 and 6.3 mg/d, respectively, and that only 10% of men and 4% of women met the new EAR for vitamin E (5). The current study shows that the maximal amounts of α-tocopherol intakes from foods alone ranged from 15 to 20 mg/d across different age-sex strata when total fat was limited to ≤35% of total energy. This suggests that U.S. men and women could double their α-tocopherol intake by improving their dietary quality.

High vitamin E–containing nuts and seeds are clearly important food choices if Americans are to meet current vitamin E intake DRI. Consumption of nuts is associated with a lower risk of heart disease (41–46) and diabetes (47). However, in this nationally representative population, 70% of men and women did not report intake of nuts or seeds. Diets without nuts or seeds provided only 13 mg/d α-tocopherol maximally, when total fat was restricted to 35% of energy. Given that the most commonly consumed types of nuts in the United States are not those with the highest vitamin E (48), use of more vitamin E- rich nuts and seeds, such as almond and sunflower seeds, would offer a higher likelihood of meeting the current RDA for Americans. For example, in a diet with 8.36 MJ energy, maximal α-tocopherol could increase by 2 mg/d if almonds, a nut with high vitamin E, replaced other nuts.

Linear programming is a useful tool, but does have limitations. Nutrient composition assumptions represent averages for each food group. Selection of foods with the highest or lowest vitamin E sources within a group could alter individual results. For example, use of peanuts (2.2 mg α-tocopherol/serving) vs. almond (7.3 mg α-tocopherol/serving) would result in lower and higher intakes than average, respectively. Use of sunflower oil (5.6 mg/ Tbsp) to replace other oils could increase maximal α-tocopherol by 4–5 mg/d. However, the purpose of our study was to identify overall relations between dietary patterns and α-tocopherol intake. Another limitation of our study is that our analyses were based on fresh foods. However, oxidation results in the destruction of α-tocopherol, thus lowering the amount in the oil. One study showed that ~20% of the α-tocopherol in olive oil was oxidized after 2 mo of typical home storage conditions, and this increased to >90% after 12 mo (49). Therefore, we may be overestimating the maximal amount of α-tocopherol provided by diets.

Our final model for a 8.368 MJ (2000-kcal) diet contained 11 servings of fruit and vegetables, and 0.6 servings of nuts and seeds. This departs greatly from commonly observed dietary patterns in the population. Therefore, although meeting current recommendations appears feasible for individuals, it is unlikely to be met by the majority of the population without dramatic dietary changes that include much greater intakes of nuts and seeds, and fruit and vegetables. Careful selection of the highest vitamin E source foods within these groups may further increase the likelihood of meeting the current RDA for α-tocopherol.

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