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Diet Optimization Methods Can Help Translate Dietary Guidelines into a Cancer Prevention Food Plan[1,2]

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Abstract

Mathematical diet optimization models are used to create food plans that best resemble current eating habits while meeting prespecified nutrition and cost constraints. This study used linear programming to generate food plans meeting the key 2007 dietary recommendations issued by the World Cancer Research Fund/American Institute of Cancer Research (WCRF/AICR). The models were constructed to minimize deviations in food intake between the observed and the WCRF/AICR-recommended diets. Consumption constraints were imposed to prevent food plans from including unreasonable amounts of food from a single group. Consumption norms for nutrients and food groups were taken from dietary intake data for a sample of adult men and women (n = 161) in the Pacific Northwest. Food plans meeting the WCRF/AICR dietary guidelines numbers 3–5 and 7 were lower in refined grains and higher in vegetables and fruits than the existing diets. For this group, achieving cancer prevention goals required little modification of existing diets and had minimal impact on diet quality and cost. By contrast, the need to meet all nutritional needs through diet alone (guideline no. 8) required a large food volume increase and dramatic shifts from the observed food intake patterns. Putting dietary guidelines into practice may require the creation of detailed food plans that are sensitive to existing consumption patterns and food costs. Optimization models provide an elegant mathematical solution that can help determine whether sets of dietary guidelines are achievable by diverse U.S. population subgroups. J. Nutr. 139: 1541–1548, 2009.

Introduction

The American diet has become energy rich but nutrient poor (1). Only a small percentage of Americans meet dietary requirements for vitamin E, potassium, calcium, magnesium, and fiber (2) or consume sufficient vegetables and fruit (2–4). Nutrient-rich diets high in whole grains, low-fat dairy products, lean meats, fish, and vegetables and fruit are typically recommended for good health and the prevention of chronic disease (5–11).

In 2007, the World Cancer Research Fund and the American Institute of Cancer Research (WCRF/AICR)[6] issued a set of guidelines for cancer prevention (12). Recommendations 3–5 and 7 set targets for the consumption of red meat, vegetables and fruit, and sodium and for energy density of the diet. A separate recommendation, number 8, which resulted from the previous ones, was that nutrient requirements should be met through diet alone.

Dietary guidelines ought to be accompanied by formal feasibility or economic analyses. The barriers to their adoption may differ among diverse population groups. For example, reducing dietary energy density in the population down to 1.25 kcal/g[7] (12,13) might result in sharply higher energy-adjusted diet costs (14). The adoption of plant-based diets in preference to meat-based ones (12) may require dramatic shifts from current eating habits (15). The requirement that all nutrients should come from dietary sources may not be feasible for everyone.

Dietary guidelines should also be accompanied by specific food plans. Some intervention studies have provided participants with little guidance beyond suggested limits on energy and fat intakes (16,17) or the broad directive to consume less fat and more vegetables and fruit (18,19). By contrast, the USDA has been using mathematical diet optimization models to develop

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[6] Abbreviations used: AI, adequate intake; DRI, dietary reference intake; MAR, mean adequacy ratio; RDA, recommended daily allowance; UL, upper limit; WCRF/AICR, World Cancer Research Fund/American Institute of Cancer Research.

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[7] 1 kcal = 4.18 kJ.

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food plans that meet prespecified nutritional and cost requirements for population groups by gender and age (20). The USDA food plans specify average daily consumption amounts for 58 food groups under different sets of budget constraints.

This study presents an application of mathematical optimization tools (21–23) to dietary guidelines for cancer prevention. The objective was to identify 2 gender-specific food plans that were as close as possible to the observed consumption patterns. The first food plan met WCRF/AICR dietary recommendations 3–5 and 7, which aim to improve nutritional intakes via more prudent food choices. The second plan had to meet the 8th recommendation alone. Its requirements helped to obtain the food choices induced by nutritional recommendations within the study population. The resulting food plans, drawn from 152 foods in a FFQ, were then assessed for their composition, quality, weight, mean energy density, and cost. To prevent the solutions from including unreasonable amounts of any one food or food group, the optimization models set lower and upper consumption bounds based on the observed eating habits of the referent population (22,24–26).

TABLE 1 Food groups and subgroups with the lower (5th percentile) and upper (90th percentile) consumption constraints used in the optimization models

Groups and percentile	Men	Women	Subgroups	Men in 90th percentile	Women in 90th percentile
Grains	*Consumption, g/d*			*Consumption, g/d*	
5th	76.9	50.6	Refined	257	207
90th	411	274	Whole	219	136
Vegetables					
5th	63.1	105	Dark green	104	106
90th	668	588	Orange	53.2	75.4
			Dry beans and peas	312	200
			Starchy	81.8	82.5
			Other[1]	242	259
Fruits					
5th	52.1	103	Juices	494	303
90th	686	633	Whole fruits	321	425
Dairy					
5th	30.6	29.4	Milk	490	399
90th	693	616	Milk-based desserts	67.4	59.0
			Cheese	56.7	56.5
			Yogurt	181	245
Meat, fish, and nuts					
5th	21.6	32.7	Meats[2]	104	69.7
90th	239	201	Poultry	62.3	66.2
			Eggs	52.5	51.7
			Nuts and seeds	50.1	33.4
			Fish	62.1	37.6
Oils					
5th	2.14	0.97	Oils	31.6	28.5
90th	40.6	33.0	Solid fats	7.0	9.9
Extras-solid					
5th	6.52	8.21	Salty	20.4	28.4
90th	94.0	110	Sweet	83.6	101
Beverages					
5th	0	0	Beverages	308	256
90th	196	254			
Meals					
5th	25.5	41.4	Composed meals	358	251
90th	361	253	Other	22.7	21.7

[1] Other vegetable subgroups included vegetables such as tomatoes, zucchini, cabbage, cauliflower, mushrooms, eggplant, asparagus, cucumbers, and vegetable juices.

[2] Meats included beef, pork, veal, lamb, game, and organ meats.

Materials and Methods

Observed food consumption patterns. Dietary intakes for 103 women and 61 men, faculty and staff of a large public university in the Pacific Northwest, were obtained using a validated FFQ developed by the Fred Hutchinson Cancer Research Center. The specific FFQ form used in the present study, the general-select (G-SEL) version, has been used in numerous past studies including the Selenium and Vitamin E Cancer Prevention Trial (27–29). The G-SEL FFQ is based on 152 foods and beverages from all food groups. Energy and nutrient intakes were calculated using the Minnesota Nutrition Coordinating Center database. Nutrient analyses yielded dietary energy (kcal), the weights of foods and beverages (g), and daily intakes of over 45 macro- and micronutrients. All study procedures were reviewed and approved by the University of Washington institutional review board.

Dietary energy density was calculated by dividing available energy by weight of foods (MJ/kg or kcal/g). It was based on foods only, excluding caloric and noncaloric beverages and drinking water (30–32). All foods were also aggregated into 9 major food groups based on the MyPyramid system (33) (additional subgroups listed in **Table 1**). Discretionary calories were split between solids ("extras") and liquids ("beverages"). Retail food prices for 2006, collected in Seattle supermarkets, were added to the G-SEL nutrient database and expressed in \$/100 g edible portion (34). Diet costs were calculated by adjusting the cost of each food by reported portion size and adding up all foods consumed by that individual, a technique similar to that used by the USDA (35).

Mathematical diet optimization model. Linear optimization is a mathematical tool used to find the optimal solution of a linear function (the objective function) while respecting a set of linear equality and inequality constraints. The general structure of linear programming models is as follows:

$$\text{Minimize/maximize: } Y(x_1, x_2, x_n) = a_1x_1 + a_2x_2 + \ldots + a_nx_n + b$$

$$\text{Subject to:} \begin{cases} x_1 < A \\ x_2 > B \\ \ldots \\ x_n = N \end{cases}$$

The present models were constructed to minimize the deviation in food intake amounts between the observed diets and the recommended food plans while simultaneously meeting the required dietary standards embodied in the WCRF/AICR guidelines.

Four gender-specific food plans were developed with 2 optimization models. The first model's food plan was designed to conform to recommendations 3–5 and 7 of the WCRF/AICR report. The second model's food plan was designed only to satisfy recommendation number 8, that nutritional needs should be met through diet alone. All linear programming models and statistical analyses were performed using the Operational Research Package of SAS software (release version 9.1, SAS Institute).

Objective function. The chosen objective function ensured that the optimal food plans were those that showed the least departure from the observed amounts of foods consumed by the referent population. The objective function was defined as the sum of the absolute values of differences between each food quantity in the observed diet and the quantity of that food selected in the optimized diet divided by the observed quantity consumed (to standardize the difference across foods):

$$Y = \sum_{i=1}^{i=152} \left| \frac{(Q_i^{obs} - Q_i^{opt})}{Q_i^{obs}} \right|,$$

where Y is the objective function to minimize, Q_i^{obs} is the observed intake of food i, and Q_i^{opt} its optimized intake.

Because of the absolute value, Y was nonlinear. To apply linear programming, Y was transformed into a linear function using the goal programming approach of Anderson and Earle (36). New decision variables ≥0 and representing the positive (P_1 to P_{152}) and negative (N_1 to N_{152}) deviation from observed food quantity were created and defined as follows:

$$\text{If } Q_i^{opt} < Q_i^{obs}, \text{ then } N_i = \frac{Q_i^{obs} - Q_i^{opt}}{Q_i^{obs}} \text{ and } P_i = 0.$$

$$\text{If } Q_i^{opt} > Q_i^{obs}, \text{ then } N_i = 0 \text{ and } P_i = \frac{Q_i^{opt} - Q_i^{obs}}{Q_i^{obs}}.$$

$$\text{If } Q_i^{opt} = Q_i^{obs}, \text{ then } P_i = 0 \text{ and } N_i = 0.$$

$$\text{Subject to: } P_i - N_i = \frac{Q_i^{opt} - Q_i^{obs}}{Q_i^{obs}}.$$

The new linear function called Y' was expressed as the sum of deviational variables and was minimized:

$$Y' = \sum_{i=1}^{i=152} P_i + N_i.$$

Each food item in the objective function was linked to the nutrient composition and cost databases. The model calculated food intakes and diet costs at all times and checked whether the food and nutrient constraints were fulfilled. If not, the model changed the quantity for 1 or more foods to come closer to the constraints while minimizing the gap between the observed diets and optimized food plans. The observed intakes were based on the mean population consumption for that food item.

Energy and consumption constraints. Optimal food plans were selected subject to several constraints (**Table 2**). First, the food plans were isocaloric with the observed diets, whereas the weight of the foods was allowed to find its own level. Second, gender-specific consumption constraints were placed on food groups and subgroups and on each food.

Optimized consumption for the 9 food groups was flanked by the 5th and 90th percentiles of the observed consumption by gender. Upper bounds for the 25 food subgroups and 152 foods were set by the 90th percentile of observed consumption by gender. These constraints for groups and subgroups were much more stringent than the USDA Thrifty Food Plan, which permits a 10-fold increase from the mean population consumption and includes those foods whose consumption by the population is close to zero (20) (Table 1). Under the present system, if a given food was not consumed by the referent population, it was not included in the optimized food plan.

Model 1: dietary guidelines for cancer prevention. Model 1 created optimal food plans with mean dietary energy density of 1.25 kcal/g (recommendation no. 3) and containing ≥600 g/d of nonstarchy vegetables and fruits (no. 4), ≤300 g/wk of red meat (other than poultry) (no. 5), ≥25 g/d of fiber (no. 4), and ≤2 g/d of sodium (no. 7).

Model 2: nutritional adequacy achieved by diet alone (recommendation no. 8). Model 2 created optimal food plans that complied with the recommended intake ranges for macronutrients, vitamins, and minerals as issued by the Institute of Medicine Food and Nutrition Board (37). Recommended dietary allowances (RDA) and adequate intake (AI) as well as tolerable upper limits (UL) were used to create acceptable nutrient ranges for 28 macro- and micronutrients separately for women and men. Every nutrient in the optimized food plan had to fall between the RDA (or AI) and the UL, if defined. The same threshold criteria were applied to linoleic and α-linolenic acids. The 30- to 50-y age group values were used for RDA and AI, because this age range was the most represented. For other macronutrients, recommendations were expressed as a percentage of energy intake.

TABLE 2 Summary of constraints used in optimization models

Constraints[1] and name	Value	Unit/d	Models[2]
Consumption			
Energy	=[4]	*Observed intakes*	1 and 2
Groups	≥5th percentile		
Groups	≤90th percentile		
Subgroups	≤90th percentile		
Items	≤90th percentile		
AICR dietary guidelines			
Energy density	=1.25	*kcal/g*[3]	1
Fruits and nonstarchy vegetables	≥600	*g*	
Red meat (My Pyramid Meats subgroup used)	≤300	*g*	
Fiber	≥25	*g*	
Sodium	≤2	*g*	
Macronutrient recommendations (DRI)			
Proteins	≥10 and ≤35	*Percentage of energy intakes*	2
Total fats	≥20 and ≤35		
Carbohydrates	≥45 and ≤65		
Added sugars	≤25		
Micronutrients recommendations (DRI)			
Linoleic acid, α-linolenic acid, fibers, vitamin C, thiamin, riboflavin, folate, vitamin B-12, vitamin A, retinol, vitamin E, vitamin D, niacin, pantothenic acid, vitamin B-6, calcium, iron, potassium, zinc, phosphorus, magnesium, copper, selenium, sodium, manganese	≥RDA (or AI) ≤UL (when defined)	*g, mg, or μg*	2

[1] Nutritional constraints come from the DRI of the Institute of Medicine.
[2] Model 1 is based on WCRF/AICR recommendations 3–5 and 7. Model 2 is based on recommendation 8.
[3] 1 kcal = 4.18 kJ.
[4] Observed diets and food plans are isoenergetic.

Quality of observed diets and optimized food plans. The nutrient quality of the observed diets and optimized food plans was independently measured using the mean adequacy ratio (MAR) (38,39). MAR values were calculated for 15 nutrients (12 micronutrients, total dietary fibers, linoleic acid, and α-linolenic acid) as follows:

$$MAR = \frac{\sum_{i=1}^{15} ratio_i}{15} \cdot 100,$$

where, for nutrient i:

$$ratio_i = \begin{cases} \frac{\text{intake}_i}{\text{RDA}_i} & \text{if} \quad \text{intake}_i < \text{RDA}_i \\ 1 & \text{else} \end{cases}$$

The MAR value could be between 0 and 100%. Provided that a mathematical solution was feasible and obtained, the target MAR values for Model 2 would by definition be 100%.

Results

Characteristics of the referent population. Mean age was 42.2 y for women and 38.0 y for men (age range: 25–65 y). Most men (92%) and women (85%) had completed a bachelor's degree or higher. A majority of women (60%) and one- half of the men (50%) had annual household incomes of ≥$55,000. The sample was largely Caucasian (84% men, 82% women), with a minority of respondents identifying themselves as Asian or Pacific Islander (6.8% men, 12% women) and African American (3.4% men, 4% women).

Total daily energy intakes, including beverages, were 2062 kcal for men and 1755 kcal for women. After excluding all beverages, mean energy intakes were 1806 kcal/d for men and 1543 kcal/d for women. Dietary energy density calculated for foods only was 1.48 kcal/g (6.2 MJ/kg) for men and 1.35 kcal/g (5.6 MJ/kg) for women (31,40). Overall MAR scores were 93.5% for men and 94.0% for women. Observed patterns of energy and nutrient intakes that served as inputs for the objective function are summarized in **Tables 3** and **4**.

The observed diet cost ($/d) was higher for men ($7.58/d) than for women ($6.95/d), reflecting the fact that men ate more food than women. However, the difference reversed after adjusting for energy. Energy costs per 2000 kcal were higher for women ($7.92) than for men ($7.35).

Diet optimization procedures. The 2 optimization models were always able to find a mathematical solution that respected all the boundaries and constraints. The cancer-preventive food plans so developed were then inspected for their composition, food weight, energy density, and cost.

Model 1: dietary recommendations. Conforming to the recommendations, Model 1 increased the amounts of whole fruits considerably for both women and men. The ceiling was imposed by the 90th percentile consumption constraint. The amounts of nonstarchy vegetables in the optimized food plans were slightly modified by increasing dark green vegetables for men and by reducing "other" vegetables for women.

The consumption of red meat by this group was already within the cancer prevention guidelines; however, amounts of salty luncheon meats were reduced in the food plan to conform to the sodium constraint. Another consequence of imposing a limit on sodium was a reduction in the amount of cheese in the optimized food plans for both men and women.

Model 1 provided mathematical proof that limiting the amount of red meat and cheese together with increasing the amount of fruits were the principal means of reducing the energy density of the diet. The food plans also placed a limit on the amounts of refined, but not whole, grains. The food plans were also more bulky than the observed diets: for the same energy intakes, the weight of foods increased by 6% for women and by 25% for men.

The overall quality of the optimized food plan, as indexed by MAR scores, was no better than the existing diet of this particular participant sample. The optimized Model 1 food plan was associated with only a 2–4% increase in cost.

Model 2: nutritional adequacy achieved by diet alone. Meeting the goals of Model 2 was more difficult and the optimized food plans had a much greater departure from the observed consumption. To meet all nutrient requirements while keeping dietary energy constant, the weight of the diet had to be increased by 51% for women and 23% for men. Energy density was allowed to find its own level; it was as little as 1.0 kcal/g for women and 1.3 kcal/g for men (Table 3). Energy-adjusted diet costs were only 2% higher for men but 15% higher for women.

The limiting nutrients for men were fiber, potassium, and linoleic and α-linolenic acids (Table 4). Potassium, vitamin E, and linoleic acid were the limiting nutrients for women. With sodium intake kept low, the recommended intake values for the limiting nutrients could be achieved only by providing excessive amounts of the easier-to-obtain vitamins and minerals well above 100% RDA. The resulting food plan was more bulky,

TABLE 3 Observed diets and optimized food plans yielded by models 1 and 2

	Men, *n* = 60			Women, *n* = 101		
Diet	Observed	Model 1[1,2]	Model 2[1]	Observed	Model 1[1,2]	Model 2[1]
Total energy, *kcal/d*	2062	2062	2062	1755	1755	1755
Total weight, *g/d*	1726	2163	2119	1552	1650	2342
Total weight, % deviation from observed		*25.3*	*22.8*		*6.32*	*50.9*
Energy density, *kcal/g*	1.48	1.25	1.30	1.35	1.25	1.01
Energy density, % deviation from observed		−15.7	−12.3		−7.69	−25.7
MAR, *%/d*	93.5	93.5	100	94.0	95.3	100
Diet cost, *$/d*	7.58	7.87	7.76	6.95	7.11	8.03
Dietary energy cost, *$/2000 kcal*	7.35	7.64	7.53	7.92	8.10	9.15
Dietary energy cost, *% deviation from observed*		3.83	2.39		2.29	15.54

[1] Model 1 is based on WCRF/AICR recommendations 3–5 and 7. Model 2 is based on recommendation 8.

[2] WCRF/AICR recommendations for model 1 are: energy density equal to 1.25 kcal/g, whole fruit and vegetable intakes ⩾ 600 g/d, red meat intakes ⩽ 300 g/wk, fiber intake ⩾ 25 g/d, and sodium intake ⩽ 2 g/d.

TABLE 4 Observed diets and optimized food plans expressed in percentage of nutrient recommendations

	Men, n = 60			Women, n = 101		
Diet	Observed	Model 1[1,2]	Model 2[1]	Observed	Model 1[1,2]	Model 2[1]
Thiamin, *% RDA*	184	170	229	154	149	195
Riboflavin, *% RDA*	204	208	256	204	206	302
Total folate, *% RDA*	147	149	228	118	117	165
Vitamin B-6, *% RDA*	209	238	365	171	191	277
Vitamin C, *% RDA*	167	261	298	182	220	341
Vitamin D, *% AI*	144	183	219	121	119	227
Vitamin E, *% RDA*	93.6	94.3	140	75.8	75.6	100
Calcium, *% AI*	125	156	155	109	107	182
Iron, *% RDA*	248	231	338	86.3	84.0	106
Magnesium, *% RDA*	89.6	94.7	122	102	108	153
Potassium, *% AI*	67.3	83.8	100	62.1	69.9	100
Zinc, *% RDA*	129	123	184	149	144	200
Sodium, *% UL*	132	87.0[4]	100	107	87.0[4]	96.0
Linoleic acid, *% AI*	91.4	81.0	100	111	101	100
α-Linolenic acid, *% AI*	97.0	82.2	100	124	106	116
Total dietary fiber, *% AI*	64.1	67.3[5]	100	86.2	100[5]	110
Total SFA[3]	4.8	3.9	3.7	4.9	4.4	3.3
Added sugars[3]	11.0	14.7	10.3	11.3	12.2	10.2

[1] Model 1 is based on WCRF/AICR recommendations 3–5 and 7. Model 2 is based on recommendation 8.
[2] WCRF/AICR recommendations for model 1 are: energy density equal to 1.25 kcal/g, whole fruit and vegetable intakes ⩾ 600 g/d, red meat intakes ⩽ 300 g/wk, fiber intake ⩾ 25 g/d, and sodium intake ⩽ 2 g/d.
[3] Intakes expressed in percentage of the energy intake for added sugars and SFA (not included as constraints in the nutrient optimization model).
[4] Corresponds to the 2-g/d limit of the AICR.
[5] Corresponds to the 25-g/d AICR recommendation.

more costly for women, and provided some nutrients in excessive amounts.

Composition of food plans by food groups. The composition of the observed gender-specific diets in MyPyramid food groups are shown in the figures. The figures also show the composition of alternative food plans generated by Models 1 and 2. Whenever a given MyPyramid food group or subgroup reached the upper bound (90th percentile of observed intake), that was indicated by the symbol "m" for maximum at either the food group total or at the upper margin of the food subgroup.

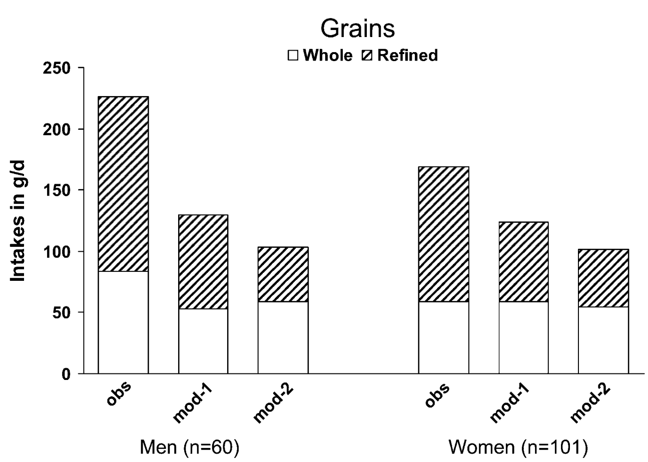

FIGURE 1 Observed and optimized amounts for grains (g/d), shown separately for men and women. obs, observed intakes; mod 1, optimization model 1; mod 2, optimization model 2.

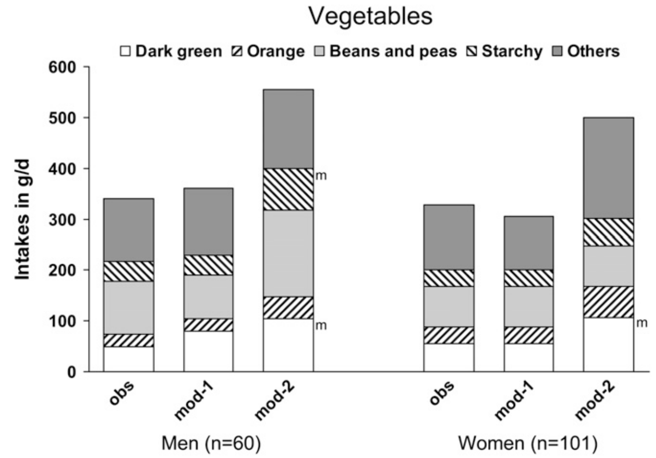

FIGURE 2 Observed and optimized amounts for vegetables (g/d), shown separately for men and women. obs, observed intakes; mod 1, optimization model 1; mod 2, optimization model 2. The m symbol indicates that the 90th percentile upper constraint is reached for the subgroup (inside the bar) or the group (above the bar).

Food plans were lower in refined grains than the observed diets (**Fig. 1**). Model 1 food plans increased in men the amounts of dark green and other vegetables in the diet, such as tomatoes, zucchini, cabbage, cauliflower, mushrooms, eggplant, asparagus, cucumber, and vegetable juices (**Fig. 2**). Model 2 increased the proportion of all vegetable subgroups, with the dark green vegetables reaching the upper limit in both genders. Starchy vegetables reached the maximum allowable limit in men.

The model 1 food plan increased the amount of whole fruit for both women and men (**Fig. 3**). Model 2 fully doubled the amount of fruit, with the result that both women and men reached the upper boundary for fruit. The 90th percentile constraint was reached for whole fruits in men and for fruit juices in women.

The model 1 food plan lowered the amount of cheese for both men and women (**Fig. 4**). The model 2 food plan greatly increased the amount of milk for both men and women but reduced the amount of cheese. Women in model 2 reached the upper boundary for milk and for the whole dairy group.

FIGURE 3 Observed and optimized amounts for fruits (g/d), shown separately for men and women. obs, observed intakes; mod 1, optimization model 1; mod 2, optimization model 2. The m symbol indicates that the 90th percentile upper constraint is reached for the subgroup (inside the bar) or the group (above the bar).

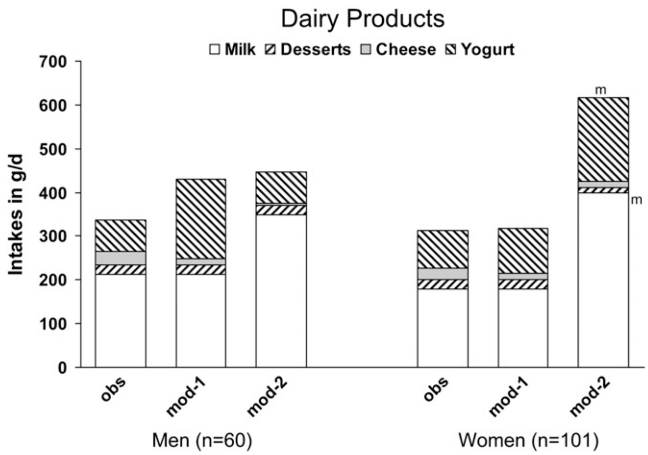

FIGURE 4 Observed and optimized amounts for dairy products (g/d), shown separately for men and women. obs, observed intakes; mod 1, optimization model 1; mod 2, optimization model 2. The m symbol indicates that the 90th percentile upper constraint is reached for the subgroup (inside the bar) or the group (above the bar).

The meat category included beef, pork, veal, lamb, game, and organ meats. Model 1 reduced meat consumption by decreasing the amount of luncheon meats (**Fig. 5**). Model 2 led to an elimination of eggs in the diets of both men and women, more nuts, and lower amounts of meats in the diets of men.

Overall, the optimized food plans led to a reduction in the amount of refined grains and an increase in the amount of vegetables, notably starchy and dark green vegetables. Stringent consumption constraints, based on the eating habits of the referent population, prevented the food plans from becoming unrealistic and nonfeasible. For dark green vegetables, the upper boundary was soon reached in both men and women, reflecting the fact that their consumption by this sample was low. The upper boundary was also reached for the amount of fruit allowed in the diet by the model. Another major dietary shift involved a sharp increase in the amount of dairy products, mostly fluid milk and yogurt, partly at the expense of cheese.

Discussion

Putting dietary recommendations into practice poses a number of challenges. Dietary strategies for health promotion need to

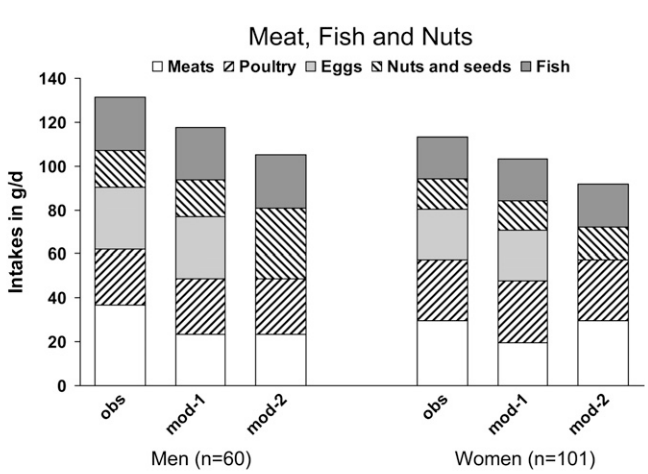

FIGURE 5 Observed and optimized amounts for meats, fish, and nuts (g/d), shown separately for men and women. obs, observed intakes; mod 1, optimization model 1; mod 2, optimization model 2.

take into account population eating habits, food prices, and diet costs. First, the recommended diets cannot deviate too much from the consumption patterns of the referent population. Consumers reject foods that are alien, unfamiliar, and outside the accepted social norms. Recommendations that require population-wide 10-fold increases in food consumption may not be feasible, as suggested by behavioral research (41). Second, food prices and diet costs, real or perceived, may be a barrier to dietary change (42,43). These issues need to be resolved if guidelines based on systematic reviews of the literature and issued by expert panels are to be translated for consumer use.

The application of mathematical diet optimization techniques to dietary guidance is, in itself, not new. The USDA has, for the past 30 y, used similar procedures to generate healthful meal plans at minimal cost. The Thrifty, Low-Cost, Moderate, and Liberal food plans show how a nutritious diet can be obtained with minimal or moderate resources (44,45). Those food plans were derived by minimizing the distance between current consumption patterns and optimized food plans while simultaneously meeting nutritional, consumption, and cost constraints.

The present models created the best obtainable food plans that met the key WCRF/AICR guidelines without departing too far from the observed diets of the study sample. Given that the observed diets were already low in red meat and had low energy density, the necessary adjustments were small. Model 1 food plans did not require major changes in dietary energy density, diet quality, diet composition, food choices, or even energy cost. The major dietary modification involved reducing refined grains and increasing the amount of whole fruit. In other words, the WCRF/AICR cancer preventive recommendations 3–5 and 7 were relatively easy to achieve by those people who already consumed a similar diet. It remains to be seen whether such diets are feasible when the optimization model starts from a sharply different socioeconomic baseline, e.g. the diets of low-income women or African-American men.

Translating the recommendation that all nutrients should be derived from the diet alone into a food plan was more problematic. To meet the requirements for limiting nutrients on a daily basis, other easier-to-find nutrients were provided in excess. Meeting potassium requirements was especially difficult for both women and men, as previously mentioned by Gao et al. (26) and by the USDA, who lowered its food plan constraint values for potassium and vitamin E (44,45). Model 2 was therefore forced to create food plans that provided many nutrients in excess. This could also be due in part to the high availability of fortified foods in the US. Indeed, starting from the mean diet consumed by French adults, similar diet optimization procedures never induced such excess in nutrient content of the optimized diets (25,46). The weight of the diet had to increase by 50% for women, whereas cost increased by 15% for women. The model 2 food plan doubled the amounts vegetables and fruit, sharply increased the amount of nuts, and increased the amounts of yogurt in the diets of women.

It is questionable whether such major shifts in food consumption at the population level are even feasible. Strategies for dietary change that require dramatic increases in the consumption of any food group would do well to conduct optimization analyses beforehand. There may be a range beyond which the weight and bulk of food that is required to reduce energy density (without drinks) may fall outside the acceptable norms. The best result obtained by the 5 A Day program was to increase fruit and vegetable consumption by one-half of 1 serving per day (41).

The present models took as the starting point the observed diets of the referent population, which was more highly educated and reported higher incomes than the U.S. median levels. Because the observed diets were already of high quality, the data are not generalizable beyond this particular group. However, the present method can be and should be applied to other population subgroups within the US that vary in their socioeconomic status. Applying this optimization technique to create food plans for low-income populations based on food consumption patterns in the NHANES data would assist in the formulation of the 2010 Dietary Guidelines for Americans. Furthermore, results obtained from model 2 showed that more consensus is needed on the application of dietary reference intakes (DRI) (47,48).

Mathematical modeling provides an elegant way to translate dietary recommendations into concrete food plans (44,45) and to develop food-based dietary guidelines (49,50). The models can be used to test the effect of guidelines on food plan composition, quality, volume, and cost. By starting from different consumption baselines by age, income, or gender, the models can help formally determine whether some dietary guidelines are even feasible for disadvantaged groups. For example, a cancer-preventive food plan for low-income groups whose baseline diets are poor may induce socially unacceptable changes in habitual dietary patterns and food intakes for these groups (23).

If no mathematical solution is possible, we need to modify the guidelines and search for alternative affordable but nutrient-rich foods. Linear programming can help tailor the 2010 Dietary Guidelines for Americans to the economic resources of different population groups in the US.

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