2012-11

Comparison of acrylamide intake from Western and guideline based diets using probabilistic techniques and linear programming

Katz, Josh M.

Elsevier

Food and Chemical Toxicology 50 (2012) 877–883

Contents lists available at SciVerse ScienceDirect

Food and Chemical Toxicology

journal homepage: www.elsevier.com/locate/foodchemtox

Comparison of acrylamide intake from Western and guideline based diets using probabilistic techniques and linear programming

Josh M. Katz [a], Carl K. Winter [a,*], Samuel E. Buttrey [b], James G. Fadel [c]

[a] University of California, Department of Food Science and Technology, One Shields Avenue, Davis, CA 95616, United States
[b] Naval Postgraduate School, Operations Research Department, Glasgow Hall 290, Monterey, CA 93943, United States
[c] University of California, Department of Animal Science, One Shields Avenue, Davis, CA 95616, United States

ARTICLE INFO

Article history:
Received 19 August 2011
Accepted 7 November 2011
Available online 15 November 2011

Keywords:
Acrylamide
Dietary guidelines
Linear programming
Dietary modeling

ABSTRACT

Western and guideline based diets were compared to determine if dietary improvements resulting from following dietary guidelines reduce acrylamide intake. Acrylamide forms in heat treated foods and is a human neurotoxin and animal carcinogen. Acrylamide intake from the Western diet was estimated with probabilistic techniques using teenage (13–19 years) National Health and Nutrition Examination Survey (NHANES) food consumption estimates combined with FDA data on the levels of acrylamide in a large number of foods. Guideline based diets were derived from NHANES data using linear programming techniques to comport to recommendations from the Dietary Guidelines for Americans, 2005. Whereas the guideline based diets were more properly balanced and rich in consumption of fruits, vegetables, and other dietary components than the Western diets, acrylamide intake (mean ± SE) was significantly greater ($P < 0.001$) from consumption of the guideline based diets (0.508 ± 0.003 μg/kg/day) than from consumption of the Western diets (0.441 ± 0.003 μg/kg/day). Guideline based diets contained less acrylamide contributed by French fries and potato chips than Western diets. Overall acrylamide intake, however, was higher in guideline based diets as a result of more frequent breakfast cereal intake. This is believed to be the first example of a risk assessment that combines probabilistic techniques with linear programming and results demonstrate that linear programming techniques can be used to model specific diets for the assessment of toxicological and nutritional dietary components.

1. Introduction

Acrylamide (prop-2-enamide, AA) is a versatile chemical used in a variety of industrial settings with roles such as an additive for water treatment, a soil conditioner, and in construction of dam foundations (Parzefall, 2008). For years, the primary health concern from AA involved occupational exposure to AA for those working in industrial, manufacturing, and laboratory settings. In 2002, however, Swedish researchers demonstrated that AA occurs widely in several common foods, with the highest levels frequently observed in fried and baked foods (Tareke et al., 2002). Subsequent research demonstrated that AA is formed in food from the condensation of the amino acid asparagine with reducing sugars when heated to temperatures above 120 °C (Friedman, 2003). According to the International Agency for Research on Cancer, AA is considered to be "probably carcinogenic to humans" due to findings from several animal carcinogenicity studies (IARC, 1999). It is also featured on California's Proposition 65 list of chemicals recognized by the state to cause cancer and reproductive toxicity (OEHHA, 2011). Studies have also shown that AA is neurotoxic in humans (Deng et al., 1993).

In the past decade, thousands of foods have been analyzed for AA content by US and foreign government agencies. The US Food and Drug Administration (FDA) has made its robust database of AA levels in foods available to the public, with data demonstrating that the highest levels of AA are typically found in French fries and in potato chips (FDA, 2011). Lower yet significant amounts of AA were also detected in foods such as baked breads, coffee, and breakfast cereals. Potential human dietary AA intake in the general population has been estimated to range from 0.4 to 0.61 μg/kg/day (Doerge et al., 2008; Mills et al., 2008), while the mean intake estimate for children ages 3–12 is 0.86 μg/kg/day (Tran et al., 2010). The US Environmental Protection Agency has set a chronic reference dose for AA at 2 μg/kg/day (EPA, 2011).

The FDA has yet to establish regulatory limits for AA, and does not recommend that consumers avoid foods that have been fried, roasted, or baked. In addressing AA in foods, FDA further

Abbreviations: NHANES, National Health and Nutrition Examination Survey; FDA, US Food and Drug Administration; AA, acrylamide; DGA, Dietary Guidelines for Americans, 2005; MPED, MyPyramid Equivalents Database 2.0; FNDDS, Food and Nutrient Database for Dietary Studies 2.0.

* Corresponding author. Tel.: +1 530 752 5448; fax: +1 530 752 4759.
E-mail address: ckwinter@ucdavis.edu (C.K. Winter).

0278-6915/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.fct.2011.11.006

recommends that "*consumers adopt a healthy eating plan, consistent with the Dietary Guidelines for Americans, that emphasizes fruits, vegetables, whole grains, and fat-free or low-fat milk and milk products; includes lean meats, poultry, fish, beans, eggs, and nuts; and is low in saturated fats, trans fats, cholesterol, salt (sodium) and added sugars*" (FDA, 2009).

Since AA levels tend to be the highest in foods with added fats such as potato chips and French fries, it seems reasonable that consumers following the Dietary Guidelines for Americans, 2005 (DGA) might expect to reduce their AA intake by reducing their consumption of such high-fat foods. Such a conclusion is speculative, however, since the reduction in consumption of some foods high in AA might be compensated by large increases in consumption of other foods that also may contain AA.

Prior AA risk assessments (Konings et al., 2003; Matthys et al., 2005; Mojska et al., 2010) estimated AA intake from the consumption of typical diets. This study estimates AA intake from the consumption of typical diets, specifically Western teenage diets (ages 13–19), and compares these intake estimates to intake estimates obtained by modeling the DGA. Teenagers were selected due to their relatively high consumption of French fries and potato chips compared with the general population (Lin et al., 2001).

The generation of AA intake estimates from Western diets follows a data-intensive, yet fairly standard method by which consumption probabilities for specific food items and probabilities of AA levels in the food items are combined using thousands of iterations to yield probabilities of daily individual AA intake. The generation of intake estimates modeling the DGA is much more challenging. Methods must enable the selection of the types and quantities of foods that typically comprise the American diet while also comporting to the DGA recommended quantities for foods and food components such as fruits, vegetables, grains, whole grains, lean meat and beans, milk, fiber, sodium, added fats, and added sugar. In recognition of this challenge, a linear programming approach was developed to model the DGA by screening reported food consumption behavior with an objective function which is subject to a set of dietary constraints. Applications of linear programming for nutritional studies are more fully described (Briend et al., 2003).

2. Materials and methods

The approaches used to determine AA and dietary component intakes from consumption of Western and guideline based diets are depicted (Fig. 1). Western diets reported by teenagers were extracted from a federal food consumption database (A), and guideline based diets were developed from the same food consumption database using linear programming to comport Western diets to DGA (B). A nutritional comparison between the Western, guideline based, and government dietary guidelines was performed (C). Food portions were combined with AA levels to generate AA Intake Events (D) which were sampled and combined with body weight estimates to allow development of probabilistic daily intake estimates of AA (E). The R Programming Language and Environment for Statistical Computing (R version 2.11.1, <http://cran.r-project.org>/) was used for all computational tasks in this study. Details of each step follow.

2.1. Input data for linear programming and Western diet models (Fig. 1, A)

Western and guideline based diets were modeled from day one of teenage diets reported in the National Health and Nutrition Examination Survey (NHANES) (NHANES, 2003–2004). The survey uses a national probability sample of the civilian population, and includes a comprehensive 24-h dietary recall and medical examination. A total of 1899 dietary records from teenage males and females (ages 13–19) were used after the exclusion of three diets: one diet was incomplete, the second diet was reported as light beer, and the third diet was reported as fruit punch.

A total of 1944 reported food types were considered; coffee, tea, drinking water, and alcohol were not included since these beverages are not well reported in surveys and contain little energy and nutrient density (Maillot et al., 2010). Quantities were aggregated for the same food type consumed at different eating events, such as lunch and dinner.

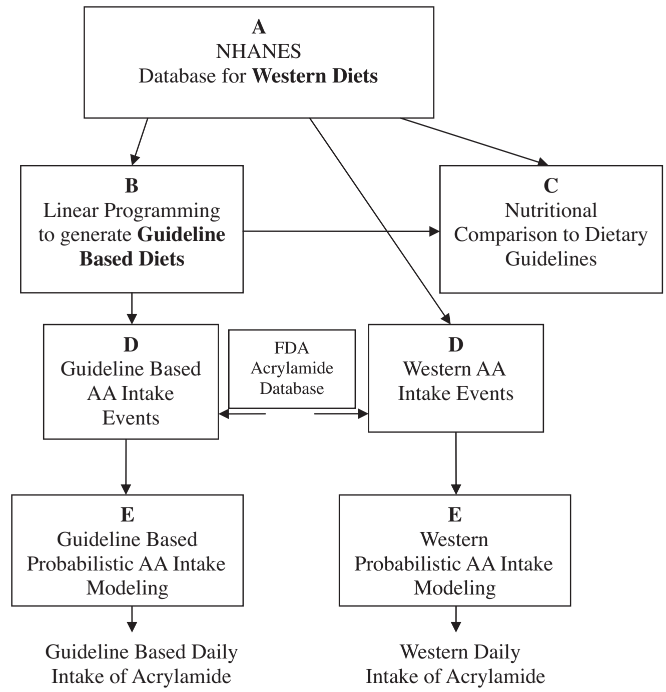

Fig. 1. Flow chart for the modeling of Western and guideline based diets to estimate nutritional adequacy and acrylamide (AA) intake.

2.2. Linear programming to develop guideline based diets (Fig. 1, B)

A total of 1899 guideline based diets were constructed from the 1899 teen dietary records (step A, Fig. 1) using the linear programming package lpSolve. The lpSolve software is open source optimization software that provides solutions for high-level linear problems (Buttrey, 2005).

Six linear programming equations were used in the development of the guideline based diets (Table 1). Eq. (1) describes the objective function which was employed to match the reported food quantities for the *i*th individual, if possible, prior to selecting quantities of non-repertoire foods: where F_i, which was minimized, is the sum of the absolute deviations between the optimal food quantity (g) and the reported food quantity (g) normalized by the reported food quantity plus the sum of a weighting factor times the optimal food quantity, for the *i*th individual, *i* is from 1 to 1899; $j \in R_i$ are the reported food types that were in the repertoire of the *i*th individual, indexed with *j* from 1 to 1944; $j \notin R_i$ are the reported food types that were not in the repertoire of the *i*th individual; abs() is absolute value of the expression in (); Q_{ij}^{opt} is the decision variable that represents the quantity (g) of the *j*th food, for the *i*th individual; Q_{ij}^{obs} is the reported quantity (g) of the *j*th food consumed by the *i*th individual. The weighting factor w_j is used to select the most popular foods reported: $w_j = (1 + 1/NC_j)/Q_j^{med}$, NC_j is the number of individuals consuming the *j*th food, Q_j^{med} is the median quantity (g) of the *j*th food consumed.

Because of the presence of the absolute value function, F_i is nonlinear. To employ linear programming, F_i was transformed to a linear function. Eqs. (2 and 3) describe the transformation, where O_{ij} and U_{ij} are non-negative decision variables for the *i*th individual and *j*th food. If $Q_{ij}^{opt} = Q_{ij}^{obs}$, O_{ij} and U_{ij} values are 0; if $Q_{ij}^{opt} > Q_{ij}^{obs}$, U_{ij} is 0 and O_{ij} is a positive number such that the left hand side (LHS) of Eq. (3) is 1; if $Q_{ij}^{opt} < Q_{ij}^{obs}$, O_{ij} is 0 and U_{ij} is a positive number such that the LHS of Eq. (3) is 1. Eq. (2) allows Eq. (1) to be expressed as a simple linear function with the constraint from Eq. (3).

Three constraints, nutritional, energy, and social acceptability (Eqs. 4–6), were used to comport each diet to recommendations from the DGA and to limit food quantities to the maximum quantities observed in NHANES. DGA contains diet and exercise recommendations for reducing risk of major chronic diseases and for optimizing health (DGA, 2005). A total of 11 nutritional constraints were used for each of the 1899 individuals. Eq. (4) describes the nutritional constraints, where Z_{jk} is the content of the *k*th nutritional constraint (units/g), *k* is from 1 to 11 as described (Table 2), for the *j*th food, *j* is from 1 to 1944, all values for Z_{jk} were obtained from the MyPyramid Equivalents Database 2.0 (MPED) (MPED, 2010) and the Food and Nutrient Database for Dietary Studies 2.0 (FNDDS) (FNDDS, 2010); Q_{ij}^{opt} is the decision variable representing the amount of the *j*th food (g) for the *i*th individual, *i* is from 1 to 1899; RHS_{ik} is the *k*th nutritional constraint value modulated by the *i*th individual's daily energy level as described (Table 2); and ($\leqslant \geqslant$) is either $\leqslant$ or $\geqslant$ as described (Table 2), for the *i*th individual.

Table 1
Description of linear programming equations to develop guideline based diets.

Equation number	Description	Equation	Indices	Number of equations per individual	Number of equations generated
1	Objective function[a]	$MinF_i = \sum_{j\in R_i} abs\left(\frac{Q_{ij}^{opt}-Q_{ij}^{obs}}{Q_{ijobs}}\right) + \sum_{j\notin R_i} w_j Q_{ij}^{opt}$	i = 1–1899, j = 1–1944	Eq. (2)	Eq. (2)
2	Adjusted objective function (linked to linear transformation constraints)[a]	$MinF_i = \sum_{j\in R_i}(O_{ij}+U_{ij}) + \sum_{j\notin R_i} w_j Q_{ij}^{opt}$	i = 1–1899, j = 1–1944	1	1899
3	Linear transformation constraints[a]	$\frac{Q_{ij}^{opt}}{Q_{ij}^{obs}} - O_{ij} + U_{ij} = 1$	i = 1–1899, j = 1–1944	R_i	$\sum_{i=1}^{1899} R_i$
4	Nutritional constraints[b]	$\sum_{j=1}^{n} Z_{jk} Q_{ij}^{opt} \{\leqslant\geqslant\} RHS_{ik}$	i = 1–1899, j = 1–1944 , k = 1–11	11	20,899
5	Energy constraints[b]	$\sum_{j=1}^{n} E_j Q_{ij}^{opt} \geqslant D_i$	i = 1–1899, j = 1–1944	1	1899
6	Social acceptability constraints[b]	$E_j Q_{ij}^{opt} \leqslant Max\{E_j Q_{ij}^{obs}\}$	i = 1–1899, j = 1–1944	1944	3,691,656

[a] Objective function variables are defined as: F_i is the objective function for the ith individual; j is each reported food type; R_i is all j food types in the reported repertoire of the ith individual; abs() is absolute value of the expression in (); Q_{ij}^{opt} is the decision variable that represents the quantity (g) of the jth food, for the ith individual; Q_{ij}^{obs} is the reported quantity (g) of the jth food consumed by the ith individual; $w_j = (1 + 1/NC_j)/Q_j^{med}$, NC_j is the number of individuals consuming the jth food, Q_j^{med} is the median quantity (g) of the jth food consumed; O_{ij} and U_{ij} are non-negative decision variables for the ith individual and jth food.
[b] Constraint variables are defined as: Z_{jk} is the content of the kth nutritional constraint (units/g) as described (Table 2) for the jth food; RHS_{ik} is the kth nutritional constraint value modulated by the ith individual's daily energy level as described (Table 2); E_j is the energy density of jth food type (kcal/g); D_i is the daily energy level (kcal) for the ith individual created by sampling with replacement from 1087 reported daily energy levels that conformed to the DGA recommended range (1600–3200 kcal/day)(DGA, 2005); 1 kcal = 4.18 kJ.

Table 2
Nutritional constraints to comport Western diets to guideline based diets.

Nutritional constraints[a]								
Energy level[b], kcal/day	1600	1800	2000	2200	2400	2600	2800	3000
Fruits[c], cups/day	⩾1.5	⩾1.5	⩾2.0	⩾2.0	⩾2.0	⩾2.0	⩾2.5	⩾2.5
Vegetables[c], cups/day	⩾2.0	⩾2.5	⩾2.5	⩾3.0	⩾3.0	⩾3.5	⩾3.5	⩾4.0
Total grains[c], oz-eq/day	⩾5.0	⩾6.0	⩾6.0	⩾7.0	⩾8.0	⩾9.0	⩾10.0	⩾10.0
Whole grains[c], oz-eq/day	⩾2.5	⩾3.0	⩾3.0	⩾3.5	⩾4.0	⩾4.5	⩾5.0	⩾5.0
Lean meat and beans[c], oz-eq/day	⩾5.0	⩾5.0	⩾5.5	⩾6.0	⩾6.5	⩾6.5	⩾7.0	⩾7.0
Milk[c], cups/day	⩾3.0	⩾3.0	⩾3.0	⩾3.0	⩾3.0	⩾3.0	⩾3.0	⩾3.0
Fiber[d], g/day	⩾22.4	⩾25.2	⩾28	⩾30.8	⩾33.6	⩾36.4	⩾39.2	⩾42
Sodium[d], g/day	⩽2.3	⩽2.3	⩽2.3	⩽2.3	⩽2.3	⩽2.3	⩽2.3	⩽2.3
Added fat[e] (oil), g/day	⩽22	⩽24	⩽27	⩽29	⩽31	⩽34	⩽36	⩽44
Added fat[e] (solid), g/day	⩽11	⩽15	⩽18	⩽19	⩽22	⩽24	⩽24	⩽29
Added sugar[f], tsp-eq/day	⩽3.0	⩽5.0	⩽8.0	⩽9.0	⩽12	⩽14	⩽15	⩽18

[a] Suggested amounts, from the Dietary Guidelines for Americans, 2005 (DGA, 2005), of each constraint per day according to energy level.
[b] 1 kcal = 4.18 kJ.
[c] Quantity is calculated according to the nutrient-dense food form (e.g. lean meat and fat-free milk); oz-eq defined as ounce-equivalent. For example, 1 oz-eq for the lean meat and beans category equals 1 oz. meat, poultry, or fish; 1 egg; ¼ cup dry beans or tofu; 1 tbsp peanut butter; ½ oz. nuts or seeds.
[d] Quantity of individual nutrient; DGA suggested fiber content is 14 g/1000 kcal.
[e] Quantity of fat present in amounts above the lowest available fat level, such as fat-free milk and skinless chicken.
[f] Amount of sugar used as ingredients in prepared and processed foods, not including naturally occurring in fruits and milk.

A total of 1899 daily energy constraints were developed in order to match the reported daily energy levels. Eq. (5) (Table 1) describes the energy constraints, where E_j is the energy density of jth food type (kcal/g), j is from 1 to 1944; Q_{ij}^{opt} is the decision variable that represents the quantity (g) of the jth food for the ith individual, i is from 1 to 1899; D_i is the daily energy level (kcal) for the ith individual that was sampled with replacement from 1087 reported daily energy levels that conformed to the DGA recommended range (1600–3200 kcal/day); this range represents the daily energy level recommended from the most sedentary to the most active teen (DGA, 2005).

A total of 1944 social acceptability constraints forced food quantities to a level at or below the maximum reported quantity. Eq. (6) describes the social acceptability constraints, where E_j is the energy density of the jth food type (kcal/g), j is from 1 to 1944; Q_{ij}^{opt} is the decision variable that represents the quantity (g) of the jth food for the ith individual, i is from 1 to 1899; and Max$\{E_jQ_{ij}^{obs}\}$ is the maximum intake (kcal) of the jth food type as reported by the 1899 teens.

2.3. Nutritional comparison between Western diets, guideline based diets, and dietary guideline recommendations (Fig. 1, C)

A total of 11 nutritional categories described as nutritional constraints (Table 2) were used to compare the nutritional adequacy of Western and guideline based diets. To account for each diet's contribution to the 11 nutritional categories, the MPED and the FNDDS were employed. For each reported NHANES food type, MPED contains estimates for the amounts of fruit, vegetables, grains, whole grains, lean meat and beans, milk, added fats (oil), added fats (solid), and added sugar. For each reported NHANES food type, FNDDS contains estimates for the amounts (g/100 g) of food components, such as fiber and sodium used in this study. Estimates obtained from MPED and FNDDS (constraint estimate/100 g) were multiplied by the food consumption (g) for each of the 1899 Western and guideline based diets. A median intake for the individual quantity of each of the 11 nutritional categories was calculated for both the Western and guideline based diets.

2.4. AA intake events for Western and guideline based diets (Fig. 1, D)

To estimate AA intake from each diet, 270 food types from the Western diet (step A, Fig. 1) and 238 food types from guideline based diet (step B, Fig. 1) were distributed into 17 consumption groups (Table 3). The 17 consumption groups were the greatest contributors of AA intake from the US diet in a dietary exposure assessment by the FDA (2006) and were reduced from 20 original groups: coffee was not used as previously discussed, restaurant style and baked French fries were aggregated into one group as differences in quantity consumed and AA levels were minimal, and chile con carne was omitted as AA levels were not available.

Attribute columns are presented for each of the 17 consumption groups for the Western and guideline based diets (Table 3). The Types column represents the number of food types for each consumption group. For example, 12 different types of French fries were consumed, which differed in how they were prepared (deep fried,

Table 3
Consumption and acrylamide (AA) data for development of acrylamide Intake Events.

Consumption groups[a]	Western diet				Guideline based diet			
	Types[b]	Eating Events[c]	Sampling Events[d]	AA Intake Events[e]	Types[b]	Eating Events[c]	Sampling Events[d]	AA Intake Events[e]
Bagels	4	62	5	310	4	135	5	675
Breaded chicken	2	155	3	465	2	124	3	372
Breakfast cereal	68	463	60	27,780	62	1807	60	108,420
Cookies	48	403	32	12,896	39	219	32	7008
Corn snacks	9	445	12	5340	9	424	12	5008
Crackers	25	178	44	7832	24	153	44	6732
French fries	12	496	67	33,232	11	398	67	26,666
Olives	2	16	26	416	2	14	26	364
Peanut butter	2	79	5	395	2	76	5	380
Pies and cakes	19	45	12	540	7	12	12	144
Pizza	15	363	2	726	12	204	2	408
Popcorn	5	113	3	339	5	107	3	321
Potato chips	8	297	65	19,305	8	287	65	18,655
Pretzels	3	71	9	639	3	64	9	576
Soft bread	37	888	55	48,840	37	1009	55	55,495
Soup mix	1	81	4	324	1	48	4	192
Toast	10	87	3	261	10	84	3	252

[a] Consumption groups used in 2006 FDA study (FDA, 2006).
[b] Number of food types used to represent each consumption group.
[c] The number of individuals that consumed a quantity from each consumption group.
[d] The number of FDA AA samples taken for each consumption group.
[e] The number of combinations (Eating Events × Sampling Events) for each consumption group.

oven baked, breaded, etc.) or which other foods (peppers, onions, cheese, etc.) they were prepared with. Eating Events represent the number of individuals that consumed a quantity from a specific consumption group. For example, among the 1899 individual dietary records for 13–19 year old teenagers, 496 from the Western diet reported French fry consumption. The Sampling Events column represents the number of FDA samples from each food consumption group that was analyzed for AA levels by the FDA during 2002–2004 (FDA, 2011). All AA food samples that were considered to be non-detections were assigned a value of zero. The AA Intake Events column reflects the product of Eating Events and Sampling Events and represents all possible combinations (determined by multiplying consumption amounts and AA levels) for each consumption group.

2.5. Probabilistic AA intake modeling for Western and guideline based diets (Fig. 1, E)

Daily AA intake was estimated for 2000 simulated individuals (replicate runs of individuals were increased until a <0.5% change in mean and SE was yielded) representing US teenagers (male and female). Each individual was assigned a static body weight sampled with replacement from the NHANES data for teenagers (ages 13–19).

Each individual's daily AA intake from the consumption of the Western or guideline based diet was calculated using the following equation:

$$X_i = \sum_{c=1}^{17} \frac{R_{ic} IE_c}{B_i}, \quad (7)$$

where X_i is the teenage daily intake of AA (μg/kg/day) for the *i*th individual, *i* is from 1 to 2000; R_{ic} is the zero-one random variable sampled from a binomial distribution employing the probability of success as the proportion of teens that consumed from the *c*th consumption group, *c* is from 1 to 17, for the *i*th individual; an AA value (μg) was sampled with replacement from IE_c which represents all possible AA Intake Events (defined in step D, Fig. 1) for the *c*th consumption group; and B_i is the body weight (kg) for the *i*th individual sampled.

As an example, NHANES dietary records indicate French fries were consumed by teenagers following the Western diet on 496 of the 1899 dietary days surveyed. This represents a probability of success for French fry consumption of 496/1899, or 26.1%, which provides the basis for generating a binomial distribution (resulting in either a 0 or 1) for the French fry consumption group.

Each individual's sampled AA intake event (μg), or IE_c, was multiplied by 0 or 1 and repeated for all 17 consumption groups; the 17 products were summed and divided by his or her body weight yielding a daily AA intake value (μg/kg/day).

For each individual, 365 daily intake values (calculated using Eq. (7) above), simulating a year of AA intake, were generated to allow determination of the average daily intake over an entire year. Distributions of intake values among the 2000 individuals allowed determination of mean average daily intake levels of AA over the one year period and upper percentiles (95th, 99th, and 99.9th) of AA intake for the Western and guideline based diets.

A two-sample *t*-test ($P < 0.001$) with the Welch correction was used for all comparisons of means.

3. Results

Eating Events from the Western diet were compared with those of the guideline based diet with respect to foods in the 17 consumption groups that contribute to AA intake (Table 3). The guideline based diet resulted in reductions in the number of Eating Events for foods not considered to be particularly healthy, such as French fries, potato chips, pizza, pretzels, pies and cakes; such reductions were offset by significant increases in breakfast cereal consumption relative to the Western diet.

Teenage Western and guideline based diets were compared with 11 nutritional constraints derived from DGA (Table 4). The guideline based diets demonstrated improved nutritional adequacy

Table 4
Nutritional comparison of teenage Western and guideline based diets to the Dietary Guidelines for Americans, 2005 (DGA).

Nutritional Constraint	DGA[a]	Western diet[b]	Guideline based diet[b]
Fruits[c], cups/day	2.00	0.47	2.00
Vegetables[c], cups/day	3.00	1.10	3.00
Total grains[c], oz-eq/day	7.00	6.80	8.00
Whole grains[c], oz-eq/day	3.50	0.00	3.50
Lean meat and beans[c], oz-eq/day	6.00	4.25	6.50
Milk[c], cups/day	3.00	1.40	3.00
Fiber[d], g/day	30.8	11.95	30.8
Sodium[d], g/day	2.30	3.20	2.30
Added fat (oil)[e], g/day	29.0	14.0	27.0
Added fat (solid)[e], g/day	19.0	45.3	19.0
Added sugar[f], tsp-eq/day	9.00	22.65	9.00

[a] DGA values are defined as recommendations based on median daily energy intake (2200 kcal/day); 1 kcal = 4.18 kJ.
[b] Median quantities per day.
[c] Quantity is calculated according to the nutrient-dense food form (e.g. lean meats and fat-free milk), oz-eq defined as ounce-equivalent. For example, 1 oz-eq for the lean meats and beans category equals 1 oz. meat, poultry, or fish; 1 egg; ¼ cup dry beans or tofu; 1 tbsp peanut butter; ½ oz. nuts or seeds.
[d] Quantity of individual nutrient.
[e] Quantity of fat present in amounts above the lowest available fat level, such as fat-free milk and skinless chicken.
[f] Amount of sugar used as ingredients in prepared and processed foods, not including naturally occurring in fruits and milk.

Table 5
Comparison of means and higher percentiles of acrylamide intake from the consumption of Western and guideline based diets.

Summary statistic	Western diet (μg/kg/day)	Guideline based diet (μg/kg/day)
Mean ± SE	0.441 ± 0.003	0.508 ± 0.003
95th	0.64	0.73
99th	0.78	0.88
99.9th	0.86	0.97

when compared to the Western diets for the following median constraint quantities: fruit (0.47–2.00 cups/day), vegetables (1.10–3.00 cups/day), lean meat and beans (4.25–6.50 oz-eq/day), milk (1.40–3.00 cups/day), fiber (11.95–30.8 g/day), sodium (3.20–2.30 g/day), added fat (solid) (45.3–19.0 g/day), and added sugar (22.65–9.00 tsp-eq/day). Median consumption of whole grains was 0.00 oz-eq/day for the Western diets as 61% of US teenagers did not report consuming any foods containing whole grains while the mean consumption for whole grains in the Western diet was 0.4 oz-eq/day, which is considerably below the 3.5 oz-eq/day determined for the guideline based diets. Consumption of total grains was slightly lower than recommended for the Western diets (6.80) and higher for the guideline based diets (8.00 oz-eq/day).

Mean daily AA intakes for teenagers over the 1 year period (mean ± SE) were 0.508 ± 0.003 μg/kg/day for the guideline based diet and 0.441 ± 0.003 μg/kg/day for the Western diet (Table 5). The guideline based diets also showed higher AA intake than the Western diet at the upper 95th, 99th, and 99.9th percentiles of intake.

Comparisons of consumption group contribution of AA intake to the Western and guideline based diets (Table 6) demonstrate that Western diets had significantly more contribution from 15 of the 17 consumption groups; only breakfast cereal and bagels showed higher AA intake from the guideline based diet. Although soft bread consumption was more frequent with the guideline based diet (1009 Eating Events) than with the Western diet (888 Eating Events) (Table 3), soft bread contributed 14% more AA to the Western diet (Table 6). The higher soft bread contribution of AA to the Western diet resulted from larger daily individual soft bread consumption means from the Western diet (72 g/individual) than the guideline based diet (56 g/individual). Similarly, while bagels were consumed more frequently in the guideline based diet (135 Eating Events) than in the Western diet (62 Eating Events), mean consumption of bagels for the guideline based diets was 53 g/individual, or less than half of the mean consumption for the Western diet (109 g/individual). As a result, AA intake from bagel consumption differed only slightly between the guideline based (0.00147 μg/kg/day) and Western diet (0.00127 μg/kg/day).

French fries and potato chips were the top contributors of AA to the Western diet contributing 56% of the total AA intake, while contributing only 24% of the total AA intake to the guideline based diet. Breakfast cereal was the top contributor of AA contributing 63% of the total AA intake to the guideline based diet while contributing only 9% to the Western diet.

4. Discussion

This study demonstrated that the teenage guideline based diets are nutritionally superior to the teenage Western diets; this was also demonstrated using diets from a small group of adults in the US Northwest (Masset et al., 2009) and using typical French diets (Maillot et al., 2010). In fact, only 1 of the 1899 NHANES reported teen diets used in this study met the daily food group quantities (minimum DGA recommendation for 1600 kcal); however, this individual consumed over 6000 kcal, 10 g of salt (over four times the DGA recommendation of 2.3 g), and 168 g of solid fat (five times the DGA recommendation of 34 g for the highest energy level 3200 kcal/day). To meet DGA whole grains and fiber recommendations, daily breakfast cereal consumption increased from 463 individuals (Western diets) to 1807 individuals (guideline based diets) (Table 3). The increased consumption of breakfast cereals in the guideline based diets is due to high whole grain and fiber densities of these foods. As an example, one breakfast cereal type had a whole grain density of 2.7 oz-eq/100 g and a fiber density of 9.6 g/100 g. Consumption of 100 g of this breakfast cereal satisfies 77% (whole grains) and 31% (fiber) of the daily DGA whole grains and fiber recommendations at an energy level of 2200 kcal/day.

The total number of food choices for all teenagers decreased 11.6% from 1944 (Western diet) to 1679 (guideline based diet). To meet DGA it was necessary to increase the number of daily food choices for 79.6% of the teenagers which is very close to a figure of 80% observed in a study of French diets (Maillot et al., 2009). On a daily basis, the number of foods consumed rose from 11 foods for the Western diet to 16 foods for the guideline based diet. This increase in average number of foods consumed per individual per day provides an indicator of greater dietary variety which has been frequently associated with improved health status (Murphy et al.,

Table 6
Comparison of consumption group contributions of acrylamide (AA) intake from Western and guideline based diets.

	Western[a] (μg/kg/day)	Percentage contribution (%)	Guideline based[a] (μg/kg/day)	Percentage contribution (%)
Bagels	1.27E-03 ± 1.41E-05	0.29	1.47E-03 ± 1.33E-05	0.29
Breaded chicken	5.02E-03 ± 3.84E-05	1.14	1.94E-03 ± 1.49E-05	0.38
Breakfast cereal	4.09E-02 ± 2.99E-04	9.29	3.19E-01 ± 1.91E-03	62.73
Cookies	2.10E-02 ± 1.74E-04	4.75	4.75E-03 ± 4.11E-05	0.94
Corn snacks	2.61E-02 ± 1.71E-04	5.93	1.92E-02 ± 1.22E-04	3.77
Crackers	1.08E-02 ± 1.09E-04	2.44	5.92E-03 ± 5.82E-05	1.17
French fries	1.66E-01 ± 1.09E-03	37.60	6.65E-02 ± 4.62E-04	13.09
Olives	1.25E-03 ± 5.30E-05	0.28	5.50E-04 ± 1.86E-05	0.11
Peanut butter	2.16E-03 ± 2.18E-05	0.49	1.69E-03 ± 1.65E-05	0.33
Pies and cakes	1.23E-02 ± 8.45E-05	2.80	1.96E-04 ± 4.40E-06	0.04
Pizza	3.42E-02 ± 2.25E-04	7.76	4.32E-03 ± 3.18E-05	0.85
Popcorn	9.56E-03 ± 8.73E-05	2.17	6.27E-03 ± 5.29E-05	1.23
Potato chips	7.95E-02 ± 6.24E-04	18.03	5.38E-02 ± 3.88E-04	10.60
Pretzels	5.22E-03 ± 5.91E-05	1.18	1.84E-03 ± 2.22E-05	0.36
Soft bread	1.60E-02 ± 1.02E-04	3.62	1.40E-02 ± 8.69E-05	2.75
Soup mix	1.16E-03 ± 1.14E-05	0.26	4.46E-04 ± 5.42E-06	0.09
Toast	8.69E-03 ± 7.82E-05	1.97	6.40E-03 ± 5.98E-05	1.26

[a] Data are given as mean ± SE.

2006; Steyn et al., 2006) although others have shown that increasing the variety of specific foods consumed is not always of health benefit (McCrory et al., 1999).

This study demonstrated that teenage mean AA intake estimates are significantly greater from the consumption of guideline based diets, 0.508 ± 0.003 μg/kg/day, than from the consumption of Western diets, 0.441 ± 0.003 μg/kg/day. Other studies have shown similar estimates for the general population's AA intake from Western diets, including an estimate of 0.44 μg/kg/day for the overall population (Doerge et al., 2008) and 0.86 μg/kg/day for children ages 3–12 (Tran et al., 2010). This study estimates AA intake from a guideline based diet for the first time.

The FDA recommendation that consumers eat a diet consistent with that of the DGA was tested with respect to its impact upon AA intake. Interestingly, consumption of a more nutritionally adequate diet increased the mean daily dietary intake of AA. AA is found in a wide range of foods (Dybing et al., 2005) and a simple dietary recommendation encouraging the consumption of a balanced diet rich in fruits and vegetables is not sufficient to reduce AA intake.

The results of this study are dependent on the linear programming inputs, objective function and constraints. If one were to modify either the objective function and or the constraints, a different diet may likely result. For example, the guideline based diet discussed in this study could be further refined with the addition of a constraint limiting breakfast cereal quantity. Therefore, a healthy diet might be achieved while limiting the intake of food substances of concern, in this case AA.

Certain attributes of the input data limit the model's ability to simulate realistic events. NHANES dietary data and FDA AA food sampling data were from 2003 to 2004 and do not account for any changes in dietary habits or reductions in AA levels based upon new food preparation techniques developed by the food industry in response to AA concerns. Fortunately, the model described in this study can accept current data as well.

While it is not possible to completely account for the uncertainty in intra-individual dietary habits (Lambe, 2002) and the variability of AA in food (Dybing et al., 2005), the probabilistic approach used in this study addresses the consumption of a wide range of potential AA intakes. Food–food associations might also improve the realism of the model diet, such as appropriate increases in salad dressing if salad is chosen in the model diet (Maillot et al., 2010) or increases in the consumption of milk with the proportional increases in breakfast cereal intake.

This study provides an approach using linear programming that can be used to construct an "optimal" diet that follows DGA while sampling from foods reported to be eaten from food consumption surveys. In this study, we demonstrated that the linear programming model combined with probabilistic intake assessment techniques demonstrated a 15% increase in AA intake among US teenagers following DGA. While this is an important finding and one that might influence subsequent dietary strategies to reduce AA intake, results from both the Western and guideline based diets still demonstrate AA intake well below the AA chronic reference dose. More importantly, the combination of probabilistic techniques to estimate exposure with linear programming to model the diet is a novel approach that provides great promise for future dietary risk assessments. Similar approaches could be used to model a variety of diets including ethnic, plant-based, gluten-free, low carbohydrate, and Mediterranean, among others.

The approach outlined in this study is also suitable for the determination of intakes of numerous other non-nutrients of toxicological concern (i.e. heavy metals, dioxins, bisphenol A, and pesticide residues) as well as for essential nutrients. A particularly appealing application of such an approach involves the simultaneous study of the influence of diet upon non-nutrients of toxicological concern and nutrients. Food-balance sheets have previously been used to assess toxicological and nutritional conflicts related to seafood consumption (Sioen et al., 2009). Applying the techniques in this study to evaluate the risk-benefit of seafood consumption would provide a more realistic assessment of both nutrients and non-nutrients. The methods developed in this study can be used for a variety of nutritional and risk assessment issues.

Conflict of Interest

The authors declare that there are no conflicts of interest.

References

Briend, A., Darmon, N., Ferguson, E., Erhardt, J.G., 2003. Linear programming: a mathematical tool for analyzing and optimizing children's diets during the complementary feeding period. J. Pediatr. Gastroenterol. Nutr. 36, 12–22.

Buttrey, S.E., 2005. Calling the lp_solve linear program software from R, S-Plus, and Excel. J Stat Softw. 14.

Deng, H., He, F., Zhang, S., Calleman, C.J., Costa, L.G., 1993. Quantitative measurements of vibration threshold in healthy adults and acrylamide workers. Int. Arch. Occup. Environ. Health 65, 53–56.

DGA, 2005. Dietary Guidelines for Americans, 2005. Available from, <http://www.health.gov/dietaryguidelines/dga2005/document/> (accessed September 7 2009).

Doerge, D.R., Young, J.F., Chen, J.J., Dinovi, M.J., Henry, S.H., 2008. Using dietary exposure and physiologically based pharmacokinetic/pharmacodynamic modeling in human risk extrapolations for acrylamide toxicity. J. Agric. Food. Chem. 56, 6031–6038.

Dybing, E., Farmer, P.B., Andersen, M., Fennell, T.R., Lalljie, S.P.D., Muller, D.J.G., Olin, S., Petersen, B.J., Schlatter, J., Scholz, G., Scimeca, J.A., Slimani, N., Tornqvist, M., Tuijtelaars, S., Verger, P., 2005. Human exposure and internal dose assessments of acrylamide in food. Food Chem. Toxicol. 43, 365–410.

EPA, 2011. Chronic Oral RfD Summary. Available from, <http://www.epa.gov/iris/subst/0286.htm> (accessed June 8 2011).

FDA, 2006. The 2006 exposure assessment for acrylamide. Available from, <http://www.fda.gov/downloads/Food/FoodSafety/FoodContaminantsAdulteration/ChemicalContaminants/Acrylamide/UCM197239.pdf> (accessed November 6 2009).

FDA, 2009. Acrylamide Questions and Answers. Available from, <http://www.fda.gov/food/foodsafety/foodcontaminantsadulteration/chemicalcontaminants/acrylamide/ucm053569.htm#stop> (accessed June 8 2011).

FDA, 2011. FDA survey on acrylamide in food: individual food products. Available from, <http://www.fda.gov/food/foodsafety/foodcontaminantsadulteration/chemicalcontaminants/acrylamide/ucm053549.htm> (accessed September 5 2009).

FNDDS, 2010. The USDA Food and Nutrient Database for Dietary Studies, 2.0. Available from, <http://www.ars.usda.gov/Services/docs.htm?docid=12083> (accessed December 8 2009).

Friedman, M., 2003. Chemistry, biochemistry, and safety of acrylamide. A review. J. Agric. Food Chem. 51, 4504–4526.

International Agency for Research on Cancer (IARC), 1999. IARC Monographs of the Evaluations of Carcinogenic Risks to Humans. Available from, <http://monographs.iarc.fr/ENG/Monographs/vol60/volume60.pdf> (accessed 06.17.11 2011).

Konings, E.J.M., Baars, A.J., van Klaveren, J.D., Spanjer, M.C., Rensen, P.M., Hiemstra, M., van Kooij, J.A., Peters, P.W., 2003. Acrylamide exposure from foods of the Dutch population and an assessment of the consequent risks. Food Chem. Toxicol. 41, 1569–1579.

Lambe, J., 2002. The use of food consumption data in assessments of exposure to food chemicals including the application of probabilistic modeling. Proc. Nutr. Soc. 61, 11–18.

Lin, B.H., Lucier, G., Allshouse, J., Kantor, L., 2001. Market distribution of potato products in the United States. J. Food Prod. Market 6, 63–78.

Maillot, M., Vieux, F., Ferguson, E.F., Volatier, Jean-Luc, Amiot, M.J., Darmon, N., 2009. To meet nutrient recommendations, most french adults need to expand their habitual food repertoire. J. Nutr. 139, 1721–1727.

Maillot, M., Vieux, F., Amiot, M.J., Darmon, N., 2010. Individual diet modeling translates nutrient recommendations into realistic and individual-specific food choices. Am. J. Clin. Nutr. 91, 421–430.

Masset, G., Monsivais, P., Maillot, M., Darmon, N., Drewnowski, A., 2009. Diet optimization methods can help translate dietary guidelines into a cancer prevention food plan. J. Nutr. 139, 1541–1548.

Matthys, C., Bilau, M., Govaert, Y., Moons, E., De Henauw, S., Willems, J.L., 2005. Risk assessment of dietary acrylamide intake in Flemish adolescents. Food Chem. Toxicol. 43, 271–278.

McCrory, M.A., Fuss, P.J., McCallum, J.E., Yao, M., Vinken, A.G., Hays, N.P., Roberts, S.B., 1999. Dietary variety within food groups: association with energy intake and body fatness in men and women. Am. J. Clin. Nutr. 69, 440–447.

Mills, C., Tlustos, C., Evans, R., Matthews, W., 2008. Dietary acrylamide exposure estimates for the United Kingdom and Ireland: Comparison between

semiprobabilistic and probabilistic exposure models. J. Agric. Food. Chem. 56, 6039–6045.
Mojska, H., Gielecinska, I., Szponar, L., Oltarzewski, M., 2010. Estimation of the dietary acrylamide exposure of the Polish population. Food Chem. Toxicol. 48, 2090–2096.
MPED, 2010. MyPyramid Equivalents Database 2.0, for USDA Survey Foods. Available from, <http://www.ars.usda.gov/Services/docs.htm?docid=17558> (accessed August 6 2009).
Murphy, S.P., Foote, J.A., Wilkens, L.R., Basiotis, P.P., Carlson, A., White, Kami.K.L., Yonemori, K.M., 2006. Simple measures of dietary variety are associated with improved dietary quality. J. Am. Diet. Assoc. 106, 425–429.
NHANES, 2003–2004. National Health and Nutrition Examination Survey. Available from, <http://www.cdc.gov/nchs/nhanes/nhanes2003-2004/nhanes03_04.htm> (accessed August 8 2009).
Office of Environmental Health Hazard Assessment (OEHHA), 2011. Proposition 65. Available from, <http://oehha.ca.gov/prop65/acrylamide.html> (accessed June 8 2011).
Parzefall, W., 2008. Mini review on the toxicity of dietary acrylamide. Food Chem. Toxicol. 46, 1360–1364.
Sioen, I., Henauw, S.D., Camp, J.V., Volatier, Jean-Luc, Leblanc, Jean-Charles, 2009. Comparison of the nutritional-toxicological conflict related to seafood consumption in different regions worldwide. Regul. Toxicol. Pharmacol. 55, 219–228.
Steyn, N.P., Nel, J.H., Nantel, G., Kennedy, G., Labadarios, D., 2006. Food variety and dietary diversity scores in children: are they good indicators of dietary adequacy? Public Health Nutr. 9, 644–650.
Tareke, E., Rydberg, P., Karlsson, P., Eriksson, S., Tornqvist, M., 2002. Analysis of acrylamide, a carcinogen formed in heated foodstuffs. J. Agric. Food. Chem. 50, 4998–5006.
Tran, N.L., Barraj, L.M., Murphy, M.M., Bi, X., 2010. Dietary acrylamide exposure and hemoglobin adducts – National Health and Nutrition Examination Survey (2003–2004). Food Chem. Toxicol. 48, 3098–3108.