Perspective: Modeling Healthy Eating Patterns for Food-Based Dietary Guidelines—Scientific Concepts, Methodological Processes, Limitations, and Lessons

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ABSTRACT

The relations between dietary features and human health are varied and complex. Health-related variables are many and they have intricate relations at different and interrelated nutritional levels: nutrients, food groups, and the complex overall pattern. Food-based dietary guidelines (FBDGs) are principally designed to synthesize this information to make it available to the public. Here, we describe the method used to establish healthy eating patterns (HEPs) for the latest French FBDGs, which consists of in-depth food pattern modeling using an enhanced optimization method that gathered all aspects of HEPs. We present the novelty of this food modeling approach for FBDGs, which aims to gather information related to nutrients, food contaminants, and epidemiological relations with long-term health, and to be combined with the objective of realistic dietary patterns that deviate minimally from the prevailing diet. We draw lessons from stepwise implementation of the method and discuss its strengths, limitations, and perspectives. In light of the modeled HEPs, we discuss the importance of food grouping; of accounting for dietary habits while not precluding modeled diets that can be realistic/acceptable; and of taking into account the exposure to food contaminants. We discuss the tolerance and flexibility to be applied to certain dietary reference values for nutrients and health-based guidance values for contaminants so that HEPs can ultimately be identified, and how account can be taken of varied health-related outcomes applied to food groups. Although the approach involves all the peculiar uncertainties of numerous optimization model parameters and input data, its merit is that it offers a rationalized approach to establishing HEPs with multiple constraints and competing objectives. It is also versatile because it is possible to operationalize further dimensions of dietary patterns to favor human and planetary health. *Adv Nutr* 2021;12:590–599.

Keywords: healthy eating patterns, food-based dietary guidelines, food pattern modeling, optimization, objective function, dietary reference values, food contaminants, food grouping

Introduction

It is now well established that public health issues, including noncommunicable diseases (NCDs), are closely related to diet and some unfavorable trends in food consumption patterns (1). Poor dietary habits increase the risk of diet-related NCDs—foods being the vehicles of nutrients whose adequate intakes are crucial to metabolism and physiology (1). Healthier food choices, along with higher physical activity, are critical to the well-being and long-term health of a population (1). However, diet involves multidimensional exposure, and the relations between diets and long-term health are complex. Synthesizing the body of scientific evidence that should be used to identify which diets to recommend is not simple but it is critical to assisting stakeholders in making informed decisions on public health. The French Ministry of Health asked the French Agency for Food, Environmental and Occupational Health & Safety (ANSES) to curate scientific evidence to provide new dietary guidelines as foundations for the French National Nutrition and Health Program. ANSES had mandated the Standing Committee on Nutrition under the aegis of which numerous working groups were set up and operated.

Since the 1990s, the WHO and the FAO have worked on key scientific areas to establish guidelines defined as "the expression of the principles of nutrition education mostly as foods" (2). These guidelines, or more precisely food-based dietary guidelines (FBDGs), are thus the result of a comprehensive approach to the relations between food, nutrients, and health. FBDGs can be considered as the translation of quantitative nutrient requirements and overall nutritional information into simple, understandable messages on diet for generally healthy populations to promote overall health

Adv Nutr 2021;12:590–599; doi: https://doi.org/10.1093/advances/nmaa176.

(3). More recently, the FAO listed all available FBDGs in a database (4), where they are considered to be "short, science-based, positive messages on healthy eating and lifestyles aimed at preventing all forms of malnutrition and keeping people well-nourished and healthy" (4). These FBDGs are available online together with the type of evidence and scientific concepts used to inform them.

Because of the differences in dietary habits between European countries, it is commonly accepted that each country needs to develop its own dietary guidelines in light of dietary habits, and that the design of FBDGs must be based on strong scientific evidence (5, 6). Several countries, such as Canada, the United States, and Belgium, are now basing their FBDGs on a large corpus of more detailed data and reviews of the literature. The methods used to synthesize evidence and define healthy eating patterns (HEPs) can differ considerably throughout the world (3, 7, 8). HEPs, that is, "quantities, proportions, variety or combinations of different foods and beverages in diets, and the frequency with which they are habitually consumed" (9), can be identified in 2 principal ways: food pattern modeling or dietary pattern analysis (8).

In 2016, ANSES chose to use its own method, inspired from the proposal of the European Food Safety Authority (EFSA) (5) using an integrative approach that includes: *1*) limiting the nutritional risk—that is, covering nutrient requirements and limiting the risk of chronic NCDs associated with the consumption of certain food groups; *2*) limiting risk with regard to foodborne chemical contaminants; and *3*) taking dietary habits into account to facilitate the acceptance and implementation of FBDGs.

According to Bechthold et al. (7), a mathematical optimization method is the best way to capture the overall complexity of a diet. The purpose of the present article is to describe and discuss the strengths and limitations of the method used by ANSES to establish HEPs for the new French FBDGs for adult men (18–65 y) and women (18–55 y, i.e., premenopausal), which consists of in-depth food pattern modeling using an enhanced optimization method gathering all the multiple aspects of HEPs.

Methodological Process for Food Pattern Modeling

The work was carried out by working groups mandated by ANSES, which adopted complementary approaches related to several nutritional levels (nutrients, food groups, and overall dietary pattern), associated with 3 tasks: *1*) to update the French dietary reference values (DRVs); *2*) to review the relations between the consumption of food groups and the risk of NCDs; and *3*) to define appropriate food groups. This information and all background data were then used to operate an optimization method for food pattern modeling (**Figure 1**). This method is used to define combinations of food groups that most effectively achieve its aims, that is, to meet all DRVs, reduce the risk of NCDs, and minimize exposure to food contaminants, while remaining within a range of intakes that are relatively close to observed consumption.

Updating the DRVs used for food pattern modeling

For this work we used the terms relative to DRVs in the now classical manner, based on both a theoretical framework and the practical methods used to estimate values: average requirement (AR), population reference intake (PRI), adequate intake (AI), reference intake range, and the tolerable upper intake level (UL) (10).

Reference values for vitamins and minerals published in international or national reports were compared in countries with a Western-type diet (11–23): to establish the DRVs, ANSES endorsed the EFSA's AR and PRI values unless strong objections were raised by the Standing Committee. In the event of an AI based on biomarkers or epidemiological outcomes, the value was retained if the approach was in line with that used in France. If an AI was derived from the average consumption observed at the European level, then the French AI was set as the average consumption for French populations [using the Second Individual and National Survey on Food Consumption (INCA2) representative study]. However, in the absence of any assessment by the EFSA, the choice of DRV was made from the DRV proposed by the agencies mentioned above on a case-by-case basis, supported where necessary by recent data from the literature.

As for the reference values relative to excessive intakes, the ULs specified at the European level by the Scientific Committee on Food and then by the EFSA were the only ones considered.

Taking account of epidemiological relations

Preventing NCDs is one of the goals of FBDGs. The working group decided to characterize the relations between food groups and the risks of major NCDs such as cardiovascular disease, type 2 diabetes, overweight/obesity, breast, prostate, and colorectal cancers, bone health, and mental health. Many international organizations had previously conducted this type of assessment and their most recent publications contributed to this work (24–30). This information was supplemented by a literature search focused on the years following these expert appraisals.

Supported by the French Agency for Food, Environmental and Occupational Health & Safety.
Author disclosures: The authors report no conflicts of interest.

Supplemental Tables 1–3 are available from the "Supplementary data" link in the online posting of the article and from the same link in the online table of contents at https://academic.oup.com/an/.

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Abbreviations used: AI, adequate intake; ALA, α-linolenic acid; ANSES, French Agency for Food, Environmental and Occupational Health & Safety; AR, average requirement; DRV, dietary reference value; EFSA, European Food Safety Authority; FBDG, food-based dietary guideline; HBCDD, hexabromocyclododecane; HBGV, health-based guidance value; HEP, healthy eating pattern; INCA2, Second Individual and National Survey on Food Consumption; NCD, noncommunicable disease; PRI, population reference intake; UL, tolerable upper intake level.

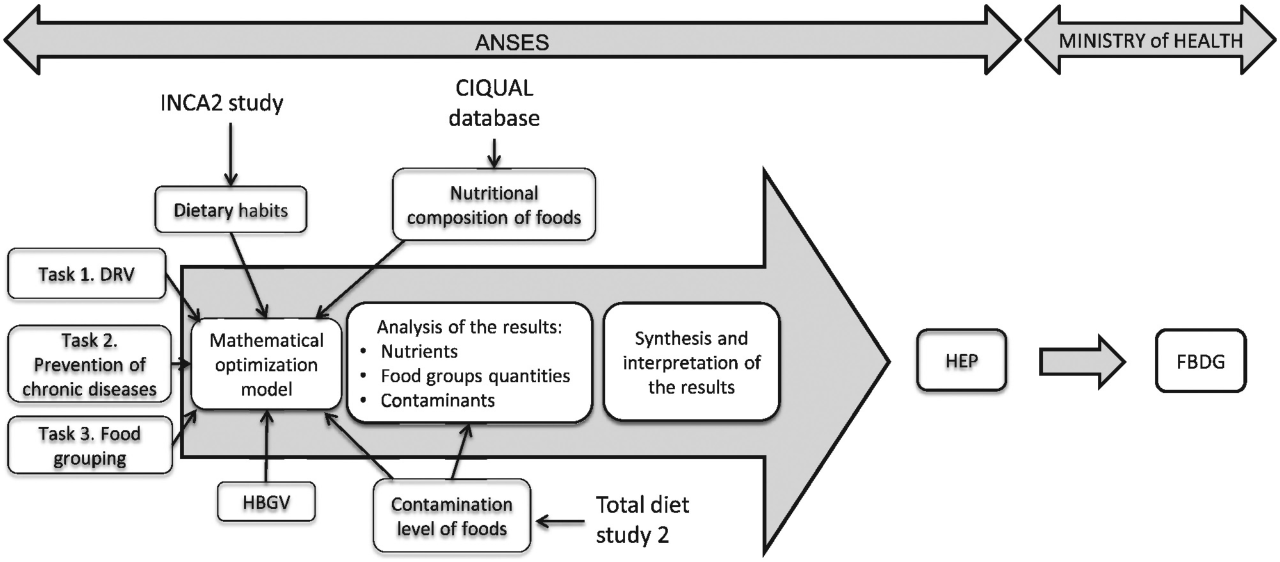

FIGURE 1 Organization and methodological process. ANSES, French Agency for Food, Environmental and Occupational Health & Safety; CIQUAL, French Information Center on Food Quality; DRV, dietary reference value; FBDG, food-based dietary guideline; HBGV, health-based guidance value; HEP, healthy eating pattern, INCA2, Second Individual and National Survey on Food Consumption; TDS2, Second French Total Diet Study.

Food grouping

Food grouping consists in making groups that represent the nutrient intake that might be expected from consuming specified quantities of foods from a food group; this is a sensitive process when establishing the structure of a dietary guideline (31–33). The working group proposed food groupings based on the homogeneous nutrient composition and dietary habits of the French population. The nutrients for which risks of insufficient or excessive intake had been identified (34) were regarded as discriminating for the identification of food groups. This mainly concerned fiber, sugar, salt, total fats, and certain fatty acids. Successive ascending hierarchical classifications were performed on some of these nutrients to assist in defining the boundaries of certain groups (e.g., distinguishing between fruit juices and nectars based on their sugar and fiber contents) (10). Thirty-two groups were finally defined (**Supplemental Table 1**).

Input data used for food pattern modeling

Food consumption data for men aged 18–64 y and women aged 18–54 y (premenopausal women) came from the INCA2 study conducted in 2006–2007 on 4079 individuals aged 3 to 79 y (1455 children aged 3–17 y and 2624 adults aged18–79 y) (35). Individual daily food intake was estimated using a 7-d food record. A weighting factor was applied to each individual to ensure their national representativeness.

Food composition data came from the French Information Center on Food Quality (CIQUAL) database (36), which contains the energy values and contents in lipids, fatty acids, carbohydrates, sugar, lactose, protein, salt, vitamins, and minerals of >2800 generic foods consumed in France.

Data on food chemical substances and individual daily exposure to contaminants and pesticide residues came from the Second French Total Diet Study (37, 38). In this study, 90% of the diets were represented, 1319 food samples were collected throughout metropolitan France, divided into 8 interregional areas, and 445 substances were analyzed in foods that could be possible contributors to the exposure. Left-censored concentration data (i.e., values below the analytical limits) were processed according to a “middlebound” assumption: values below the limits of detection or quantification were assumed to be equal to half this limit.

The health-based guidance values (HBGVs) used in the present work were those selected in the latest French Total Diet Study (39, 40).

Optimization method used for food pattern modeling

A mathematical optimization model based on the simplex algorithm (10) was implemented to establish HEPs. This model identifies a modeled diet consisting of the daily consumption of each of the 32 food groups that most effectively meet the aims previously defined. Optimization consists of minimizing an evaluation function known as the “objective function.” Constraints were integrated by means of inequalities (10). Nutrient constraints were set so that the modeled diet complied with the DRVs. Maximal limits were added as constraints to food groups whose consumption is associated with an increased risk of NCDs. Dietary habit constraints were set so that the modeled diet remained within the range of observed consumption, whereas contaminant constraints were determined to ensure that output exposure remained at or below the HBGV, or, when the HBGV was a benchmark dose limit, below the median of the observed exposure of the population. Taken together, these constraints defined a set of possible modeled diets, where the optimal diet was identified as minimizing the objective function. This function combines several criteria to minimize deviations from observed consumption, minimize (or maximize) the consumption of certain food groups to prevent NCDs, and possibly minimize exposure to contaminants.

A step-by-step approach

To assess the weight of each constraint and test their compatibility with each other, a step-by-step approach was adopted, separately for men and women. First, nutrient and epidemiological constraints alone were integrated to test their mutual compatibility while integrating epidemiological criteria (scenario A). Dietary habits were then taken into account as well by including constraints relative to the consumption bounds and the criteria designed to minimize deviations from the average consumption (scenario B). Lastly, the constraints and criteria concerning contaminants were added to test the compatibility of all the constraints and estimate the impact on the modeled diet of taking them into account (scenario C) (10). In this last scenario, authorized pesticides and food additives were not included as constraints. Because their use is regulated by law, any potential for excessive exposure should not constrain the establishment of HEPs but rather cause an adjustment to the specific regulations. Exposure levels in the modeled diets were, however, compared to HBGVs and observed exposures.

During the course of this optimized step-by-step food pattern modeling, some adaptations were necessary to find modeled diets when the model was not identifiable. These adaptations either consisted of introducing flexibility (i.e., considering that the reference value was no longer a strict constraint but involved an additional objective of getting as close as possible to the reference value) or tolerance (i.e., accepting that the reference value was reached with a certain percentage deviation from the nominal value). When choosing to add flexibility to a constraint, an additional term was included in the objective function in order to minimize the breaching of corresponding constraint. These criteria enabled the flexibility of certain constraints (i.e., by allowing the optimization tool not to achieve certain DRVs or to exceed certain HBGVs) but they introduced the objective of remaining as close to them as possible.

More details on the optimization model and the definition of nutrient, epidemiological, contaminant, and consumption constraints and criteria are provided in the **Supplemental Tables 1, 2** and **3**.

Lessons from Implementation of the Methodological Process

Integrating health-related epidemiological relations in food pattern modeling

Most of the studies included were of a prospective and observational type, which could be considered as insufficient to ascertain the existence of a cause and effect relation. However, only relations characterized by a "convincing" or "probable" level of evidence were considered for inclusion in the optimization model for food pattern modeling (10).

The consumption of food groups that should be reduced (red meat, processed meat, and sugar-sweetened beverages, which are linked to an increase in the risk of NCDs) or increased (fruits, vegetables, and wholegrain products) was integrated in the optimization model by adding constraints and criteria in the objective function. Supplemental Table 2 shows that 71 g/d red meat [i.e., ∼500g/wk, as proposed by the World Cancer Research Fund (27)] was selected as a maximum, and a value of 25 g/d for delicatessen meats was adopted. An upper consumption limit was set for all sugar-sweetened beverages (juices, nectars, and sodas) corresponding to the median volume of 1 glass consumed in the INCA2 study, that is, 263 g for men and 216 g for women (Supplemental Table 2).

Introducing these groups to be maximized or minimized in the objective function ultimately appeared to have a marked impact on the modeled diet. Indeed, many food groups to be maximized or minimized were found at high or low levels in the modeled diet. Fruits, vegetables, and wholegrain products in particular were at the highest possible levels in all the modeled diets identified.

Some epidemiological studies have reported that consuming certain food groups can both increase the risk of certain diseases and reduce the risk of others. The consumption of milk reduces the risk of colorectal cancer, with a "probable" level of evidence, but the literature also suggests a 6% increase in the risk of prostate cancers for each additional intake of 200 g/d low-fat milk, with "limited but suggestive" level of evidence (29). In this case, the working group decided not to assign any maximization or minimization objectives to milk consumption. Similarly, epidemiological studies have shown that consuming fish reduces the risk of cardiovascular disease and dementia, with a "probable" level of evidence (6% reduction in mortality from coronary heart disease for each additional weekly intake) (26), although there is large heterogeneity between countries (41). However, the consumption of fish cooked at a high temperature, salted, or smoked could be associated with an increased risk of prostate cancer, with a "limited – suggestive" level of evidence (29). Choosing not to integrate this knowledge was dictated by simplicity but constituted a limitation of the approach. This knowledge could be integrated by modeling the attributable risk for each disease with a comparative risk assessment and comparing the burden of disease with common metrics such as disability-adjusted life years (42). Such an approach might also enable the introduction of different weightings for the maximization/minimization terms of the objective function rather than considering that all subobjectives are equal for health for the sake of simplicity. Furthermore, although use of the upper consumption limit offers a means to account for changes in the relation to risk, information on the relation between consumption and risk was mostly considered to be linear when integrating it in the model as an objective of maximization or minimization, whereas

TABLE 1 Diets modeled according to scenarios A, B, and C for adult men and the prevailing diet according to the Second Individual and National Survey on Food Consumption (INCA2)

Food groups	Consumption in the modeled diet according to scenario A,[1] g/d	Consumption in the modeled diet according to scenario B,[2] g/d	Consumption in the modeled diet according to scenario C,[3] g/d	Prevailing diet, g/d
Vegetables	1352	285	285	123
Fresh fruits	0	376	376	115
Dried fruits	0	0.8	2.9	0.8
Processed fruits: purées and cooked fruit	0	8.5	5.5	8.5
Oilseeds	0	8.6	8.6	1.5
Refined bread and bread products	0	0	0	102
Plain wholegrain bread and bread products	0	79	70	16
Starch-based, sweet/fatty processed products	0	14	31	14
Starch-based, savory/fatty processed products	0	27	16	27
Other refined starches	0	14	14	113
Other plain wholegrain starches	798	243	243	2.5
Pulses	0	36	50	14
Poultry	0	97	122	38
Red meat	63	71	71	64
Delicatessen meats	25	9.7	0	39
Oily fish	26	21	22	5
Other fish	0	23	7	23
Eggs	158	13	46	13
Milk	0	386	0	98
Plain fresh dairy products	0	28	122	28
Sweetened fresh dairy products	0	42	0	42
Sweetened dairy desserts	0	18	15	18
Cheeses	29	36	81	36
Butter and reduced-fat butter	12	6	0	6
Vegetable oils rich in ALA	23	20	21	0.3
Vegetable oils and margarines poor in ALA	11	0.4	0.4	4.5
Sauces, fresh creams, and condiments	0	13	4.4	13
Sweet or sweet and fatty products	0	68	28	68
Drinking water	722	965	1002	775
Sugar-sweetened beverages such as soda	0	0	0	93
Fruit juice	0	5	263	59
Salt	0.7	0.0	0.0	0.2

[1] Scenario A includes nutrient and epidemiological constraints and criteria alone. The energy level of this modeled diet is 2730 kcal.

[2] Scenario B includes nutrient, epidemiological, and food habits constraints and criteria. The energy level of this modeled diet is 2502 kcal.

[3] Scenario C includes nutrient, epidemiological, food habits, and contaminants and chemical substances constraints and criteria. The energy level of this modeled diet is 2470 kcal.

this relation is often nonlinear (e.g., fruits and vegetables) (43).

Integrating dietary habits in food pattern modeling

The step-by-step approach offered opportunities to analyze the importance of taking account of prevailing dietary habits in food pattern modeling, in this case comparing the results of scenarios A and B (**Table 1**). Optimization performed according to scenario A identified a modeled diet that contained only 11 food groups out of a total of 32. This modeled diet provided appropriate amounts of nutrients when compared with lower and upper DRVs and was the most effective in achieving this while minimizing/maximizing the intake of food groups for epidemiological reasons, but it was clearly very distant from the French dietary habits described in the INCA2 study (44). By zeroing the intake of 21 groups out of 32, it also produced a monotonous food pattern. In addition, some groups were proposed in large quantities, such as vegetables (1.3 kg/d) and plain wholegrain cereal products (800 g/d), and such levels might not be acceptable for physiological reasons (Table 1).

Under scenario B, consumption limits were set for each food group to account for the dietary habits of the population (Supplemental Table 2). In most cases, these lower and upper limits were based on the consumption levels estimated in the INCA2 study (i.e., fifth percentile and 95th percentile). Making the modeled diet fit within the range of observed levels of intake is indeed a simple way to restrict it to realistic food patterns that would in principle be acceptable. However, it constitutes a simplification because the acceptability of the level of intake for each group is not independent of that of the other food groups. Some groups should be considered to be more easily substitutable for each other when they belong to the same overall food group. The working group chose to make these adjustments when it became apparent that they were necessary, and this proved to be the case for groups that were important contributors to nutrients with very low levels of intake in the prevailing diet of the population as compared with the DRV, namely fiber and α-linolenic acid (ALA) (10). It was therefore considered that:

- "Wholegrain bread and bread products" consumption could replace "Refined bread and bread products" consumption;
- "Other wholegrain starches" such as brown rice and whole wheat pasta consumption could replace "Other refined starches" consumption;
- "Vegetable oils rich in ALA" consumption could replace "Vegetable oils poor in ALA and margarines" consumption.

In the optimization model, the working group set no upper consumption limit for any of these 3 groups that could be used to replace others but an upper limit corresponding to the 95th percentile of consumption of the sum of the 2 replaceable groups.

This illustrates the importance of correctly representing the substitutability of food groups when accounting for the acceptability of a modeled diet when compared with prevailing dietary habits, and also the fundamental importance of food grouping and its associated hierarchical structure system. We used a simple representation that only introduced complication when it seemed necessary, but a more complex representation could be used in the future.

It should also be considered that foods might be grouped according to the dietary habits, so that they can be translated to the public in relevant information on practical grounds while also taking account of nutrient composition to offer a nutritional lever to identify optimal food patterns (33, 45). The importance of further distinguishing food groups as a function of their nutrient contents, and particularly those with upper constraints of intake was discussed in the context of developing food patterns for the Dietary Guidelines for Americans (46–48) and Australian dietary guidelines (33).

Adapting the model to achieve DRVs

Although the modeled diet identified under scenario A met all DRVs, no modeled diet was found in the first instance when adding the constraints related to dietary habits (scenario B). The working group therefore chose to make some adaptations regarding vitamin D for men and vitamin D, iron, and fiber for women. Because it is widely acknowledged that the DRVs for vitamin D and iron are very difficult to achieve (34), it was not surprising that they finally precluded finding a modeled diet when considering dietary habits that did not differ to a great extent from the prevalent situation. One reason is that PRI values were set using maximalist criteria and hypotheses. Indeed, the PRI for vitamin D was established assuming endogenous synthesis via exposure to the sun to be zero. This extreme hypothesis was selected because it is not possible to estimate the level of endogenous synthesis in the population and it was found necessary to cover the requirements of virtually all the population.

Another situation is when the nutrient requirement varies markedly within a population for which the PRI needs be set. Among females, the distribution of iron requirements is dependent on menstrual losses, which vary considerably and could be qualified as "low or normal" or "high". These 2 levels produce 2 populations with markedly differing PRI values: 11 mg/d for low-to-normal losses (corresponding to ∼80% of menstruating women), and 16 mg/d for high losses (∼20% of menstruating women) (10). Because of this difference in prevalence and in constraints regarding the PRI value for iron, it was considered that 2 food pattern modeling processes should be performed. The PRI for iron was less constraining in females with low-to-normal losses, so fewer adaptations were necessary to determine modeled diets when compared with females with high losses. Despite an exploratory approach, no modeled diet could be identified with optimization requiring 16 mg/d iron; the highest value modeled was 15.2 mg/d iron but this was at the expense of meeting certain other DRVs (calcium, ALA, EPA+DHA, vitamins C and D, and fiber). The optimization model parameters and modeled diet identified for women with low iron requirements was therefore generally retained, especially when deriving the iron PRI to other specific female populations such as adolescents.

As expected, because the DRVs for some nutrients were the same as for men but the energy requirements were lower, more adaptations in women were necessary to determine modeled diets achieving the DRVs. In particular, a 15% tolerance was applied to the constraint for fiber, which produced a food pattern with an intake >25 g/d. This adaptation to the model was chosen because fiber was proving to be compelling, and indeed the DRV for fiber at 30 g/d was based on an epidemiological dataset indicating a beneficial effect that started at 25 g/d.

These examples illustrate the need to understand the setting of DRVs so that some flexibility or tolerance can be included in the optimization process when this is necessary.

Another type of adaptation was made to identify modeled diets achieving the DRVs; this consisted of waiving the upper group intake constraint, that is, allowing a modeled diet with a food group intake that exceeded the 95th percentile of prevailing intake. This was implemented for a few groups identified as constituting potential levers for limiting nutrients in women (such as fiber and iron), and the consumption observed was deemed to be low in absolute values. In this case, indeed, a higher consumption was at odds with current dietary habits (a maximum of half a serving per week) but was considered to be relatively acceptable because the overall final intake remained reasonable in absolute value terms (a few servings per week) and could enable acceptable substitution with other groups (10). This was the case for legumes, which not surprisingly were identified from the nutrient-based food grouping as a specific group within the larger starchy food group; they are well known to convey an interesting nutrient package that includes limiting nutrients such as fiber and iron (49). At present, legumes are consumed at low levels, but could be considered as a replacement for other starchy groups while not disrupting dietary habits. This example illustrates the possible integration of information at the intersection of food groupings and dietary habits to identify appropriate nutritional solutions for modeled diets.

Integrating information on food contaminants

For men, when contaminants were integrated under scenario C, an acceptable modeled diet was identified by introducing flexibility in 3 constraints relative to hexabromocyclododecane (HBCDD) and polybromobiphenyls (brominated flame retardants) and polycyclic aromatic hydrocarbons. For HBCDD, exposure resulting from the modeled diet was twice that observed in the population (50). Because the resulting margin of safety was much higher than the critical margin (51), this exposure was unlikely to involve a health risk. All the other constraints were satisfied. By contrast, in women, no optimized modeled diet could be found when including contaminant constraints and criteria. Indeed, under scenario B, the exposure of women to several contaminants (nickel, lead, inorganic arsenic) already exceeded the exposure threshold retained. As previously mentionned, this situation could be explained by the fact that many DRVs and HBGVs are identical for men and women, but energy requirements are lower for women, thus driving the model toward more nutrient-dense food groups and limiting the modeled diets available. An exploratory review was conducted to identify the set of constraints that prevented the optimization, but the list and types of contaminants are extensive. It was decided not to prolong this review because it would have led to an excessive number of constraints to which either tolerance or flexibility should have been applied, without clearly identifying the robustness of the many possible complex adaptations that would have been made. This would have taken us too far away from the initial objective.

The addition of contaminant constraints and criteria in men (i.e., scenario C compared with scenario B) did not result in a very different food pattern. Because an identified food pattern is a global and unique modeled diet produced by an optimization model that is markedly multifactorial, it remains difficult to ascribe differences in food patterns between scenarios to one parameter. It is important to note that the modeled diet identified as optimal by the optimization model is not the only one solution. There are other solutions that are nearly as effective with regard to the objective (suboptimal solutions) but are quite different from the final optimal solution. Indeed, it can be noted that the modeled diet in scenario C does not include milk, but it does not necessarily imply that milk is too contaminated to be included; the correct interpretation is that this model diet is the best compromise taking into account all of the objectives and the multiple constraints. There are other solutions, such as including higher milk consumption, but they are less optimal globally. Lastly, a shift from nonfat fish (including tuna) and other seafood in the food pattern under scenario B to eggs and poultry under scenario C caused a 50% reduction in methylmercury exposure while meeting the DRV for EPA+DHA (Table 1). This also further illustrates in the case of contaminants, the importance of food grouping (46–48). For 85% of the contaminants for which a contaminant constraint was included, exposure levels were lower under scenario C than scenario B, by $\leq$90% for some substances. In addition, exposure was also reduced when compared with that for some substances that represent a health concern, for example, acrylamide, aluminum, lead, or cadmium. As for pesticides, no food patterns resulting from any scenario reflected exposure higher than the tolerable daily intake.

Uncertainties and limitations

As shown by the different points discussed above, many of the variables and parameters used in the optimization model involve considerable uncertainties and presumably systematic bias. These uncertainties concern DRVs, HBGVs, food composition and contamination databases, dietary intake estimates, epidemiological risk associations, and indeed all the data required to establish FBDGs (5, 7). Because the method uses all these data at the same time, it also gathers all their related uncertainties, which presumably results in marked uncertainty, thus limiting the usefulness of the results. Two types of uncertainties should in particular be mentioned. The first concerns numerical uncertainties when estimating values that are then applied as strict constraints in the model, such as an upper value for a contaminant. This marked uncertainty might simply reflect the limitations of our knowledge, but that should not hinder its use if it stems from an evidence-based framework (3, 52). The second is theoretical uncertainty linked to the strength of the relation between a nutrient and the health-related outcome that has been used to set the DRV for that nutrient. However, when a DRV is set as an AI that is not based on health-related criteria but just the mean of intake in prevailing diets, the value was not used as a constraint in the model.

Our approach also has some other important theoretical limitations. In particular, and as discussed above, it uses a very simplified method to integrate the different relations between the consumption of some food groups and long-term health. Future developments could benefit from using finer models for comparative risk assessment and trying to integrate the information in the optimization model.

Conclusions and Perspectives

The approach presented here for identifying HEPs in France proved efficient and highly informative. The first basic but important finding was that the modeling study was able to determine modeled diets, that is, identify diets that complied with the extensive series of constraints fixed beforehand (such as lower and upper values for DRVs, HBGVs, and upper values for the consumption of different food groups), thereby proving their compatibility. The optimization model also succeeded in finding diets that resulted in optimum achievement of the objectives, that is, optimal changes to food groups and minimal exposure to contaminants, with a minimal deviation from prevailing diets. Although this result had indeed been expected, this work at the level of the average population also allowed little room for combined compliance with all constraints, because these were set to protect the entire population from the insufficient or excessive intake of nutrients and contaminants. Indeed, the process was designed to cover the requirements of almost all individuals while taking account of any variability and not exceeding values that would be protective even when uncertainties and interindividual differences were considered. Although a nutrient-based compared with a dietary pattern approach has been criticized (8, 53, 54), our method allowed us to gather this information and produce a solution combining both basic approaches, which should avoid any confusion in terms of messages for the public (55). The advantage of the approach presented here is that it not only highlights one diet or a series of diets that meet the constraints and health objectives but also identifies scenarios where the constraints become active and require a degree of tolerance or flexibility. The fact that we were forced to waive the vitamin D requirement, consider 2 populations and PRIs for iron levels in menstruating women, and add some tolerance for the fiber PRI in women all constitute nutritional insights gained from implementing this methodological process.

More generally, we were also able to show that certain nutrients appear to be critical (e.g., iron, iodine, zinc, fiber, EPA, and DHA), particularly in women, and so are some food groups that convey an interesting nutrient package (e.g., legumes). Greater nutrient density is known to be crucial when modeling diets (46, 48). Future directions could consist of intensive use of the optimization model to identify the active constraint and more generally to conduct a sensitivity analysis to clarify the critical nature of certain parameters such as DRVs or the level of consumption of a food group (48) and thus further rationalize the approach. Efficient methods to identify active constraints in a large and heterogeneous set of constraints and running sensitivity analysis would also be helpful to further explore situations that are overconstrained, such as the case of adding contaminants when modeling a diet for women. Overall, our insights are of considerable value to understanding the key issue in diet optimization and elaborate specific features of dietary guidelines while insisting on these key parameters. Our approach enables the exploration of potential conflicts or alignments between the nutritional levels (nutrient intakes compared with dietary patterns) that traditionally affect the FBDGs (8, 31, 54). It also offers perspectives for public health nutrition because it highlights the lever that needs to be activated to reduce the number of modeled diets or find better options than those already identified. This is particularly the case when considering strategies for diet fortification with nutrients that are too constraining, or when reinforcing strategies to reduce excessive quantities of chemicals in the foods produced and processed at present (e.g., acrylamide in women, or pesticides where HEPs contribute to increasing exposure). However, a limitation of the model is that it considers HBGVs separately for each substance but not any mixture effects. Both methodological developments and contaminant data are still required to address the issue of mixture effects in such models.

The method is also very useful when reasoning the degrees to which the varied objectives of optimization are aligned or in conflict. We were able to show that the minimal deviation from the prevailing diet, and in particular the constraint of not exceeding the highest levels of consumption observed for some food groups, might hinder the identification of interesting modeled diets. In this regard, it was particularly significant that permitting a relatively high intake of legumes and whole grains (i.e., higher intakes than the observed intakes, which are indeed very low) resulted in finding better modeled diets to ensure an adequate nutrient intake, especially for women. Little deviation from the usual diet is indeed a simple way to account for cultural acceptability, one component of diet sustainability as defined by the FAO (56). However, it remains difficult to assess the actual acceptability of these changes, especially when considered at the level of each specific food group that might be identified as a lever from a nutritional standpoint. The general approach presented here could therefore be of considerable value when further exploring the tradeoffs between the acceptability and quality of a diet.

In this regard, the method should be very useful when determining optimal food patterns for groups in the population with a different background diet that yields different constraints and levers—for example, special diets such as those adopted by vegetarians or minorities, or specific subpopulations such as young adults or the elderly (7, 31, 45, 48). It might also be very useful when defining a series of optimal diets that deviate gradually from prevailing diets and eventually become very different from the currently observed diets.

Lastly, because the method is reliant on multicriteria optimization, it naturally offers an opportunity to integrate new criteria, which is key to the FBDGs (7, 31). Environmental issues are critical to defining sustainable diets and, as has previously been argued, the environmental changes induced by diet can markedly affect the safe operating space for humanity and have direct implications for food systems (7, 57). It is therefore advocated that environmental sustainability should be integral to the definition of FBDGs (58, 59). The alignment of current dietary recommendations with environmental sustainability can be studied at a second stage (60, 61). However, it might be better to integrate these criteria in the optimization model to identify those diets that best combine such multiple criteria, and more precisely characterize the tradeoffs between different dimensions of sustainability, for example, the conflict between environmental sustainability and limited deviations from the prevailing diet (62–64).

As we have discussed above, our method is not perfect inasmuch as it aggregates uncertainties and is reliant on a complex definition of constraints and the objective, and often latent weighting of the multiple criteria that are critical to understanding the intricate behavior of the optimization model. However, the approach provides a unique, rational, and systematic method to conceptualize and operationalize these aspects to enable the derivation of FBDGs based on multiple criteria containing all the information available (3, 7, 8). The method that we used offers a unique approach for the establishment of HEPs for dietary guidelines and it will probably become increasingly essential as the evidence base grows and requires a holistic approach (7).

Acknowledgments

The authors' responsibilities were as follows—SH, IM, FM, AM, PN, VS, and SW: were involved in the conceptualization, planning, drafting, and editing of the manuscript; SH, IM, FM, AM, PN, VS, and SW: contributed to specific sections and editing of the manuscript; and all authors: read and approved the final manuscript.

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