Design of Optimal Food-Based Complementary Feeding Recommendations and Identification of Key "Problem Nutrients" Using Goal Programming[1,2]

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Abstract

The WHO is urging countries to promote improved complementary feeding practices to ensure optimal health, growth, and development of young children. To help achieve this, a rigorous 4-phase approach for designing optimal population-specific food-based complementary feeding recommendations (CFRs) was developed and is illustrated here. In phase I, an optimized diet is selected, using goal programming (Model #1), which aims to provide a desired nutrient content with respect to habitual diet patterns and cost. Based on its food patterns, a set of draft CFRs is designed. In phase II, their success for ensuring a nutritionally adequate diet is assessed via linear programming (Model type #2) by sequentially minimizing and maximizing the level of each nutrient (i.e., worst and best-case scenarios) while respecting the CFRs. For nutrients that are <70% of desired levels, the best food sources are identified via linear programming in phase III (Model #3). Different combinations of these foods are incorporated into the original draft of the CFRs to produce alternative CFRs, which are then compared on the basis of their cost, flexibility, and "worst-case scenario" nutrient levels (Model type #2) to select, in phase IV, a final set of CFRs. A hypothetical example is used to illustrate this approach. Outcomes include a set of optimal, population-specific CFRs and practical information regarding key "problem nutrients" in the local diet. Such information is valuable for nutrition promotion, as well as nutrition program planning and advocacy, to help achieve global initiatives for improving the complementary feeding practices of young children living in disadvantaged environments. J. Nutr. 136: 2399–2404, 2006.

Introduction

Ensuring optimal complementary feeding practices for young children living in developing countries is a global public health priority because of their overwhelming importance for optimal growth, development, and well-being of infants and young children. In this respect, the WHO and UNICEF provide, as a high priority action in their Global Strategy for Infant and Young Child Feeding, guidance on appropriate complementary feeding, with an emphasis on the use of suitable locally available foods (1).

Several approaches exist for designing population-specific recommendations that are based on locally available foods (2–5). These approaches usually involve expert consultation that takes into account the most common nutritional problems, as well as such factors as cultural food consumption patterns, acceptable foods (available, affordable, and regularly consumed), realistic food portion sizes, and the impact of recommendations on other nutrients and the environment. To facilitate this consultation process, a multifactorial approach based on linear programming analysis, which simultaneously takes into account multiple factors, including diet, nutrient content, cost, and cultural was recently developed (6). However, its disadvantage for designing realistic food-based complementary feeding recommendations is that nutritionally adequate combinations of local foods often do not exist, especially for rural infants living in developing countries (7–9). This results in nonfeasible solutions unless model nutrient constraints are arbitrarily changed. Hence, a new approach was needed to overcome this shortcoming. In this new approach, using goal programming, the desired nutrient levels are modeled as goals instead of constraints, therefore allowing for feasible solutions even when realistic combinations of local foods do not provide the desired nutrient levels. Hence, unlike other diet problems modeled via linear programming (6,10–13), the optimal results will not necessarily ensure that current nutrient recommendations are

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achieved. Instead, the primary aim is to identify realistic and sustainable complementary feeding recommendations for the target population, given their habitual dietary practices and the local food supply, and to objectively define the key "problem nutrients" for their complementary feeding diet. Such information can then be used for intervention program planning and advocacy, as well as nutrition promotion, to help realize global initiatives for improving complementary feeding practices. Our aim is to describe in detail the technical aspects of the approach, using an illustrative hypothetical example.

Materials and Methods

Population-specific food-based recommendations are designed using a 4-phased approach based on linear programming. Phase I formulates, via a goal programming model (Model #1), a first draft set of food-based complementary feeding recommendations (CFRs)[7] that are realistic, i.e., that correspond to the target population's actual dietary practices and promote an affordable and nutritionally favorable diet. In phase II, the first draft CFRs are evaluated via a set of linear programming models (Model type #2) to assess their success at ensuring that diets, which strictly fulfill them, will achieve the desired nutrient levels. The results of these analyses indicate whether modifications to the first draft CFRs are required. They also can be used to justify alternative intervention strategies, such as fortification. In phase III, another linear programming model (Model #3) is used to identify nutrient-dense food(s) that can be incorporated into the first draft CFRs to improve them. Alternative combinations of these nutrient-dense foods are then incorporated into the first draft CFRs to produce alternative CFRs that are comparatively evaluated in phase IV (Model type #2) to select the best alternative CFR for further evaluation in community trials. Models #1 and #3 are run once (in phases I and III, respectively), whereas Model type #2 is run multiple times with 1 variable minimized or maximized (i.e., a nutrient or cost) per analysis. The decision variables in all models, which are variables whose values change to achieve a model solution, are the weights of the food (in grams) provided in the optimized diet. For the goal programming model (Model #1), additional decision variables are required to allow for the underacheivement and/or overachievement of specific goals in the final optimized diet. In all models, constraints on diet energy content, food pattern ranges, food portion sizes, diet cost, food groupings, or food combinations (linkages) can be used to ensure realistic optimized diets (see **Table 1**).

The data required for the models include a list of foods consumed by the target population, and then, for each food, its minimum portion (= 0, for most foods), its average-sized daily portion (g/d), its maximum weekly portion (g/wk), its cost per gram, its food group category, and its energy and nutrient content. In addition, information to define Model #1 goals (i.e., desirable diet nutrient content, cost, and/or food patterns) is required.

If the goals or model constraint levels differ for different subgroups within the target population, then a separate set of models (phases I –IV) are run for each subgroup. For example, for a target population of 6 to 11-mo–old infants, it would be run twice, i.e., one time each for the 6 to 8-mo–old and 9 to 11-mo–old infants independently, because of age group differences in energy requirements and dietary practices (food portions, the types of food eaten, and food patterns). Likewise, to formulate CFRs for target populations of similar-aged breast-fed and nonbreast-fed infants, separate sets of models (phases I–IV) are required. For breast-fed infants, a constraint is included to force a specific amount of breast milk into the Model #1 and Model type #2 optimized diets; whereas, for nonbreast-fed infants, breast milk is excluded from all optimized diets. All linear programming analyses were done using the Simplex procedure of the Premium Solver 3.5 for Excel (Frontline Systems), although the regular solver function, which is accessed from the "tool" menu in Excel, can also be used when only a few foods are modeled (10). The parameters for each model are described in detail below.

[7] Abbreviations used: CFRs, food-based complementary feeding recommendations; IMCI, Integrated Management of Childhood Illness; RNI, recommended nutrient intakes.

TABLE 1 Nonmathematical descriptions of model constraints and the models in which they can be used[1]

Model constraints	Models[2]
1. To ensure food portions and deviation factors (model #1 only) are ≥0	1,2 & 3
2. Goal constraints to define the deviation factor values, i.e., [(goal– actual) / goal] + negative deviation − positive deviation = 0	1
Hard constraints:	
3. To ensure food group patterns (servings/wk from food groups) ≤maximum	1 & 2
4. To ensure food group patterns (servings/wk from food groups) ≥minimum	1 & 2
5. To ensure diet energy content = average energy requirement of target group	1 & 2
6. To ensure food portions sizes ≤maximum amounts, *g*	1,2 & 3
7. To ensure food portions sizes ≥minimum amounts, *g* (usually zero)	1 & 2
8. To ensure servings/wk per food group ≥CFR	2
9. To ensure optimized food combination's nutrient content ≥specific level	3
10. To ensure the optimized diet cost ≤specific cost	1,2 or 3
11. To ensure g of base food ≥ratio × g of dependent food (food linkages)	1,2 or 3
12. To ensure the number of servings/wk of similar foods (e.g., different kinds of biscuits) ≤specific number of servings/wk (e.g.,7 servings/wk)	1,2 or 3

[1] Mathematical descriptions of constraints are available in supplemental Tables 1 and 2.
[2] The models in which the constraint can be used are represented by Model #1, Model type #2, and Model #3.

Phase I: Formulation of first draft CFRs. In phase I, the first draft CFRs are formulated via a goal programming model (Model #1) because it allows trade-offs to occur among conflicting goals, which, in the context of formulating CFRs, include the diet's desired nutrient content (nutrient goals), cost (cost goal), and food group patterns (food pattern goals). The objective function in a goal programming model minimizes the undesirable deviations from the target goal levels instead of minimizing or maximizing the goals themselves. In the context of formulating CFRs, an undesirable deviation for a nutrient goal is the extent to which the optimized diet's nutrient content falls below the target nutrient level (e.g., an undesirable negative deviation of 2 mg/d occurs when the optimized diet's iron content is 3 mg/d instead of a targeted 5 mg/d); for the cost goal, it is the extent to which the optimized diet's cost is > target cost level (e.g., an undesirable positive deviation of \$1/d occurs, when the optimized diet's cost is \$2/d instead of the targeted \$1/d); and for the food pattern goals, undesirable deviations are those both > (positive deviations) and < (negative deviations) the target food pattern levels. In Model #1, to standardize the undesirable deviations, they are expressed as a ratio difference (i.e., (desired − actual) / desired) instead of an absolute deviation. In addition, differential weighting can be applied to more strongly penalize an undesirable goal deviation in relation to others, e.g., weighting the iron deviation more strongly than other deviations because widespread iron deficiency is common. The algebraic structure of the phase I objective function is:

$$\text{Minimize}\left[\underbrace{\left(\sum_{i=1}^{m_1} w_i d_i^-\right)}_{\text{Nutrient goals}}+\underbrace{\left(w_{m_1+1} d_{m_1+1}^+\right)}_{\text{Cost goal}}+\underbrace{\left(\sum_{g=m_1+2}^{m_1'} w_g\left(d_g^-+d_g^+\right)\right)}_{\text{Food pattern goals}}\right],$$

where m_1 = the total number of nutrients modeled and m_1' = the total number of goals in the model; d_i^- = the negative deviation factor for nutrients; $d^+_{m_1+1}$ = the positive deviation factor for cost; d^-_g *and* d^+_g = the positive and negative deviation factors for the food consumption patterns. Each goal's relative importance is defined by the weights (i.e., w_i, w_{m_1+1}, w_g).

In these models, goal constraints establish the deviation factor values and hard constraints ensure a realistic optimized diet (see Table 1). The mandatory hard constraints are those that ensure a specific diet energy content, food pattern range, maximum food portion sizes, and, if breast-feeding infants are the target population, a specific amount of breast milk. For a goal constraint, its format is as follows: [(desired – actual) / desired] + $d^-_v - d^+_v = 0$; where "desired" is the target goal level, "actual" is the amount selected in the optimized diet; d^-_v is a negative deviation factor, and d^+_v is a positive deviation factor. Hence, if the desired and actual values differ, a deviation factor will take the necessary value for the equation to equal zero.

Once a satisfactory phase I optimized diet is obtained, the number of average-sized servings of food/food group (e.g., 1 banana + 1 guava = 2 servings/d of fruit) defines the first draft CFRs. This process is necessary because an actual diet (i.e., list of individual foods) is too specific to use as a CFR. This approach also assumes that CFRs resembling the target population's mean dietary patterns will be more readily adopted than alternatives; and that diets providing ≥ the phase I optimized diet's number of food servings/food group, are more likely than others to achieve the desired nutritional and cost target levels.

Phase II: Test the first draft CFRs. In phase II, these draft CFRs are tested via a set of linear programming models (Model type #2). In this set of models, the CFRs are imposed via a set of food-based recommendation constraints (e.g., diet must provide ≥2 servings of fruit/d). Other model constraints (see Table 1) ensure that each optimized diet is a realistic one for the target population. In the initial set of runs in phase II, the objective function minimizes each nutrient and cost individually to estimate the CFRs' robustness for ensuring a nutritionally adequate diet, i.e., defining the "worst-case scenario" nutrient levels and the lowest diet cost (e.g., a total of 13 optimized diets for 12 nutrients and cost). In the second set of runs (optional), it maximizes selected nutrients (i.e., those which did not achieve 100% of desired levels in the phase I optimized diet) to determine if locally available foods can provide the desired nutrient levels, i.e., defining its "best-case scenario" nutrient levels. These analyses, therefore, define, for a given dietary energy level and food pattern range, the extreme nutrient/cost values expected in a diet that fulfills the CFRs. They also classify the "problem nutrients" into 2 categories, namely, outright "problem nutrients," which are necessarily low in the local diet (i.e., both the minimized and maximized levels < desired amounts) and partial "problem nutrients," for which only the minimized levels are < the desired amounts.

The objective functions for the Model type #2 analyses, which are each analyzed independently, are shown below.

$$\text{Minimize} \sum_{i=1}^{r}\sum_{j=1}^{n_i}\left(X_{ij}\times \boldsymbol{nut}_{ijn}\right); n \in \mathrm{N},$$

$$\text{Minimize} \sum_{i=1}^{r}\sum_{j=1}^{n_i}\left(X_{ij}\times \cos t_{ij}\right),$$

$$\text{Maximize} \sum_{i=1}^{r}\sum_{j=1}^{n_i}\left(X_{ij}\times \boldsymbol{nut}_{ijn}\right); n \in \mathrm{N},$$

where X_{ij} = g selected of food item *"i"* in food group *"j"; nut_{ijn}* = the nutrient content *"n"* of food item *"i"* in food group *"j"* from the set of *N* nutrients; $cost_{ij}$ = the cost/g of food item *"i"* in food group *"j"*; r = number of food groups; n_i = number of food items "j" in food group "i."

In these models, the model constraints (see Table 1) ensure that each optimized diet provides a specific amount of energy, remains within a given food pattern range, provides realistic food portions, and achieves the CFRs. Similar to the phase I model, if breast-fed infants are the target group, then model constraints also ensure that a specific amount of breast milk is included in the optimized diet. Additional constraints, depending on the target population's diet complexity, can also be included (see constraints #10–12 in Table 1). Hence, the objective function values, for the set of phase II models, will never equal zero.

In the phase II analyses, if all nutrients achieve or exceed a defined level in their "worst-case scenarios" (e.g., 70% of RNIs), then the CFRs are accepted without further modification. If, however, ≥1 of the nutrients fall below this level, then the nutrient-dense foods that will provide them are identified in phase III.

Phase III: Identify specific foods to improve the first draft CFRs. In phase III, a linear programming model (Model #3) identifies nutrient dense foods that can be incorporated into the draft CFRs to help improve them. Specifically, this model, which is run only once, identifies the minimum number of foods that together will provide the desired amounts of each "problem nutrient," e.g., those nutrients that were <70% of their desired nutrient levels in phase II. The required amount is equal to the difference between the desired nutrient content (or its optimal level if this was <100% of the desired level in the optimized Model #1 diet) and its "worst case scenario" level (from Model type #2). For example, if the Model #1 optimized diet provided 50% of the desired 5 mg/d of iron and the "worst-case scenario" for iron (Model type #2) was 20% of this desired level, then Model #3 would select foods that provide 1.5 mg/d of iron (i.e., 0.5 × 5 – 0.2 × 5). Here 50 instead of 100% of the desired nutrient levels was used because 100% is unrealistic. The objective functions for this analysis is:

$$\text{Minimize} \sum_{i=1}^{r}\sum_{j=1}^{n_i}\left(\frac{X_{ij}}{av_{ij}}\right),$$

where X_{ij} = grams selected of food item *"i"* in food group *"j"; av_{ij}* = the grams of an average portion of food item *"i"* in food group *"j"*; r = number of food groups; and n_i = number of food items *"j"* in food group *"i."*

In these models, model constraints (see Table 1) ensure that each optimized diet provides ≤ specific amount of energy, ≤ an upper food pattern range, ≤ specific maximum food portion sizes, and ≥ specific nutrient content. Unlike the previous models, breast milk is never included in the list of eligible foods. Similar to the above models, additional constraints from Table 1 can be included.

Phase IV: Compare alternative second draft CFRs. The results from Model #3 identified the number of portions of nutrient dense foods that together will provide the desired amount for all "problem nutrients." If the number of foods is excessive, then only the most important 3–4 food sources for these nutrients are selected. Alternative second draft CFRs are then formulated, using alternative combinations of these foods incorporated into the original first draft CFRs (from phase I). For example, if Model #3 selected 2 servings each of chicken liver and anchovies, then, within a full set of CFRs, a recommendation "≥4 servings/wk of animal source foods" could be changed to several alternatives including "≥4 servings/wk of animal source foods, including at least 2 servings/wk of chicken liver" or to "≥4 servings/wk animal source foods, including at least 2 servings/wk of anchovies and 1 serving/wk of chicken liver." Local experts with an in-depth knowledge of local food preferences and patterns could help formulate these alternative second draft CFRs while taking into account their acceptability in relation to expected nutrient benefits. These alternatives are then rapidly tested (e.g., <15 min overall), using the minimization process in Model type #2 to define their lowest cost and, for the "problem nutrients," their "worst-case scenario" nutrient levels. Based on these results as well as additional considerations, such as food-based recommendation flexibility, complexity, and acceptability, the final set of CFRs is selected from among the alternatives for further field trials and consultation.

Data to illustrate the approach. Dietary data, which were based on a subset of dietary data collected from rural breast-fed 9 to 11-mo–old Indonesian infants, were used to illustrate our approach. Only a subset of the original data were used, so that the model parameters (see **Table 2**) could be shown for readers interested in replicating our analyses. A food not consumed by these infants was also used (i.e., peanut sauce) to illustrate the use of a food linkage constraint. Ethical approvals for

TABLE 2 The data used in the models for illustrating the mathematical optimization approach to developing complementary feeding recommendations[1]

Food types	Mean,[2] *g/serving*	Maximum,[3] *g/wk*	Price, *cost unit/g*
Breast milk	616	4312	0
Staples[4]	21	28	
Cooked white rice	35	50	1.2
White rice flour	20	30	5.0
Fortified cereal	20	20	40.0
Animal Source Foods[4]	2	3	
Chicken liver	30	45	78.0
Dried anchovies	20	30	29.0
Large fish	40	60	13.0
Egg yolk	15	23	35.8
Legumes[4]	3	7	
Soya product	35	53	4.7
Peanut sauce	15	23	7.0
Vegetables[4]	7	14	
Leaves	10	15	1.7
Tomato	15	23	4.5
Snacks[4]	14	28	
Banana	60	90	3.0
Papaya	75	112	6.0
Plain biscuits	12	18	12.0
Frilly biscuits	15	23	14.4
Cassava	30	45	1.3
Peanuts	10	15	7.0

[1] The data include the list of foods and their mean (g/serving) and maximum weekly amounts (g/wk); the food pattern descriptors and their mean and maximum allowed levels (servings/wk); and the price of each food (cost unit/g).

[2] For individual food items, mean = mean daily portion size (g/serving); and, for the food pattern descriptors, mean = mean number of servings/wk in a given food group (i.e., staples, animal source foods, legumes, vegetables and snacks).

[3] Maximum portions are expressed as g/wk, for individual food items and servings/wk for the food pattern descriptors.

[4] A food pattern descriptor; its mean value was used for the objective function goals (Model #1) and its maximum value as a model constraint in all models.

collecting the dietary data were obtained from the Ethics Committees of the Medical Research of the Faculty of Medicine, University of Indonesia and the University of Otago. The data used in our example included a list of foods, food pattern descriptors and their acceptable ranges, and, for each food item, its price (cost units/g), its realistic portion size (g/serving), and an acceptable maximum weekly amount (g/wk) (Table 2). Breast-fed infants were the target population, so consequently, both the minimum and maximum constraint levels for breast milk were identical to ensure that a specific amount of breast milk was included in the Model #1 and the set of Model type #2 optimized diets. In this example, the food pattern descriptors (expressed as the number of servings/wk) were cereal staples, animal source foods, legumes, vegetables, and snacks.

In phase I, the nutrient goals in Model #1 aimed to achieve or exceed the FAO/WHO Recommended Nutrient Intakes (RNI) (14), the cost goal aimed to remain at or below 12.00 cost units/d, and the food pattern goals aimed to provide 21 servings/wk of cereal staples, 2 servings/wk of animal source foods, 3 servings/wk of legumes, 7 servings/wk of vegetables, and 14 servings/wk of snacks. These values represent acceptable levels for the target population (e.g., mean levels in the population). Moderate bioavailability was assumed for the iron and zinc nutrient goal levels. All goal weights were set as 1, except for the iron goal, which was weighted by 10 to reflect its higher relative importance compared with the other goals. The constraints, modeled from Table 1, were those on minimum and maximum food pattern levels (see Table 2 for food pattern descriptors and values); maximum food portion sizes (see values in Table 2); diet energy content, i.e., 2870 kJ/d (15); daily breast milk intake level, i.e., minimum and maximum portion sizes for breast milk = 616 g/d (16); a food linkage between the quantities of peanut sauce and rice, i.e., g rice $>20 \times$ g peanut sauce; on groups of similar foods for biscuits, i.e., $\leq$7 servings/wk; and on maximum diet cost, i.e., 25.00 cost unit/d. The first draft CFRs, which were formulated from the phase I optimized diet (Model #1), were based on the optimized diet's number of servings/wk of foods in the selected food group categories i.e., the cereal staples, animal source foods, legumes, vegetables, and snacks.

Results

The optimized phase I diet contained 2 servings/d of rice and 1 serving/d of fortified infant cereal (i.e., 3 servings/d of cereal staples); 3 servings/wk of soy products (i.e., 3 servings/wk of legumes); 2 servings/wk of chicken liver (i.e., 2 servings/wk of animal source foods); 1 serving/wk of biscuits; 5 servings/wk of banana; 6 servings/wk of cassava snack (i.e., ~2 snacks/d); and breast milk every day. The first draft of CFRs formulated in phase I (Model #1), therefore, included the following 6 recommendations: *1)* ≥3 servings/d of cereal staples, *2)* ≥2 servings/wk of animal source foods, *3)* ≥3 servings/wk of legumes, *4)* vegetables every day, *5)* ≥2 servings/d of snacks and *6)* breast milk every day. In formulating these recommendations, the diet cost exceeded the desired levels (i.e., 18.01 vs. 12.00 cost units/d) and, in the optimized diet, 100% of the RNI (14) were not achieved for calcium (70% RNI), iron (51% RNI), zinc (65% RNI) and niacin (80% RNI) (see **Table 3**; optimal nutrient levels*)*. In contrast, the goals for all other nutrients (i.e., ≥100% of the RNI for protein, thiamin, riboflavin, vitamin A, vitamin C, folate, and vitamin B-12) and food patterns were met.

The phase II analyses (Model type #2) showed that, in the "worst-case scenario," diets fulfilling the first draft CFRs provided >70% of the FAO/WHO RNIs (14) for all nutrients, except calcium (50% RNI), iron (12% RNI), zinc (36% RNI), niacin (42% RNI), and thiamin (67% RNI) (see Table 3). Of these, only iron and zinc did not achieve 100% of their RNIs for their "best-case scenarios" (i.e., their maximized levels were 65 and 83% RNIs, respectively; Table 3). Thus, iron and zinc were classified as outright "problem nutrients" and calcium, niacin, and thiamin were classified as partial "problem nutrients." Based on the phase II results, modifications to the first draft set of CFRs focused on providing higher amounts of iron, calcium, zinc, thiamin, and niacin.

The 5 nutrient-dense foods selected to provide the outright and partial "problem nutrients" in the phase III analysis (Model #3), were: chicken liver (2 servings/wk), anchovies (1 serving/wk), soy products (4 servings/wk), fortified infant cereal (7 servings/wk) and bananas (3 servings/wk). These foods, therefore, represent the lowest number of foods in the local complementary food supply that, together, will provide the desired amounts of calcium, iron, zinc, thiamin, and niacin (not taking into account nutrient bioavailability and the niacin contribution from tryptophan). Including each of these 5 foods individually into the CFRs (i.e., first 5 alternative second draft CFRs in Table 3) showed the comparative nutritional advantage of recommending a daily serving of fortified infant cereal for all problem nutrients [a range of 1.19 (niacin) to 2.75 (iron) times higher than other "worst-case scenarios"; Table 3] and of recommending anchovies for a source of calcium (1.48 times higher than other "worst-case scenarios"; Table 3). Of the other 3 foods selected, banana was the only one that did not improve the problem-nutrient "worst-case scenario" levels (Table 3). Hence, it was not considered further.

Of the 12 alternative second draft CFRs considered, numbers 10–12 (Table 3) were the most promising, because they ensured >70% FAO/WHO RNI for calcium and thiamin, >60% FAO/

TABLE 3 Comparisons of the ''problem nutrient'' levels and cost of the optimal diet (phase I), the first draft CFRs (phase II; minimized and maximized values), and alternative second draft CFRs (phase IV; minimized values only)[1,2]

		Ca	Fe	Zn	B_1	B_3	Cost
				%R[1]			*CU[1]/d*
	Phase I, optimal	70	51	65	103	80	18.01
	Phase II, "best-case scenario"	120	65	83	128	125	NA[1]
	Phase II, "worst-case scenario"	50	12	36	67	42	5.12
No.[1]	Alternative second draft CFRs[3] – phase IV – "worst-case scenarios"						
1	2 servings/w of chicken liver (L)	50	19	44	76	63	10.30
2	2 servings/w of anchovies (A)	74	13	42	67	52	5.22
3	4 servings/w of soy product (S)	54	22	36	68	42	5.35
4	7 servings/w of fortified cereal (FC)	64	33	57	84	50	12.37
5	3 servings/w of banana	50	12	36	68	43	5.29
6	1 L + 1 A	62	16	43	71	58	7.76
7	1 L + 1 A + 4 S	66	26	43	72	58	7.99
8	2 A + 4 S	78	22	42	68	52	5.45
9	1 A + 4 S	66	22	40	68	47	5.40
10	1 A + 4 S + 7 FC	81	43	60	85	55	12.64
11	2 A + 4S + 7FC	93	44	64	85	61	12.70
12	1 L + 1 A + 4 S + 7 FC	81	47	64	89	66	15.23

[1] The definitions used in the table are: CFRs, food-based complementary feeding recommendations; No.,the alternative second draft CFR number; %R, optimized diet's nutrient content expressed as a percentage of the FAO/WHO recommended nutrient intake level (14); CU, cost unit; N/A, not analyzed; FC, fortified infant cereal; L, chicken liver; A, anchovies; S, soy product.

[2] The first draft CFRs evaluated, in phase II, were: *1)* ≥3 servings/d cereal staples, *2)* ≥2 servings/wk animal source foods, *3)* ≥3 servings/wk legumes, *4)* vegetables every day, *5)* ≥2 servings/d snacks, and *6)* breast-fed every day.

[3] CFRs evaluated in phase IV were based on the 6 first draft CFRs plus, for each alternative, the foods specified in the table expressed as the number of weekly servings (i.e., 1 L + 1 A = ≥2 servings/wk animal source foods, including 1 serving/wk of chicken liver and 1 serving/wk of anchovies).

WHO RNI for zinc, and >40% FAO/WHO RNI for iron. At this point, a decision is required as to whether the nutritional advantages for iron and niacin sufficiently outweighed the disadvantages of recommending chicken liver (cost, availability, and perishability) or an inflexible guideline for animal source foods (i.e., 2 servings/wk of anchovies). Similarly, the cost implications of recommending fortified infant cereal, which is the most expensive of the alternative foods selected (Tables 2 and 3), must be considered. In this hypothetical example, from among the 3 best alternatives, we selected the 10th set of recommendations for its greater flexibility and lower cost, even though its iron, zinc, and niacin "worst-case scenarios" were <65% and lower than some alternatives (see Table 3). The final set of CFRs, therefore, became: *1)* ≥3 servings/d cereal staples, including 1 serving/d of fortified infant cereal; 2) ≥2 servings/wk animal source foods, including at least 1 serving/wk of anchovies; *3)* ≥4 servings/wk soy products; *4)* vegetables every day; *5)* ≥2 servings/d snacks; and 6) breast milk every day. Assuming a breast milk intake of 616 g/d and an energy intake of 2870 kJ/d, a diet that fulfils the final set of CFRs and conforms to the local food consumption pattern, will ensure ≥70% of the FAO/WHO RNIs (14) for all nutrients except iron, niacin, and zinc (Table 3).

Discussion

The development of this objective and the rigorous mathematical optimization approach to design population-specific food-based recommendations is timely, given the global initiative to promote optimal complementary feeding practices. Unlike our previous approach (6), it selects an optimal diet even when nutrient recommendations are unachievable. This is particularly advantageous for designing complementary feeding recommendations in disadvantaged environments because micronutrient recommendations, especially those for calcium, iron, and zinc, are often impossible to achieve using local foods (9). This approach also provides critical information for nutritional program planning and advocacy by identifying and classifying the key "problem nutrients" in the local diet.

The design of food-based dietary recommendations often requires resolution of conflicting goals, such as low costs, nutritional adequacy, cultural acceptability, and environmental sustainability. For expert committees without an optimization tool such as ours, the process is time consuming, can lack transparency, and is prone to subjective and potentially biased judgments. Our approach, which is based on mathematical optimization, overcomes these problems, because all factors are modeled simultaneously and the model's goals can be weighted to establish their levels of relative importance. As such, decisions are transparent, objectively defined, and optimal solutions rapidly selected from among the countless alternatives. In addition, the nutritional and cost implications of alternative second draft CFRs (phase IV) are rapidly compared, which enhances confidence in decisions made and provides justification for the final CFRs selected. For example, in our hypothetical analyses, considerations of recommendation flexibility, cost, and food preference outweighed those of nutritional adequacy, and the nutritional implications of this choice were transparent (see comparisons made among alternative second draft CFRs in Table 3). In addition, this process addresses several important caveats raised in the FAO/WHO consultation report on the preparation of food-based dietary guidelines, particularly those related to cultural acceptability, practicality, and possible negative nutritional consequences (3).

In addition to the design of optimal population-specific food-based complementary feeding recommendations, our approach provides pertinent information for nutrition program planning. First, in phase II, the key "problem nutrients" are identified, including their predicted minimum, maximum, and optimal dietary intake levels for a given energy intake and food-pattern range (Table 3). For example, calcium, iron, zinc, thiamin, and niacin were the key "problem nutrients" in our hypothetical example, which also showed that dietary iron and zinc recommendations will be very difficult to achieve using local foods. Such information provides strong justification for nutrition intervention efforts that focus on these nutrients, especially if direct or indirect (via nutrient interactions) functional consequences of low intakes are common. It is also useful for purposes of nutrition advocacy.

A second pertinent type of information provided for nutrition program planning are the defined lowest nutrient levels predicted from the "worst-case scenario" analyses (phase IV). For example, in our hypothetical analyses, justification is provided for increased iron and zinc fortification levels in the fortified infant cereal. If this was unfeasible or insufficient, an evaluation of alternative strategies, such as food or nonfood supplements (8) is warranted to select and justify a final intervention strategy. Notwithstanding, caution is advised against the literal acceptance and overinterpretation of specific "worst-case scenario" values, because their exact values depend on specific model parameters.

Our approach would make a valuable addition to established protocols for designing food-based complementary feeding recommendations, such as the WHO/UNICEF's Integrated Management of Childhood Illness (IMCI) (17) or the Trial of Improved Practices (TIPS) (18). For example, if our approach was incorporated into the IMCI protocols (17), formulation of population-specific complementary feeding recommendations is possible using data from IMCI's worksheet 2 (i.e., food list, frequency, and amounts) plus additional information to define the goals for desired food patterns, costs (optional), and nutrient levels. An integration of approaches would allow an expansion, for example, of the IMCI from individual counseling to the promotion of population-specific food-based complementary feeding recommendations; and the qualitative procedures described in the IMCI and TIPS protocols provide an excellent framework for further evaluation and refinement of the CFRs via field trials and expert consultation. Clearly, the integration of approaches would be advantageous.

The major disadvantages of our approach include: the time required to set up the models, especially when the required data are not available; the potential sensitivity of results to data accuracy, especially in relation to the food pattern descriptors and the important food sources of the "problem nutrients"; issues related to nutrient bioavailability; and the need for a competent analyst. Of these limitations, the most important for wide-scale adoption and successful application are data accuracy and the need for a competent analyst. A robust, user-friendly interface, if successfully developed, would overcome the latter, and would also substantially reduce the time required to set up the models. With a user-friendly interface, nutritionists working for governments (down to the regional office level), universities, or nongovernmental organizations could use our approach with only a limited understanding of the underlying modeling process. In consultation with local experts, such as village midwives, they could use our approach to interactively formulate and try out alternative CFRs to select a final set to promote. Detailed survey data are probably not essential to define model parameters (6), however, validation studies are required to confirm this. For bioavailability, as described elsewhere (12,13), the models could incorporate absorbed nutrient level or prediction algorithms. In all cases, expert scrutiny of the optimized diets is advised.

In conclusion, we have developed and presented here a rigorous approach for formulating and evaluating culturally appropriate, population-specific food-based complementary feeding recommendations. Its distinct advantages over our previous approach (6) are that model solutions are feasible even when desired nutrient levels are unachievable, and it provides pertinent additional information for nutrition program planning and advocacy. Nevertheless, further research is required to evaluate and refine our approach for use under different field conditions, including its use at local vs. national levels, at rural vs. urban levels, for different age groups, and in countries with vastly different dietary patterns. In addition, for model inputs, the development and validation of rapid data collection techniques is a priority, because these will eliminate a reliance on detailed survey data. Once this is done, and a robust "user-friendly" interface is developed, our approach could make an important contribution toward the realization of global initiatives to improve complementary feeding practices. This, in turn, will help ensure optimal health, growth, and development of young children living in disadvantaged environments.

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