Food-Based Dietary Guidelines Can Be Developed and Tested Using Linear Programming Analysis

Elaine L. Ferguson,[1] Nicole Darmon,* André Briend,*† and Inguruwatte M. Premachandra**

*Department of Human Nutrition, University of Otago, Dunedin, New Zealand; *Institut Scientifique et Technique de la Nutrition et de l'Alimentation and the Institut National de la Santé et de la Recherche Médicale, Paris, France; †Institut de Recherche pour le Développement, Paris, France; and **Department of Finance and Quantitative Analysis, University of Otago, Dunedin, New Zealand*

Downloaded from https://academic.oup.com/jn/article-abstract/134/4/951/4757153 by guest on 07 November 2019

ABSTRACT Effective food-based dietary guidelines (FBDGs) are required to combat micronutrient deficiencies. This study aimed to develop a rigorous approach for designing population-specific FBDGs. A 4-phase approach based on linear programming analysis was used to design, test, and refine the FBDGs. This was illustrated for Malawian children. In phase I, the objective function minimized the difference in the energy contributed by different food groups between modeled and observed diets for 16 observed diet types, while preferentially selecting foods most often consumed. Constraints ensured nutrient adequacy and diet palatability. In phase II, the meal/snack patterns of the phase I modeled diets were examined to develop season-specific FBDGs. In phase III, the robustness of these FBDGs, for ensuring a nutritionally adequate diet, was tested. The objective function, in this analysis, minimized selected nutrient levels in the modeled diets (i.e., chose the "worst-case scenario"), while respecting the FBDGs, palatability, and energy constraints. The FBDGs were refined in phase IV. In the Malawian example used to illustrate our approach, the FBDGs promoted daily consumption of maize flour, small dry fish (≥20 g), leaf relish, and 2–3 snacks. The last mentioned included mangoes, in the food-shortage season, and pumpkin in the food-plenty season. In addition, legume relish was recommended in the food-shortage season. The approach presented here can be used to design and then test the robustness of FBDGs for meeting nutrient recommendations. J. Nutr. 134: 951–957, 2004.

KEY WORDS: • *linear programming* • *food-based dietary guidelines* • *recommendations* • *children* • *Africa* • *Malawi*

Young, rural children in African countries often have low intakes of essential micronutrients, resulting in compromised health, growth, and development (1). In rural Malawi, intakes of vitamin A, iodine, iron, and zinc are often below recommendations, and biochemical deficiencies of these micronutrients are common (2–7). Effective nutrition intervention strategies to increase the micronutrient density of childhood diets in countries like Malawi are urgently needed to improve childhood nutritional status and health.

Of the micronutrient intervention programs available, effective food-based dietary strategies will be the most sustainable, as long as nutritionally adequate diets based on local foods can be successfully identified and promoted (8). For this to occur, food-based dietary guidelines (FBDGs)[2] must be formulated that are simple, realistic, regionally specific, culturally appropriate, and take into account the multiple factors influencing food choice (9). One of the barriers, to formulating such FBDGs is the cumbersome, time-consuming and potentially biased consultation process required to develop them (9). This process could be done more effectively using a computer-based modeling approach to reduce the errors and biases that can occur when using a consultation process alone.

Linear programming analysis is an operational research approach that is used to model complex multifactorial problems, including diet-related problems (10–16). Its advantages for this task are that models can be developed to formulate robust FBDGs, which resemble current dietary practices as closely as possible, while at the same time ensuring that diets based on them simultaneously meet selected nutrient recommendations. Clearly, the development of such a method, based on linear programming, would be a valuable tool for working groups or committees brought together to design FBDGs. The aim of this study, therefore, was to develop a rigorous, reproducible and objective approach, based on linear programming analysis, which can be used to formulate practical FBDGs for high-risk populations. Its use was demonstrated here by formulating, as an example, two season-specific FBDGs for rural Southern Malawian children.

SUBJECTS AND METHODS

Our technique to create population-specific FBDGs was based on linear programming analysis. Linear programming, itself, is a mathe-

[1] To whom correspondence should be addressed.
E-mail: elaine.ferguson@stonebow.otago.ac.nz.

[2] Abbreviations used: FBDG, food-based dietary guideline; LP diet, an optimal diet selected by a linear programming model; MFE, meat, fish, poultry, eggs; OF, objective function; RNI, recommended nutrient intake level.

0022-3166/04 $8.00 © 2004 American Society for Nutritional Sciences.
Manuscript received 9 October 2003. Initial review completed 11 November 2003. Revision accepted 11 January 2004.

matical approach that optimizes (minimizes or maximizes) a linear function of a set of decision variables, while respecting multiple linear constraints. The linear function, called the objective function (OF), is expressed as follows:

$$OF = a_0 + \sum_{j=1}^{j} a_j X_j$$

where a_0 and a_j are constants, and, in our models, the decision variables Xj are a set of food weights (e.g., grams of bananas, grams of boiled maize). The goal of optimization is to find the optimal solution from among the many potential solutions. This will correspond to the set of decision variables (e.g., combination of food weights) that provides the optimal value for the objective function (i.e., best solution), while satisfying all of the imposed constraints. The basic structure of a linear programming model was described in detail elsewhere (17).

In the present study, the FBDGs were created using a 4-phase approach. Linear programming analysis, itself, was carried out in 2 of the 4 phases (i.e., phases I and III). In the other two phases, the results from these analyses were examined to create (in phase II) and then refine (in phase IV) the FBDGs. Specifically, in phase I, linear programming models were formulated to generate optimal diets (LP diets) that corresponded to the main diet types consumed by the population of interest. The term "diet type" is used throughout this paper to represent different diets distinguished on the basis of the inclusion/exclusion of different food groups in the diet, specifically from the food groups cereals, roots, fruits, vegetables, legumes, meat/poultry fish/eggs (MFE) and miscellaneous. The term "LP diets" is used to distinguish the optimal diets selected by linear programming analysis from the "observed diets," i.e., the diets actually consumed by 3- to 6-y-old rural Malawian children. In phase II, the phase I LP diets were examined to identify the dietary patterns (i.e., the number of daily portions of main meal dishes and snacks), which then formed the basis of the first draft of the FBDGs formulated. In phase III, the robustness of these FBDGs was evaluated, using a different linear programming model to confirm that diets fulfilling them would effectively meet the FAO/WHO recommended nutrient intake (RNI) levels (18). Finally (phase IV), the FBDGs were refined on the basis of this evaluation. Each phase of this analysis is described in detail below, and is illustrated by developing season-specific FBDGs for 3- to 6-y-old rural Malawian children.

The data used in all analysis were as follows: *1*) a food composition database specific for Malawi that was based on analyzed and literature values (19) and *2*) 3-d weighed food records collected from 3- to 6-y-old rural Malawian children during the food-plenty (March–April; $n = 60$) and food-shortage (November–December; $n = 62$) seasons of 1986 (19). The food database included the foods items consumed by ≥10% of the target population, which were 36 and 43 food items for the food-plenty and food-shortage seasons, respectively. Each of these food items was classified into 1 of 7 food groups and into 1 of 3 categories, i.e., staples, relishes, or snacks. For example, pumpkin was classified as a vegetable snack, okra as a vegetable relish, and maize flour as a cereal staple. In Malawi, a relish is similar to a sauce/stew prepared from boiled legumes, vegetables, or MFE.

Phase I: creating LP diets that correspond to observed diet types

In the Malawian example presented here, linear programming models were designed to select 9 and 7 different phase I LP diets for a 3-d period (i.e., a total of 16 diet types) corresponding to the diet types consumed by >10% of the population in the food-plenty and -shortage seasons, respectively. A 3-d period was chosen merely because the observed diets, used to formulate the LP diets, were 3-d weighed food records collected from rural 3- to 6-y-old Southern Malawian children. In both seasons, one diet type included foods from the cereals, roots, legumes, fruits, vegetables, MFE, and miscellaneous food groups, whereas other diet types excluded all foods from one or more of these food groups. For example, one diet type included cereals, legumes, fruits, vegetables, MFE, and miscellaneous, but excluded roots.

Objective function: phase I linear programming analysis

The objective function (OF) used in all phase I linear programming models was designed to minimize the difference in the mean percentage of energy contributed by each food group from the observed diet in the rural Malawian preschool diets, while preferentially selecting the most frequently consumed foods. In other words, the OF was designed to select LP diets that resembled the observed diet types as closely as possible, while meeting the imposed constraints. It was defined as:

$$OF = \text{Minimize}\left\{10\sum_{i=1}^{7} D_i + \sum_{i=1}^{7}\sum_{j=1}^{n} Y_{j,i}/F_{j,i}\right\} \quad (1)$$

where D_i comprises the the standardized differences in the energy provided by food group "*i*" in the observed diet type compared with the LP diet; $Y_{j,i}$ is a binary variable for each food item "*j*" in food group "*i*" whose value (0 or 1) depends on whether the food item is selected in the LP diet; and $F_{j,i}$ is the the observed frequency of consumption for each food item "*j*" selected from food group "*i*." Food group "*i*" comprises cereals, roots, legumes, MFE, fruits, vegetables or miscellaneous foods, and "*n*" is the total number of eligible food items in the database.

D_i was weighted relative to $Y_{j,i}/F_{j,i}$ by multiplying it by 10 to ensure that the observed diet type was given priority, and then the most frequently consumed foods were preferentially selected. The exact weighting value chosen for D_i (i.e., 10 here) is not critical, as long as it exceeds the maximum value for the sum of $Y_{j,i}/F_{j,i}$, and the model is properly scaled.

The variable D_i, in the first component of the objective function, is defined by the sum of absolute values for the difference between the energy contributed by each food group in the LP diet and the observed diet (mean) divided by the energy contributed by each food group in the observed diet (mean). In other words, D_i was expressed as:

$$D_i = ABS(LP_i - OD_i)/OD_i \quad (2)$$

where ABS is the absolute value; LP_i is the percentage of energy from food group "*i*" in the LP diet; and OD_i is the mean percentage of energy from food group "*i*" in the observed diet. D_i, as expressed above, is not a linear function. Therefore, the percentage of energy provided by each food group was transformed into the amount of energy provided by it, and an indirect approach was used to meet the conditions of linearity for the absolute value, as described in detail elsewhere (14).

In the food-plenty season, the mean percentage of energy contributed by cereals, roots, legumes, MFE, fruits, vegetables, and miscellaneous in the observed diets (i.e., OD_i) were 51.6, 5.0, 21.4, 4.9, 4.0, 8.5, and 4.6%, respectively, and 68.9, 5.7, 5.6, 5.9, 10.1, 1.7, and 2.1%, respectively, in the food-shortage season. When selecting LP diets that excluded foods from one or more food groups, the desired energy contributed by the excluded food group(s) was set to 0 in the objective function, and the observed energy contributed by other food groups proportionately adjusted to sum to 100%.

The second component in the objective function, ($Y_{j,i}/F_{j,i}$) was included to ensure that the most frequently consumed foods were selected. The frequency of consumption (i.e., $F_{j,i}$) was defined as the number of days each food item "*j*" in food group "*i*" was consumed at least once during each season. The maximum frequency per food item in the food plenty and food shortage seasons was, therefore, 180 and 186, respectively (e.g., 60 children × 3 d of food intake = 180 in the food plenty season; and 62 children × 3 d of food intake = 186 in the food shortage season). The variable $Y_{j,i}$ is a binary variable that takes the value of 1 when a food item is selected in the LP diet (i.e., food weight > 0 g); otherwise it take a value of 0. Hence, $Y_{j,i}/F_{j,i}$ is smaller when the selected food item's $F_{j,i}$ is larger (i.e., when $F_{j,i}$ corresponds to a frequently consumed food). Minimization of the sum of $Y_{j,i}/F_{j,i}$ in the objective function will therefore lead to preferential selection of

Downloaded from https://academic.oup.com/jn/article-abstract/134/4/951/4757153 by guest on 07 November 2019

the more frequently consumed foods when there is a choice between 2 or more different foods in the LP diet.

Constraints: phase I linear programming analysis

Constraints were introduced into all phase I models to ensure that LP diets met the expected nutrient needs of 97.5% of children in the population at a given energy level (i.e., *nutritional constraints*), to ensure that LP diets were palatable for 3- to 6-y-old rural Malawian children (i.e., *acceptability constraints*), and to create the binary variable $Y_{j,i}$.

Nutritional constraints. An energy constraint was introduced in all models to ensure that the optimal LP diets provided a specified amount of energy per day over a 3-d period, which was 6.0 MJ/d (i.e., 18.0 MJ/ 3 d). This energy level was chosen because it was close to the mean amount of energy consumed during the food-plenty season and the FAO/WHO recommendations for 3- to 6-y-old children (20).

Nutrient constraints were also introduced into all models to ensure that each modeled diet achieved the recent FAO/WHO nutrient recommendations (18) over a 3-d period ($\geq 3 \times$ RNI). For the iron and zinc requirement levels, low bioavailability was assumed. The format for each nutrient constraint was as follows:

$$\sum_{j=1}^{n} G_j N_{x,j} \geq \mathrm{RNI}_x \times 3 \tag{3}$$

where G_j is the grams of food item "j"; $N_{x,j}$ is the amount of the nutrient of interest "x" per gram of food item "j"; and RNI_x is the FAO/WHO nutrient recommendation for the nutrient of interest "x" (18). Nutrient constraints were tripled in all models to define the desired content for a 3-d period. The format for the energy constraint was identical to the nutrient constraints except that it was expressed as an equality constraint instead of a $\geq$ constraint.

Acceptability constraints. Three acceptability constraints were introduced into all models to ensure the following: *1*) realistic diet types; *2*) realistic 3-d portion sizes (g/3 d) for 3- to 6-y-old rural Malawian children; and *3*) a realistic number of 1-d portions of main meal dishes and snacks in the LP diets. For the first constraint, the percentage of energy provided by food groups, i.e., cereals, roots, MFE, legumes, fruits, vegetables, and/or miscellaneous, was limited to between the 25th percentile and the 75th percentile of the observed season-specific population food consumption patterns. The lower and upper constraints for these were defined as follows:

$$\sum_{j=1}^{n} EFG_{j,i} \geq EFG25_{i,s} \quad \text{and} \quad \sum_{j=1}^{n} EFG_{j,i} \leq EFG75_{i,s} \tag{4}$$

where $EFG_{j,i}$ is the energy provided by food items "j" in food group "i", food group "i" comprises cereals, roots, fruits, vegetables, legumes, MFE, and miscellaneous, $EFG25_{i,s}$ is the 25th percentile and $EFG75_{i,s}$ is the 75th percentile of energy provided by food group "i" in season "s" observed for the 3- to 6-y-old Malawian children.

For the second constraint, the portion size of each food item selected was limited to $\leq$ the 90th percentile of 3-d portion sizes observed in the population of children who had consumed the food. This constraint was defined as follows:

$$G_j \leq MG_j \tag{5}$$

where G_j is the grams of food item "j" and MG_j is the 90th percentile of 3-d portion sizes (g/3 d) observed in the population for food item "j."

For the third set of constraints, the total number of 1-d portions of main meal dishes and snacks selected for a 3-d period was limited to $\leq$ the 75th percentile observed in the population per season. In addition, because cereal-based staples are consumed daily, another constraint was introduced to ensure that the number of 1-d portions of the cereal-based staple was $\geq$ the 25th percentile of the population intake distributions. The number of 1-d portions for each main meal dish and snack was calculated by dividing the total 3-d portions (g/3 d) in the LP diet by the mean-sized 1-d portion (g/d) observed among consumers in the population of Malawian children. These constraints were defined as follows:

$$\sum_{p=1}^{n} DS_{p,y} \leq MDS_y \quad \text{and} \quad \sum_{p=1}^{n} DS_{p,y} \geq MCD_y \tag{6}$$

where $DS_{p,y}$ is the number of 1-d portions "p" of the main meal dish or snack "y" in the LP diet; MDS_y is the maximum number of 1-d portions allowed for each "y" over a 3-d period, which was defined by the 75th percentile observed in the population; and MCD_y is the minimum number of 1-d portions allowed, defined as the 25th percentile observed in the population for a 3-d period.

Binary variable constraint. A binary variable was required, in the objective function, to inverse the frequency of consumption for each food item selected in the LP diets. The following two constraints were needed to create this binary variable:

$$Y_{j,i} = \text{binary} \quad \text{and} \quad X_{j,i} \leq 7000 \times Y_{j,i} \tag{7}$$

where $Y_{j,i}$ is a binary variable for food item "j" in food group "i", which takes the value of 0 when $X_{j,i}$ is 0 (i.e., the food was not selected) and 1 when $X_{j,i}$ is >0 (i.e., the food was selected); and $X_{j,i}$ is the grams of food item "j" selected from food group "i" in the LP diet. The number 7000, in the second of these two constraints, is an arbitrary number. The only criterion used to select its value is that it exceeds the maximum grams selected for any food item in the LP diet. This second constraint will, therefore, force the binary variable (i.e., $Y_{j,i}$) to equal 1 for a food when it is included in the LP diet (i.e., $X_{j,i} > 0$); otherwise the binary variable is 0 (i.e., when $X_{j,i} = 0$).

Phase II: formulation of the FBDGs

Tables were created in which the number of mean-sized 1-d portions of cereal staples, relishes (i.e., MFE, legume, and vegetable), and snacks for each feasible LP diet were presented per season. A LP diet was unfeasible when a solution was not found for a given objective function and set of constraints. The first draft of the FBDGs was formulated for each season from this table by selecting the lowest number of 1-d portions of cereal staples, relishes, and snacks observed across all feasible LP diets. The lowest number was chosen to make the FBDGs as easy to achieve as possible.

Phase III: testing the robustness of the FBDGs

The robustness of the FBDGs was evaluated by linear programming analysis using a different objective function and set of constraints from those used in phase I. In these analyses, the new objective function minimized the amount of one selected nutrient per LP diet, while respecting the proposed FBDGs, the acceptability constraints, and the constraint on energy. Unlike the models used in phase I, nutritional constraints were not imposed, except for energy, based on an assumption that individuals in this population chose foods for their energy and not their nutrient content. However, new constraints were introduced to ensure that the LP diets respected the FBDGs (i.e., FBDG constraints). These phase III models, therefore identified the lowest achievable level for each nutrient (i.e., worst case scenario) when the FBDGs are put into practice, for a given energy level and food consumption pattern range.

Objective function: phase III linear programming analysis

The objective function used in the phase III models was defined as follows:

$$\mathrm{OF} = \text{Minimize} \sum_{j=1}^{n} G_j N_{x,j} \tag{8}$$

where G_j is the grams of food item "j" and $N_{x,j}$ is the content of nutrient "x" per gram of food item "j."

The nutrients (x) minimized in these 12 different analyses were

Downloaded from https://academic.oup.com/jn/article-abstract/134/4/951/4757153 by guest on 07 November 2019

calcium, iron, zinc, copper, vitamin A, vitamin C, vitamin B-12, vitamin B-6, folate, riboflavin, thiamin, and niacin.

FBDG constraints: phase III linear programming analysis

The exact format of each FBDG constraint depends on the individual guidelines in the first draft of the FBDGs formulated in phase II. The general format of these constraints in the current study was as follows:

$$\sum_{d=1}^{n} MDP_d \geq TP \tag{9}$$

where MDP_d is the mean 1-d portion of the main meal dishes, snacks, or specific foods "d" in the LP diet and TP is the total number of 1-d portions recommended in the FBDGs.

Phase IV: refinement of recommendations

If the draft FBDGs did not achieve at least 70% of the FAO/WHO RNIs (18) for all selected nutrients in phase III, they were modified to achieve this by specifying foods or types of foods that must be included in the diet; 70 instead of 100% of the FAO/WHO RNIs (18) was selected to avoid creating overly prescriptive FBDGs. The criteria for choosing these foods or food types were that they were frequently consumed and were important food sources for the nutrient of interest in the phase I LP diets. However, in some cases, choices were made between apparently identical food choice options. On the basis of these analyses, specific messages in the first FBDG draft were refined to create the final season-specific FBDGs.

All linear programming analysis was conducted using the Simplex procedure of the Premium Solver 3.5 for Excel (Frontline Systems). The objective functions and constraints used for each model are summarized in **Table 1**. The Human Ethics Committee, University of Guelph, Canada and the Centre for Social Research, University of Malawi, Malawi, granted ethical approval for the survey in Malawi.

RESULTS

Phases I to II

Feasible nutritionally adequate LP diets, similar to those consumed by rural Malawian children, were achievable for all modeled diet types, except for those that excluded all foods from the MFE food group ($n = 2$ LP diets) in both seasons or all vegetables in the food plenty season ($n = 1$ LP diets). Foods from these 2 food groups are clearly important for achieving nutritional adequacy in these rural Malawian childhood diets.

For the feasible LP diets, calcium and zinc were the nutrients most often provided at 100% of their respective FAO/WHO RNIs (18) (**Table 2**). All other nutrients, except vitamin A in LP diets that excluded vegetables, were above their FAO/WHO RNIs (18) (i.e., >120%) in the LP diets (data not shown). The range in the number of 1-d portions for cereal staples, relishes, and snacks was relatively narrow for feasible LP diets in each season (Table 2). On the basis of these observed ranges (Table 2), the first drafts of the season-specific FBDGs specified that the daily number of 1-d portions in the food-plenty and food-shortage seasons were 0.9 and 1.1 for the cereal-based staple, 1.2 and 1.4 for the MFE relish, 0.9 and 0 for the vegetable relish, and 2 and 3 for the snacks, respectively.

Phases III and IV

The linear programming analysis carried out in phase III, to test the robustness of the first drafts of the FBDGs, showed that intakes of all nutrients except protein, niacin, vitamin B-6, and copper could be <70% of the FAO/WHO RNIs (18) in a diet that respected them. Moreover, calcium, zinc, folate, vitamin A, vitamin C, thiamin, and/or riboflavin could be as low as <50% of the FAO/WHO RNIs (18). To overcome this, a snack of pumpkins in the food-plenty season, a snack of mangoes and a legume relish in the food-shortage season, as well as small dry fish, green leafy vegetable relishes, and cereal staples prepared from the less-refined maize flour (i.e., 95 instead of 65% milling extraction flour) in both seasons were specified in the final guidelines (**Table 3**). These specific food items were selected because they were important sources of these nutrients in most phase I LP diets and were frequently consumed by the rural Malawian children. The inclusion of these food items ensured that >70% of the FAO/WHO RNIs (18) were met for all nutrients when energy intakes were ≥6.0

Downloaded from https://academic.oup.com/jn/article-abstract/134/4/951/4757153 by guest on 07 November 2019

TABLE 1

Summary of the linear programming models used in phases I–II and III–IV

Phase I–II models	Phase III–IV models
Purpose To select optimal LP diets[1] that resemble current diets and meet FAO/WHO RNIs[2] Objective function To minimize the difference from observed diet types in the LP diet Constraints 1. Nutrients ≥ FAO/WHO RNIs[2] 2. Energy = 6.0 MJ/d 3. % energy from food groups ≥25th and ≤75th percentile of observed diets 4. 3-d food portions ≤90th percentile of observed diets for consumers 5. 1-d portions of main meal dishes and snacks ≤75th percentile of observed diets 6. 1-d portion of cereal-based staple ≥25th percentile of observed diets 7. To create a binary variable per food that takes a value of 1 when the food is selected; otherwise it takes a value of 0	Purpose To evaluate the robustness of the draft FBDGs developed in phase II Objective function To minimize the quantity of a selected nutrient in the LP diet Constraints 1. Energy = 6.0 MJ/d 2. % energy from food groups ≥25th and ≤75th percentile of observed diets 3. 3-d food portions ≤90th percentile of observed diets for consumers 4. 1-d portions of main meal dishes and snacks ≤75th percentile of observed diets 5. 1-d portions of cereal-based staple ≥25th percentile of observed diets 6. ≥lowest number of 1-d portions of main meal dishes, snacks and specific foods included in the FBDGs

[1] The LP diet is the diet selected by linear programming analysis.
[2] FAO/WHO RNIs are the recently recommended intake levels (18, 20).

TABLE 2

The limiting nutrients and the number of 1-d portions of main meal dishes (staple and relishes) and snacks in each feasible LP diets presented by season[1]

	Limiting nutrients[4]	Cereal staples[5]	MFE[2] relish[6]	Legume relish	Vegetable relish	Snacks[3]
			portion/d			
			Food-plenty season			
All foods[7]	Ca	0.9[8]	1.2[8]	0[8]	1.3	4.7
Roots excluded	Ca	1.0	1.3	0	1.3	4.0
Legumes excluded	Ca, Zn	1.1	1.6	0	1.3	4.2
Fruits excluded	Ca	1.0	1.3	0	1.3	3.0
Miscellaneous excluded	Ca	1.0	1.3	0	1.3	3.2
Fruit + root excluded	Ca, Zn	1.0	1.3	0	1.3	2.6[8]
Roots + miscellaneous excluded	Zn	1.0	1.3	0	0.9[8]	2.8
			Food-shortage season			
All foods	Ca	1.2	1.4[8]	0.7	0.7	4.2
Roots excluded	Ca	1.2	1.5	0.7	0.5	3.3
Vegetables excluded	Ca, Zn, A[9]	1.1[8]	1.5	1.0	0[8]	4.2
Legume excluded	Ca, Zn	1.2	1.5	0[8]	0.7	4.3
Miscellaneous excluded	Ca	1.2	1.5	0.7	0.6	3.1[8]
Roots + miscellaneous excluded	Ca	1.2	1.5	0.7	0.5	3.2

[1] 1-d portions refer to a mean-sized daily portion instead of a meal-based one.
[2] MFE indicates meat, poultry, fish, or eggs.
[3] Snacks included fruits, roots, groundnuts, fresh maize, pumpkin, soaked cereal grain and maize flour cakes.
[4] Limiting nutrient(s) i.e., nutrient(s) that just met the FAO/WHO RNI (18) in the LP diet.
[5] Cereal-based staples are prepared from cereal flour (i.e., maize or sorghum) and eaten either as a thin porridge, phala, or as a thick porridge, nsima.
[6] Relishes are prepared from boiled vegetables, MFE, or legumes and served as a sauce with nsima.
[7] Includes foods from all food groups, namely, from cereals, roots, MFE, legumes, fruits, vegetables, and miscellaneous.
[8] Indicates the number of mean sized 1-d portions from each food type that were used to formulate the first draft of the FBDGs in each season.
[9] A, vitamin A.

MJ/d. Even for children with lower dietary energy intakes (i.e., 5.0 MJ/d), these guidelines ensured this (data not shown). An intake of 5.0 MJ/d is close to the 25th percentile for energy intakes observed in this population of children.

DISCUSSION

A rigorous method to formulate culturally specific, practical FBDGs was developed and presented here. The FBDGs formulated using this method will, by definition, resemble the population's mean dietary patterns as closely as possible (the phase I objective function), and the changes advocated will ensure that all nutrient recommendations are met simultaneously (the phase I constraints). This will not only increase the chances for program success via enhanced rates of adoption, but will also avoid inadvertent negative effects on current dietary practices. In these respects, our approach addresses several key caveats raised in the joint FAO/WHO consultation report on the preparation of FBDGs (9), particularly those related to cultural acceptability, practicality, and possible negative nutritional consequences.

Another unique feature in our approach is that the robustness of the FBDGs for ensuring a nutritionally adequate diet, can easily be tested. This feature is particularly valuable for precisely defining the lowest attainable nutrient levels for any diet based on the FBDGs at a given energy level (i.e., worst case scenario). This is important because, as noted elsewhere

Downloaded from https://academic.oup.com/jn/article-abstract/134/4/951/4757153 by guest on 07 November 2019

TABLE 3

The final food-based dietary guidelines derived for 3- to 6-y-old rural Malawian children using linear programming analysis

Food-plenty season	Food-shortage season
1. A 1-d portion[1] of maize flour (≥205 g/d) every day, which should be 95% extraction flour	1. A 1-d portion of maize flour (≥230 g/d) every day, which should be 95% extraction flour
2. A large 1-d portion (≥20 g/d) of fish relish every day, which must be small dry fish	2. A large 1-d portion (≥20 g/d) of fish relish every day, which must be small dry fish
3. A 1-d portion (≥70 g/d) of leaf relish at least twice every 3 d	3. A 1-d portion (≥70 g/d) of leaf relish at least once every 3 d
4. At least 2 snacks every day, which should include a 1-d portion of pumpkin (≥180 g/d) at least once every 3 d	4. A 1-d portion of legume relish (>30 g/d of dry beans) at least once every 3 d
	5. At least 3 snacks every day, which should include a 1-d portion of mangoes (≥120 g/d) every day

[1] A 1-d portion refers to a mean-sized daily portion not a meal-based one.

(21), FBDGs do not automatically result in a more adequate diet. In our Malawian example, the lowest acceptable nutrient level was defined as at least 70% of the FAO/WHO RNI (18) to avoid overly prescriptive guidelines. Of the nutrients analyzed, dietary intakes of folate and/or vitamin C could be as low as 74 and 73% of their FAO/WHO RNIs (18), respectively, in a diet based on the FBDGs and an energy intake of 6.0 MJ/d. On the basis of this information, these nutrients could be monitored, if desired, after the FBDGs were put into practice.

A key concept in our approach is that even though many alternative LP diets met the FAO/WHO recommendations (18) (Table 2), these were used only to identify the desirable meal/snack patterns required to achieve nutritional adequacy. These patterns, which represented the nutritionally adequate diets most similar to the observed mean food consumption pattern, were then used to formulate the FBDGs.

In our Malawian example, nutritionally adequate diets that excluded either vegetables or legumes were feasible (Table 2). However, as demonstrated by our example, choosing the smallest portion size from the phase I LP diets (i.e., 0 for both legume and vegetable relishes) to formulate the first draft of the FBDGs is not always the most efficient or desirable approach. Diets that simultaneously excluded foods from both of these 2 food groups were not consumed by these rural Malawian children. It was therefore not surprising that vegetable and legume relishes were recommended in the final FBDGs (phase IV), on the bases of our criteria of frequency of consumption and nutrient content per 1-d portion size (Table 3). In both seasons, alternative dietary guideline options existed for the final FBDGs. In such cases, final decisions regarding alternative individual foods specified in the FBDGs should be made by the target population, as described elsewhere in the Trial of Improved Practices Manual (22). Similar trials are also recommended to assess the acceptability of the final FBDGs and to identify key communication messages for promoting them.

The availability of detailed dietary data and a competent analyst to carry out the linear programming analysis will clearly facilitate the use of our approach. However, it is not limited by this requirement because rapid assessment techniques can be used to define model parameters, including information on minimum and maximum portion sizes and the local dietary patterns. Moreover, in the future, a "user friendly" LP tool could be developed to eliminate the need for a competent analyst.

Our approach is also not limited to populations consuming simple diets, based on a limited number of foods. Indeed, complex diets can easily be modeled using a larger food composition database, if necessary, and/or including constraints that link specific food items when they are always eaten together. On the other hand, our approach is somewhat sensitive to numerical scaling, especially when the range in values for each component in the objective function is large. This can result in an accumulation of rounding errors and an erroneous message that model conditions for linearity are not met. In addition, the validity of the FBDGs will depend on the accuracy of the food composition database, as well as the RNIs used to define the nutrient constraints, particularly for the limiting nutrients. In our Malawian example, calcium and zinc were the most common limiting nutrients in the LP diets (Table 2). However, reducing their constraints to lower recommended levels of 450 mg/d for calcium and 5 mg/d for zinc (23,24) resulted in only minor changes to the FBDGs, specifically a 5-g reduction in small dried fish (data not shown). This suggests that FBDGs developed using our approach are relatively robust to actual nutrient requirement constraints, presumably because multiple constraints are influential in their formation. Issues related to nutrient bioavailability, as well as cooking losses, also require critical examination, especially if vitamin A, iron, and/or zinc deficiencies are common in the target population. In Malawi, these deficiencies were common, and dietary fat intakes were low (3,4,7). In our FBDGs, green leafy vegetables were selected as an important food source of vitamin A and small fish were selected for iron and zinc. The success of the former recommendation, in particular, warrants monitoring because green leafy vegetables alone may be inadequate for normalizing vitamin A status, particularly when dietary fat intakes are low (25).

Even though our linear programming approach, by definition, ensures that the FBDGs formulated resemble the population's mean dietary practices as closely as possible, one guideline deviated somewhat from observed dietary practices. This was the guideline to consume 3 MFE relishes + 2 vegetable relishes (i.e., at least 5 relishes) over a 3-d period. Indeed, only 18 and 21% of the observed diets in the food-plenty and food-shortage seasons, respectively, included 5 relishes over a 3-d period. These guidelines might therefore be the most difficult to adopt, especially for poorer families in the community, who might struggle to do this. For these families, providing 20 g of small dry fish per day could also be difficult. Indeed, for families unable to feed their children small dry fish, practical, nutritionally adequate food-based strategies based on unfortified local foods are not feasible on the basis of our analysis that showed LP diets were unfeasible when MFE were excluded (Phase I).

In conclusion, a method for formulating population-based FBDGs was developed and illustrated using as an example 3- to 6-y-old rural Malawian children. The advantage of our approach is that numerous factors (constraints) can be considered simultaneously, guaranteeing that all desirable criteria, such as nutrient recommendations, will be met simultaneously at a given energy level. This will avoid an inadvertent negative effect. In addition, the FBDGs developed using our approach will, by definition, resemble a population's current mean diet as closely as possible, which should help increase adoption rates.

LITERATURE CITED

1. Ramakrishnan, U. (2002) Prevalence of micronutrient malnutrition worldwide. Nutr. Rev. 60: S46–S52.
2. Burgess, H., Burgess, A. & Driessen, F. (1975) The nutritional status of children ages 0–5 years in Nkhotakota, Malawi. Trop. Geogr. Med. 27: 375–382.
3. Fazio-Tirrozzo, G., Brabin, L., Brabin, B., Agbaje, O., Harper, G. & Broadhead, R. (1998) A community based study of vitamin A and vitamin E status of adolescent girls living in the Shire Valley, Southern Malawi. Eur. J. Clin. Nutr. 52: 637–642.
4. Ferguson, E. L., Gibson, R. S., Opare-Obisaw, C., Ounpuu, S., Thompson, L. U. & Lehrfeld, J. (1993) The zinc nutriture of preschool children living in two African countries. J. Nutr. 123: 1487–1496.
5. Furnee, C. (1997) Prevention and control of iodine deficiency: a review of a study on the effectiveness of oral iodized oil in Malawi. Eur. J. Clin. Nutr. 51: S9–S10.
6. Hotz, C. & Gibson, R. (2001) Complementary feeding practices and dietary intakes from complementary foods amongst weanlings in rural Malawi. Eur. J. Clin. Nutr. 55: 841–849.
7. Yeudall, F., Gibson, R., Kayira, C. & Umar, E. (2002) Efficacy of a multi-micronutrient dietary intervention based on haemoglobin, hair zinc concentrations, and selected functional outcomes in rural Malawian children. Eur. J. Clin. Nutr. 56: 1176–1185.
8. Trowbridge, F., Harris, S., Cook, J., Dunn, J., Florentino, R., Kodyat, B., Mannar, M., Reddy, V., Tontisirin, K., Underwood, B. & Yip, R. (1993) Coordinated strategies for controlling micronutrient malnutrition: a technical workshop. J. Nutr. 123: 775–787.
9. FAO/WHO (1998) Preparation and Use of Food-Based Dietary Guidelines. World Health Organization, Geneva, Switzerland.
10. Dantzig, G. B. (2002) The diet problem. Interfaces 20: 43–47.
11. Anderson, A. M. & Earle, M. D. (1983) Diet planning in the Third World by linear and goal programming. J. Oper. Res. Soc. 34: 9–16.

Downloaded from https://academic.oup.com/jn/article-abstract/134/4/951/4757153 by guest on 07 November 2019

12. Briend, A., Ferguson, E. & Darmon, N. (2001) Local food price analysis by linear programming: a new approach to assess the economic value of fortified food supplements. Food Nutr. Bull. 22: 184–189.

13. Darmon, N., Ferguson, E. & Briend, A. (2002) Linear and non-linear programming to optimize the nutrient density of a population's diet: an example based on rural Malawian preschool diets. Am. J. Clin. Nutr. 75: 245–253.

14. Darmon, N., Ferguson, E. & Briend, A. (2002) A cost constraint alone has adverse effects on food selection and nutrient density: an analysis of human diets by linear programming. J. Nutr. 132: 3764–3771.

15. Lareo, L. R., Gracia, B. N. D., Fajardo, L., Romero, L. H., Acciarri, G., Pradilla, A., Maldonado, C., Reed, M. & Daza, C. H. (1990) From food basket to food security. The food factor in nutritional surveillance. Arch. Latinoam. Nutr. 40: 22–43.

16. Tiefenthaler, J. (1995) Deviations from the least-cost diets for infants. J. Popul. Econ. 8: 281–300.

17. Briend, A., Darmon, N., Ferguson, E. & Erhardt, J. G. (2003) Linear programming: a rigorous method for analysing and optimising children's diets during the complementary feeding period. J. Pediatr. Gastroenterol. Nutr. 36: 12–22.

18. FAO/WHO (2002) Human Vitamin and Mineral Requirements, Report of a joint FAO/WHO expert consultation, Bangkok, Thailand. Food and Nutrition Division, FAO, Rome, Italy.

19. Ferguson, E., Gibson, R. S., Opare-Obisaw, C., Osei-Opare, F., Lamba, C. & Ounpuu, S. (1993) Seasonal food consumption patterns and dietary diversity of rural preschool Ghanaian and Malawian children. Ecol. Food Nutr. 29: 219–234.

20. FAO/WHO/UNU (1985) Energy and Protein Requirements. World Health Organization, Geneva, Switzerland.

21. Lowik, M.R.H., Hulshof, K.F.A.M. & Brussard, J. H. (1999) Food-based dietary guidelines: some assumptions tested for the Netherlands. Br. J. Nutr. 81: S143–S149.

22. Dickens, K. & Griffiths, M. (1997) Designing by Dialogue. A Program Planner's Guide to Consultative Research for Improving Young Child Feeding. Academy for Educational Development, Washington, DC.

23. Food and Nutrition Board (2002) Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium and Zinc. National Academy Press, Washington, DC.

24. Department of Health (1991) Dietary Reference Values for Food Energy and Nutrients for the United Kingdom. MMSO, London, UK.

25. Ruel, M. T. (2001) Can Food-Based Strategies Help Reduce Vitamin A and Iron Deficiencies? International Food Policy Research Institute, Washington, DC.

Downloaded from https://academic.oup.com/jn/article-abstract/134/4/951/4757153 by guest on 07 November 2019