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

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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) 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-
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:

\[ \text{OF} = a_0 + \sum_{j=1}^{n} a_j X_j \]

where \( a_0 \) and \( a_j \) are constants, and, in our models, the decision variables \( X_j \) 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 days each food item was consumed at least once during each season) and into 1 of 3 categories, i.e., staples, relishes, or snacks. For example, pumpkin was classified 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 to reflect 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) was 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 contribution was set to 0 in the OF function; while the energy contributed by the excluded food group(s) was set to 0 in the OF 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 phase-plenty season, the mean percentage of energy contributed by cereals, roots, legumes, MFE, fruits, vegetables, and miscellaneous in the observed diet was 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 contribution was set to 0 in the OF function, and the observed energy contributed by other food groups proportionately adjusted to sum to 100%.

The second component in the objective function, \( \sum_{j=1}^{n} Y_{j,i} F_{j,i} \), 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 \( i \) in food group \( j \) 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 \( \times 3 \) of food intake = 180 in the food-plenty season; and 62 children \( \times 3 \) 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, \( \sum_{j=1}^{n} Y_{j,i} F_{j,i} \) 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...
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. The format for the energy constraint was identical to the nutrient constraints except that it was expressed as an equality constraint instead of a ≥ 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 the 25th percentile of the observed season-specific population food consumption patterns. The lower and upper constraints for these were defined as follows:

$$
\sum_{j=1}^{n} G_j N_{i,j} \geq \text{RNI} \times 3
$$

where $G_j$ is the grams of food item “j”; $N_{i,j}$ is the amount of the nutrient of interest “x” per gram of food item “j”; and RNI, 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 ≥ constraint.

**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:

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

where $Y_{j,i}$ is a binary variable for food item “j” in food group “i”, which takes the value of 0 when $X_{j,i} = 0$ (i.e., the food was not selected) and 1 when $X_{j,i} > 0$ (i.e., the food was selected); and $Y_{j,i}$ 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:

$$
\text{OF} = \text{Minimize } \sum_{j=1}^{n} G_j N_{i,j}
$$

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

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

\[ \sum_{d=1}^{n} MDP_d \geq TP \]  

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 \( \approx 6.0 \) MJ/d.

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**TABLE 1**

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

<table>
<thead>
<tr>
<th>Phase I–II models</th>
<th>Phase III–IV models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpose</td>
<td>To select optimal LP diets(^1) that resemble current diets and meet FAO/WHO RNIs(^2)</td>
</tr>
<tr>
<td>Objective function</td>
<td>To minimize the difference from observed diet types in the LP diet</td>
</tr>
<tr>
<td>Constraints</td>
<td>1. Nutrients ( \geq ) FAO/WHO RNIs(^2)</td>
</tr>
<tr>
<td></td>
<td>2. Energy ( = 6.0 ) MJ/d</td>
</tr>
<tr>
<td></td>
<td>3. % energy from food groups ( \geq 25 )th and ( \leq 75 )th percentile of observed diets</td>
</tr>
<tr>
<td></td>
<td>4. 3-d food portions ( \geq 90 )th percentile of observed diets for consumers</td>
</tr>
<tr>
<td></td>
<td>5. 1-d portions of main meal dishes and snacks ( \leq 75 )th percentile of observed diets</td>
</tr>
<tr>
<td></td>
<td>6. 1-d portion of cereal-based staple ( \geq 25 )th percentile of observed diets</td>
</tr>
<tr>
<td></td>
<td>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</td>
</tr>
<tr>
<td>Purpose</td>
<td>To evaluate the robustness of the draft FBDGs developed in phase II</td>
</tr>
<tr>
<td>Objective function</td>
<td>To minimize the quantity of a selected nutrient in the LP diet</td>
</tr>
<tr>
<td>Constraints</td>
<td>1. Energy ( = 6.0 ) MJ/d</td>
</tr>
<tr>
<td></td>
<td>2. % energy from food groups ( \geq 25 )th and ( \leq 75 )th percentile of observed diets</td>
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<tr>
<td></td>
<td>5. 1-d portions of cereal-based staple ( \geq 25 )th percentile of observed diets</td>
</tr>
<tr>
<td></td>
<td>6. ( \geq ) lowest number of 1-d portions of main meal dishes, snacks and specific foods included in the FBDGs</td>
</tr>
</tbody>
</table>

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\(^1\) The LP diet is the diet selected by linear programming analysis.

\(^2\) FAO/WHO RNIs are the recently recommended intake levels (18, 20).
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 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.

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**TABLE 2**

<table>
<thead>
<tr>
<th>Limiting nutrients4</th>
<th>Cereal staples5</th>
<th>MFE6 relish</th>
<th>Legume relish</th>
<th>Vegetable relish</th>
<th>Snacks3</th>
</tr>
</thead>
<tbody>
<tr>
<td>portion/d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Food-plenty season**

| All foods7          | Ca             | 0.98        | 1.28          | 08             | 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, Zn        | 1.0         | 1.3           | 0              | 1.3    | 2.68   |
| Fruit + root excluded | Ca, Zn       | 1.0         | 1.3           | 0              | 1.3    | 2.68   |
| Roots + miscellaneous excluded | Zn | 1.0 | 1.3 | 0 | 0.98 | 2.8 |

**Food-shortage season**

| All foods7          | Ca             | 1.2         | 1.48          | 0.7            | 0.7    | 4.2    |
|---------------------|----------------|-------------|---------------|----------------|--------|
| Roots excluded      | Ca             | 1.2         | 1.5           | 0.7            | 0.5    | 3.3    |
| Vegetables excluded | Ca, Zn, A9     | 1.18        | 1.5           | 1.0            | 0.9    | 4.2    |
| Legume excluded     | Ca, Zn         | 1.2         | 1.5           | 08             | 0.7    | 4.3    |
| Miscellaneous excluded | Ca            | 1.2         | 1.5           | 0.7            | 0.6    | 3.18   |
| Roots + miscellaneous excluded | Ca | 1.2 | 1.5 | 0.7 | 0.5 | 3.2 |

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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.

**TABLE 3**

<table>
<thead>
<tr>
<th>Food-plenty season</th>
<th>Food-shortage season</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. A 1-d portion1 of maize flour (≥205 g/d) every day, which should be 95% extraction flour</td>
<td>1. A 1-d portion1 of maize flour (≥230 g/d) every day, which should be 95% extraction flour</td>
</tr>
<tr>
<td>2. A large 1-d portion (≥20 g/d) of fish relish every day, which must be small dry fish</td>
<td>2. A large 1-d portion (≥20 g/d) of fish relish every day, which must be small dry fish</td>
</tr>
<tr>
<td>3. A 1-d portion (≥70 g/d) of leaf relish at least twice every 3 d</td>
<td>3. A 1-d portion (≥70 g/d) of leaf relish at least once every 3 d</td>
</tr>
<tr>
<td>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</td>
<td>4. A 1-d portion of legume relish (≥30 g/d of dry beans) at least once every 3 d</td>
</tr>
<tr>
<td>5. At least 3 snacks every day, which should include a 1-d portion of mangoes (≥120 g/d) every day</td>
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</tr>
</tbody>
</table>

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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 alternative LP diets met the FAO/WHO recommendations practice. 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 1).

In conclusion, a method for formulating population-based FBDGs was developed and illustrated using 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**


...sumably 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. 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.