Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

Original Article

Mathematical modeling to inform the development of national guidelines on infant feeding in Thailand

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The development of national dietary guidelines promoting healthy food choices is a public health priority in Thailand. In developing the recent national complementary feeding guidelines (CFGs) for 6- to 12-month-old children, mathematical modeling was used to inform decisions. Model parameters were derived from nationally representative dietary data and analyzed for 11 micronutrients by age group, using linear programming analysis in Optifood. Models were run to identify micronutrients whose nutrient reference values could not be met using local foods as consumed (problem nutrients), evaluate the original 2012 Thai CFGs, and predict the nutritional benefits of a specific fortified complementary food. The results identified three problem nutrients (iron, calcium, and zinc), which, for 9- to 11-month-olds, were reduced to one when the fortified food was modeled. The number of servings/week of vegetables and meat, fish or eggs were higher, and of oil and fruit were lower, in the modeled nutritionally best rather than observed diets (medians). When modeled, the original Thai CFGs were not feasible because the energy constraint was exceeded; hence, in revising them, the recommended number of servings/week of oil and fruit were reduced. This study demonstrates the advantages of using mathematical modeling, when revising national CFGs, to evaluate and improve them.

Keywords: Thailand; linear programming analysis; complementary feeding recommendations; fortified complementary food

Introduction

Thailand has undergone a period of rapid economic growth and industrial development since the early 1980s. It has made significant progress in reducing child undernutrition, particularly through its effective policy and community-based nutrition programs.[1,2] Increased globalization accompanied by developments in communications technology has led to marked changes in the diets and physical activity levels of the Thai people,[3] which may have contributed to the rise in childhood overweight and obesity observed, particularly in urban areas.[4–6] Among young children, iron deficiency is also common.[6]

Ensuring adequate nutrition during the first 2 years of life is critical for optimal health, growth, and development,[7] and will encourage lifelong healthy eating patterns. During this period of economic transition that Thailand is experiencing, the promotion of good nutrition is paramount, especially during the complementary feeding period, to avoid an overconsumption of unhealthy, ultra-processed high-fat and sugary products. The promotion of healthy food choices using population-specific food-based dietary guidelines (FBDGs) is a common public health strategy in many countries.[8] Such guidelines offer a sustainable, broad-based approach to improve the overall quality of the diet

doi: 10.1111/nyas.14738

of a population. In Thailand, a set of FBDGs, the "Nutrition Flag," was created for the general population (≥6 years of age) to provide guidance on the selection of food portions from basic food groups.[9] These FBDGs emphasize the importance of consuming foods from five basic food groups on a daily basis.[10] For infants, infant feeding guidelines have been used in Thailand since the 1980s. The initial guidelines specified the age of introduction of solid foods and provided general guidance on complementary feeding. In 2009, complementary feeding guidelines (CFGs) were formulated based on the concepts used in the FBDGs for the general population. These CFGs are included in the "maternal and child" booklet given to pregnant women attending antenatal care services in the public health system to provide guidance on the number of servings of foods to feed an infant from specific food groups (based on household utensil units). The recommended number and food portion sizes were not based on actual age-specific food consumption data, but on theoretical calculations to meet recommended daily energy and protein intakes, and to promote dietary diversity (i.e., foods from at least five basic food groups). It was not known whether these CFGs were realistic or would ensure dietary adequacy for Thai infants, especially for micronutrients.

Dietary micronutrient recommendations, especially iron, calcium and zinc, are difficult to meet during infancy because infants have high nutrient requirements to support rapid rates of growth.[11] For this reason, the WHO recommends the use of a fortified complementary food or vitamin and mineral supplements for infants, as needed, to ensure adequate micronutrient intakes.[12] In response, efforts have been made in Thailand to develop an affordable fortified infant cereal, based on broken rice, to help ensure Thai infants meet their nutrient requirements during this nutritionally vulnerable period in life.[13,14] It is not known whether its daily consumption along with other foods recommended in the Thai CFGs will ensure that recommended nutrient intakes for infants are met.

A mathematical modeling tool based on linear programming (LP) analysis (i.e., Optifood) was developed to formulate, test, and refine food-based recommendations using dietary survey data.[15,16] It simulates the nutritionally best diets to determine whether a nutritionally adequate diet can be formulated using local foods as consumed, to identify problem nutrients, and guide selection of population-specific food-based recommendations (Optifood's Module II). It can also be used to evaluate existing/proposed sets of food-based recommendations by simulating the lower and upper tails of a population's nutrient intake distributions when they adhere to the set of recommendations being tested, to determine the extent to which they lie within age-appropriate nutrient reference values (Optifood's Module III analyses).

In this study, we illustrate the use of this modeling approach in Thailand to[1] identify problem nutrients (if any) in diets consumed by 6- to 11.9-month-old Thai infants to determine whether a food-based approach using unfortified foods alone can meet their nutrient needs,[2] guide the revision of the 2012 Thai CFGs, and[3] evaluate the nutritional benefits of promoting a specific affordable fortified complementary feeding product that was recently developed for Thai infants. This analysis demonstrates how Optifood can be used to evaluate and improve national CFGs and evaluate the formulation of special fortified complementary feeding products.

Materials and methods

Revision of the Thai CFGs

Multiple stakeholders, including nutritionists and health personnel from Thai universities and the Ministry of Public Health, have met periodically to review the Thai CFGs initially developed in 2009. At these meetings, to ensure the CFGs promote dietary adequacy and health, the stakeholders review scientific evidence and reach a consensus on revisions to them. In the most recent revision of the CFGs, mathematical modeling was introduced to determine whether the diets of Thai infants would meet the FAO/WHO-recommended intakes[17–19] if they followed the 2012 Thai CFGs, identifying modifications to improve them. This modeling was done by members of staff from Mahidol University and the London School of Hygiene & Tropical Medicine who presented the results to the stakeholder working group to inform revisions. The outcome of this process was the 2015 Thai CFGs.

The modeling process

All analyses were done in Modules I, II, and III of Optifood (version 4.0.9), which is a software based on LP analyses.[15,16] The modeling process and model parameters are summarized in Tables S1–S4 (online only). The model parameters for each age group (6–8 months and 9–11 months) were generated from dietary (i.e., food frequency questionnaires and 24-h recalls) and anthropometric data collected from 6- to 11-month-old infants in the nationally representative 2003–2005 National Food Consumption survey of Thailand. Data from this survey were eligible for defining the model parameters if the infant was between 6.0 and 11.9 months of age inclusive and breastfeeding at the time of data collection ($n = 111$). Overall, 13.6% and 30.0% of these 6- to 8-month-old and 9- to 11-month old infants were stunted, respectively, and 14.0% and 2.6% were wasted, respectively.

The model decision variables were the weight of food in grams in a 7-day diet. The foods modeled were those consumed by ≥ 5% of infants in each age group or nutrient-dense foods consumed by some members in each group (Table S2, online only). Constraints on the modeled diet's energy content and food consumption patterns (upper and lower constraints at the food group, food subgroup, staples, snacks, and individual food levels) were used to ensure all modeled 7-day diets were realistic (Tables S3 and S4, online only). The energy constraint (an equality constraint of 590 and 670 kcal/day for 6- to 8-month-olds and 9- to 11-month-olds, respectively) was equal to the average energy requirements of each age group. It was calculated using the FAO/WHO equations[17] from their estimated mean body weights (i.e., energy requirement = 77 kcal/day × average body weight). The upper and lower constraints on food groups, food subgroups, starchy staples, and snacks (expressed as the number of servings per week from each) were equal to the 10th and 90th population-level percentiles estimated from food frequency questionnaire data. All foods were categorized into only one food subgroup and food group, whereas some foods from these food subgroups or food groups were also labeled as a snack or staple. For foods, the lower constraint level was zero, except for breastmilk (6.99 servings/week), and the upper constraint levels were the 90th percentiles from the food frequency questionnaire data for each age group, except for breastmilk (7.01 servings/week). The serving size for each food, except breastmilk, was its observed median serving size for consumers from the 2003–2005 Food Consumption Survey 24-h recall data. For breastmilk, it was 607 and 557 g/day, for the 6- to 8-month-old and 9- to 11-month-old groups, respectively, which were based on published average breastmilk energy intakes, assuming the energy content of breastmilk was 68.1 kcal/100 g (see Table S5, online only, for its energy and nutrient composition).[11] Local yield factors were used to estimate edible portion weights (unpublished data, Institute of Nutrition, Mahidol University). In all models, energy, protein, and 11 micronutrients (i.e., Ca, Fe, Zn, folate, vitamins A, B1, B2, B3, B6, B12, and C) were modeled, assuming 10% absorption for iron and moderate bioavailability for zinc.[18,19] A nonfeasible solution occurs if any of the model constraints were violated. It generally occurs when the energy required for the set of food-based recommendations being tested in Module III exceeds the average energy requirement of the population (i.e., violation of the model's energy constraint).

Ethics approval for the survey was obtained from Mahidol University, and ethics approval for the data analyses was obtained from the Ethics Committee of the London School of Hygiene & Tropical Medicine, UK.

Data analyses

After checking the model constraints in Module 1 to ensure that realistic diets were modeled, the Module II and III analyses were done to address three questions. First, we assessed whether the FAO/WHO Nutrient Reference Values (NRVs) for infants in each age group could be met using local foods as consumed. To answer this question, we examined the %NRVs of the Module III maximized nutrient content diets, which model the highest nutrient contents possible for any modeled diet given the food lists and food pattern constraints (i.e., best-case scenario nutrient levels). The problem nutrients were defined as those that were < 100% of their NRVs when no recommendations were tested.

Second, we examined the Module II nutritionally best diets, which aimed to come as close as possible to meeting nutrient goals (i.e., achieving 100% of the NRVs), while respecting the model constraints on energy and diet food patterns. These results showed whether a realistic diet could be modeled that met the FAO/WHO NRVs for 12 nutrients. In this step, we examined the food group patterns of the modeled diet in relation to the population's median observed patterns (i.e., 50th percentiles for the number of foods in each food group) to gain insights into changes in dietary patterns that would improve dietary adequacy. We also compared these results to the number of servings per week recommended in the original 2012 Thai CFGs after adjusting the food serving sizes to align with those observed. For example, the reported (from the Food Consumption survey) average serving sizes of foods in the meat, fish, and egg (MFE) food group were higher than those recommended (in the original Thai CFGs; Table S6, online only), so we multiplied the Thai CFGs recommended frequency of consumption of MFE per week by the ratio of recommended/observed serving sizes. We also examined the best food sources of nutrients in this nutritionally best diet to identify good food sources of nutrients.

Third, we evaluated the original 2012 Thai CFGs for each age group to determine whether they would ensure population-level adequate nutrient intakes, if adopted, using Optifood's Module III worst-case analyses (i.e., minimized nutrient content modeled diets). In these analyses, we introduced additional model constraints to ensure that all modeled diets achieved the 2012 Thai CFGs. Specifically, depending on the age group, constraints were introduced to ensure that all diets had 2 or 3 servings/day for each of rice, MFE, and vegetables; 2 servings/day of fruit; and 1 serving/day of oil. We selected a minimized nutrient value (i.e., a worst-case scenario level) of ≥65% of the FAO/WHO NRV as an acceptable minimized value, assuming a relatively low percentage of the population would be at risk of inadequate intakes if the lowest value of its nutrient intake distribution was at 65% of its FAO/WHO NRV. If the full set of recommendations was not feasible because the model energy constraint was exceeded, then selected individual or combinations of individual recommendations from the original set were either deleted from the set or its recommended frequency of consumption was reduced to ameliorate the unfeasible model results. The individual recommendations modified in these analyses were those identified in the Module II nutritionally best diet as less essential for ensuring dietary adequacy. Based on these analyses, the original set of Thai CFGs was modified and retested until one or more feasible sets of CFGs were identified.

Fourth, we did a series of sensitivity analyses to determine whether changes in model constraints for energy or the quantity of breastmilk modeled would modify the conclusions. In the sensitivity analyses for energy, the energy equality constraint was reduced to 500 kcal/day or increased to 700 kcal/day, for the 6- to 8-month age group, and reduced to 600 kcal/day or increased to 800 kcal/day, for the 9- to 11-month age group. In these analyses, the percentage of dietary energy provided by breastmilk was equal to its percentage of dietary energy in the original modeled diets (i.e., 70.0% or 56.6% of the total energy content of the 6- to 8-month-old and 9- to 11-month-old model diets, respectively). In the sensitivity analyses for breastmilk, the low, medium, and high quantities of breastmilk modeled were 276, 525, or 774 g/day for the 6- to 8-month age group and 186, 450, and 712 g/day for the 9- to 11-month age group. These values were based on the percentage of total dietary energy provided by low, moderate, and high breastmilk intakes for these age groups, as reported elsewhere.[11]

Finally, we modeled a nutrition intervention that promotes the replacement of 2 servings of rice/rice porridge per day with a special fortified complementary cereal product based on broken rice. This product was developed by the Institute of Nutrition, Mahidol University, but it is not currently commercially available (see Table S5, online only, for its nutrient composition).[13,14] The forms of the fortificants are ferrous sulfate and ferric sodium ethylenediaminetetraacetic acid (NaFeEDTA), calcium chloride and calcium lactate gluconate, thiamine hydrochloride, folic acid, and zinc sulfate. These analyses were done in Module III for each age group to simulate the influence of this special fortified complementary feeding cereal on the number of problem nutrients (maximized best-case scenario diets) and to assess the value of recommending a special fortified complementary feeding cereal in the revised set of Thai CFGs (minimized worst-case scenario diets).

Results

Problem nutrients

The problem nutrients observed in modeled diets that did not include the special fortified complementary feeding cereal were calcium, iron, and zinc for both age groups (Table 1). When the special fortified complementary feeding product was added to the models' food list, only iron remained a problem

Table 1. The problem nutrients identified in the models using the original food list and in the models including a special fortified infant cereal in the original food list presented by age group

	6- to 8-month-old, breastfed		9- to 11-month-old, breastfed	
	Problem nutrients[a]	% NRV[b]	Problem nutrients	% NRV
Original food list[c]	Iron	38	Iron	53
	Zinc	50	Zinc	63
	Calcium	58	Calcium	57
Original food list + fortified infant cereals[d]	Iron	79	Iron	98
	Zinc	87		
	Calcium	83		

[a] Problem nutrients are nutrients whose nutrient reference values[18,19] are not achieved in a Module III maximized (best-case scenario) diet, indicating they cannot be achieved in any modeled diet using locally available foods in the amounts habitually consumed. For all other nutrients, the maximized nutrient content was ≥ their NRVs in the Module III diet that maximized their nutrient content (best-case scenario diet).

[b] Percentage of the WHO/FAO recommended nutrient intake (RNI)[18,19] achieved in the Module III maximized (best-case scenario) diets. The RNIs for iron, calcium, and zinc were 9.3, 400, and 4.3 mg/day, respectively. These percentages represent the nutrient content of the modeled diet that has the highest nutrient content possible for that nutrient. Each %NRV represents the nutrient content of a different (i.e., extreme) modeled diet.

[c] The model's food list included foods/beverages consumed by ≥5% of children in each age group or nutrient-dense foods consumed by some members in each group as recorded in the 2003−2005 National Food Consumption survey of Thailand. Fortified infant cereals were excluded from the food lists. Breastmilk was included in the food lists (i.e., 607 g/day for 6- to 8-month-olds and 557 g/day for 9- to 11-month-olds). The food list is presented in Table S2 (online only).

[d] The model's original food list and breastmilk. Cerelac and a special fortified infant cereal based on broken rice were added to the original food list.

nutrient for the 9- to 11-month age group. Calcium, iron, and zinc, however, remained problem nutrients for the 6- to 8-month age group, although their %NRV in the Module III maximized diets (best-case scenarios) increased from less than 60% to over 75% (Table 1).

The Module II nutritionally best diet

The Module II results showed in the nutritionally best diet that the numbers of servings of vegetables and MFE were higher and the numbers of servings of oil and fruit were lower in the Module II nutritionally best diet than the observed median food consumption levels (Fig. 1). When the serving size–adjusted recommendations from the original 2012 Thai CFGs were compared with the Module II nutritionally best diet and observed diets, the number of servings/week for oil, fruits, and vegetables was higher and the number of servings/week of MFE was lower in the 2012 Thai CFGs than the others (Fig. 1). The best food sources of nutrients in the Module II nutritionally best diet were eggs and liver from the MFE group and ivy gourd leaves from the vegetable group (Table S7, online only), suggesting that examples of these foods should be highlighted in promotional material.

Evaluation of the original Thai CFGs and the fortified complementary feeding product

Results of the Module III analyses to evaluate the original 2012 Thai CFGs were not feasible because the energy content of a diet to achieve them exceeded the estimated average energy requirements of the population (i.e., the energy constraint was violated; Table 2). Thus, three scenarios were modeled for decreasing the dietary energy required to achieve the CFGs without compromising nutrition, which were to either omit oil or fruit from the original set of CFGs or decrease the number of servings of each. These scenarios were based on the results in Figure 1 showing that the number of servings of fruit and oil in the Module II nutritionally best diet were lower than those recommended in the original 2012 Thai CFGs. The results of these scenario analyses showed the revised sets of Thai CFGs were feasible and the Module III worst-case scenario diets were ≥65% for 7 and 8 nutrients, respectively, for the 6- to 8-month-old and 9- to

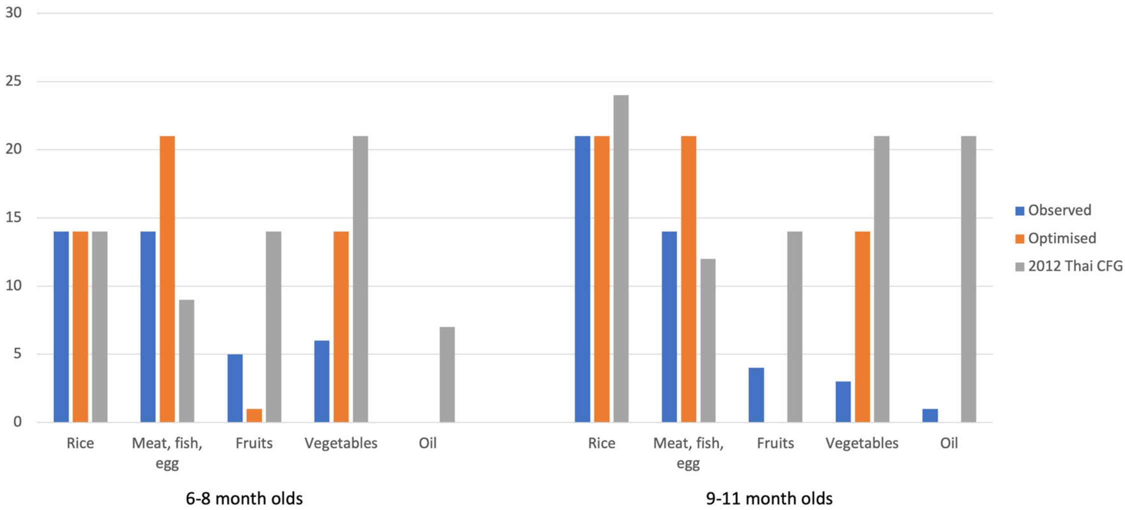

Figure 1. **Comparison of the number of servings/week from food groups in observed diets (50th percentile), Module II nutritionally best diets, and the 2012 Thai complementary feeding guidelines (equivalent serving number) by age group.**

11-month-old age groups in all three scenarios (Table 2 and Table S8, online only). If 2 servings/day of rice was replaced by the special fortified infant cereal for these three scenarios, then only the Module III minimized iron and niacin values were <65% of their NRVs, but for 9- to 11-month-olds, they were just under 65% (Table 2 and Table S8, online only). The Module III minimized values for the other nine nutrients were ≥65% of their NRVs.

The revised 2015 Thai CFGs

The revision of the Thai CFGs was informed by three outcomes of the modeling process. First, results showing the original 2012 Thai CFGs were not feasible indicated that modifications were required to avoid exceeding the estimated average energy requirement of Thai infants. Second, results from the Module II nutritionally best diet indicated that reducing the number of servings of oil and fruit and increasing the number of servings of vegetables and MFE would increase the nutrient content of diets, although it would not ensure adequate intakes (AIs) of calcium, iron, and zinc for all infants in the population (i.e., the problem nutrients). Third, when different scenarios were modeled that modified the recommended number of servings of oil and fruit, the Module III modeled diets were feasible and would ensure dietary adequacy for seven to eight nutrients, which was increased to nine nutrients if 2 servings/day of rice were replaced by the special fortified infant cereal. Based on these results, the recommended number of servings/day of oil and fruit were reduced in the revised compared with original Thai CFGs. These modifications also meant the revised Thai CFGs could be followed without compromising the consumption of breastmilk (Table 3). The models predicted that if these sets of recommendations were adopted, the nutrient content of most infant diets would meet or exceed the NRVs modeled for all nutrients except calcium, iron, and zinc (i.e., these three nutrients were <65% NRV in their Module III minimized diets; Table S8, online only). A recommendation to consume a special fortified infant cereal would increase the calcium, iron, and zinc content of infant diets; however, it was not included in the revised Thai CFGs. The original 2012 Thai CFGs and revised 2015 Thai CFGs are presented in Table 3.

Sensitivity analyses

The sensitivity analyses showed that conclusions were not overly sensitive to the amount of breastmilk or diet energy modeled. Calcium, iron, and zinc remained problem nutrients in all analyses (Table S9, online only). Similarly, when the revised Thai CFGs were evaluated (Module III minimized diets), calcium, iron, and zinc were <65% of their NRVs for all feasible modeled diets. The energy constraint was violated (i.e., model results were unfeasible) when high breastmilk values (both age groups)

Table 2. **Evaluation of the original 2012 Thai complementary feeding guidelines (CFGs) alone and with inclusion of a special fortified complementary feeding cereal and three scenarios for modifications presented by age group**

Complementary feeding guidelines	No. of nutrients ≥65% NRV[a]	Nutrients ≤65% NRV[b]
	6- to 8-month-olds	
Original Thai CFGs[c]		Not feasible[d]
Original Thai CFGs with a special fortified infant cereal[e]		Not feasible
Modifications		
Delete recommendation for oil	7	Ca, Fe, Zn, and niacin
Delete recommendation for fruit	7	Ca, Fe, Zn, and niacin
Halve number of servings of oil and fruit	8	Ca, Fe, and Zn
Halve number of servings of oil and fruit plus a special fortified infant cereal	9	Fe and niacin
	9- to 11-month-olds	
Original Thai CFGs[f]		Not feasible
Original Thai CFGs with a special fortified infant cereal		Not feasible
Modifications		
Delete recommendation for oil	8	Ca, Fe, and Zn
Delete recommendation for fruit	8	Ca, Fe, and Zn
Halve number of fruit servings and a third number of oil servings	8	Ca, Fe, and Zn
Halve number of fruit and a third number of oil servings plus a special fortified infant cereal	9	Fe and niacin

NOTE: Evaluations were done using Optifood's Module III minimized nutrient models.

[a] The number of nutrients in the Module III minimized diets that were ≥65% Nutrient Reference Value (NRV), when sets of CFGs were tested. Breastmilk was included in the modeled diets (i.e., 607 g/day for 6- to 8-month-olds and 557 g/day for 9- to 11-month-olds).

[b] The nutrients that were ≤65% of their NRV when a set of CFGs was tested (Module III minimized nutrient content diet).

[c] The Thai CFGs for 6- to 8-month-olds were: 2 servings/day each of rice, fruits, vegetables; 2 servings/day of meat, fish, or eggs (MFE), including 1 serving/day of eggs; and 1 serving/day of oil.

[d] The models were not feasible when the CFGs being tested exceeded the model energy constraint (i.e., to fulfill the CFGs requires more than the children's average energy requirements).

[e] Two recommended servings of rice in the 2012 Thai CFGs were replaced in the modeled diets by a special fortified complementary feeding cereal based on broken rice.[13]

[f] The Thai CFGs for 9- to 11-month-olds were: 3 servings/day each of rice, vegetables, oil, and MFE, including 1 serving/day of eggs; and 2 servings/day of fruit.

or low energy diets were modeled (only the 6- to 8-month age group). Vitamin A and vitamin C (both age groups) and riboflavin and folate (6- to 8-month age group) were also < 65% of their NRVs when low breastmilk intakes were modeled. Finally, niacin was also < 65% of its NRV for the 6- to 8-month age group when high energy intakes or moderate breastmilk intakes were modeled (Table S9, online only).

Discussion

This study illustrates the advantages of using mathematical modeling to inform decisions when revising national CFGs or evaluating the fortification levels of food products developed for infants. The modeling process first showed that it would be difficult to select diets that achieve the FAO/WHO NRVs for 6- to 8-month-old and 9- to 11-month-old breastfed

Table 3. Comparison of the original and revised sets of Thai complementary feeding guidelines expressed as the number of servings/day

Food groups	6- to 8-month-olds		9- to 11-month-olds	
	Original 2012 Thai CFRs (number of servings/day[a])	Revised[b] 2015 Thai CFRs (number of servings/day)	Original 2012 Thai CFRs (number of servings/day)	Revised 2015 Thai CFRs (number of servings/day)
Breastmilk	Breastfeed on demand	Breastfeed on demand	Breastfeed on demand	Breastfeed on demand
Rice group	2	2	3	3
Meat, fish, or egg group	2	2	3	3
Vegetable group	2	2	3	2
Fruit group	2	1	2	1
Oil	1	0.5	1	0.5

[a] Serving sizes (g/serving) for foods in each food group are detailed in Table S2 (online only).
[b] The final set of complementary feeding recommendations (CFRs) adopted for the 2015 Thai National Complementary Feeding Guidelines. Mathematical modeling using Optifood informed the revisions made to the original 2012 set of complementary feeding guidelines.

Thai children for iron, zinc, and calcium using local foods as habitually consumed. The calcium, iron, and zinc contents of their maximized and nutritionally best modeled diets were well below their respective FAO/WHO NRVs (i.e., < 65% NRVs). For the 9- to 11-month age group, the number of problem nutrients was reduced to one (i.e., iron) when the fortified complementary feeding product of interest was included in the model's food list, whereas it did not change the number of problem nutrients for the 6- to 8-month-old age group. Overall, the insights gained from these analyses suggest a need for policy changes that increase the availability of affordable complementary foods that are rich in these micronutrients for breastfed 6- to 11-month-old infants because local food supplies, given the current consumption patterns, will not ensure that all children in the population achieve dietary adequacy. They also indicate that the fortification levels for iron, calcium, and zinc in the special fortified infant cereal may require reformulation.

Our results identifying calcium, iron, and zinc as problem nutrients for 6- to 11-month-old infants were not sensitive to the energy constraints and quantities of breastmilk modeled. They are also consistent with results from other studies, which have reported that calcium, iron, and zinc are problematic for infants, using LP analyses[20–23] and other methods of analyses.[6,11,24,25] Together, these studies reinforce the public health priority of increasing the micronutrient density of foods commonly consumed by infants, given the negative implications of micronutrient deficiencies on the health, growth, and long-term development of young children.[26]

The second important insight gained from the modeling exercise was that the original 2012 Thai CFGs would exceed the estimated average energy requirements of breastfed 6- to 11-month-old Thai infants if followed, and assuming an average quantity of breastmilk is consumed. To avoid promoting excessive energy intakes, the modeled revisions of the Thai CFGs focused on the oil and fruit guidelines because the number of servings/day from these food groups were lower in the Module II optimized nutritionally best diets than in the original Thai CFGs. In the revised 2015 Thai CFGs compared with the original 2012 Thai CFGs, the number of servings/day of oil and fruit were both reduced instead of modifying the number of recommendations, in order to maintain consistency in the guidelines promoted between the original and revised sets of Thai CFGs. The recommendation to reduce the number of servings/day of oil fed to breastfed 6- to 8-month-olds and 9- to 11-month-olds was justified because unfortified oil provides energy but it is not a source of micronutrients. Oil was included in the original Thai CFGs to ensure an infant's essential fatty acid requirements are met, although for breastfed children in Thailand, it is likely not necessary because the essential fatty acid content of breastmilk is high if mothers are well nourished.[12,27,28] The revised 2015 Thai CFGs continue to encourage the consumption of fruit from an early age, which is important for developing healthy life-long food consumption practices.

The analyses, however, predicted that even if the revised Thai CFGs were followed, some infants might not meet their iron, calcium, and zinc needs because the Module III minimized and maximized values for these nutrients were below 65% of the FAO/WHO-recommended intake levels. These results were not sensitive to the model constraint on the diet's energy content or to the quantity of breastmilk modeled. They were also not sensitive to the serving size suggestions in the Thai CFGs for rice because the number of servings of rice selected in the Module II nutritionally best diets was higher than those recommended in the Thai CFGs (i.e., 14.3 versus 14.0 and 25.4 versus 21 servings/week) even though its constraints allowed the selection of only 7 servings/week.

In Thailand, where there has been rapid economic growth and the food industry is well developed, the promotion of fortified commercial infant products is a viable micronutrient intervention to increase the micronutrient content of complementary feeding diets. Our analyses show that regular consumption of a special fortified complementary feeding product can increase the micronutrient content of infant diets to levels that meet most modeled FAO/WHO NRVs if promoted within a comprehensive set of CFGs. Two servings/day of the modeled special fortified complementary feeding product alone also resulted in seven nutrients meeting or exceeding 65% of their NRVs in the Module III minimized worst-case scenario diets, which increased to nine nutrients when the fortified infant cereal was combined with the recommendations to consume 2–3 servings/day each of vegetables and MFE. The nutrients that did not achieve 65% of their NRVs in these analyses were iron and niacin. For niacin, micrograms of niacin instead of niacin equivalents were modeled, which would overestimate inadequacy because the contribution of niacin from tryptophan was not considered. Iron is a concern because iron deficiency is common among young Thai children.[6] The iron contents of the Module III minimized diets, however, were close to 65% of the NRV when the fortified infant cereal was modeled (i.e., 56% and 64% for the 6- to 8-month and 9- to 11-month age groups, respectively), indicating that reformulation of its iron content may not be necessary, especially given its high bioavailability.[14] Alternative food-based approaches, however, also exist to increase the nutrient content of complementary feeding diets in Thailand. For example, all nutrients achieved 65% of their NRVs (Module III minimized model diets) when 2–3 servings/week of liver (10–15 g per serving) was modeled (data not shown).

A complementary intervention such as the use of a fortified infant cereal is an important consideration for complementary feeding intervention programs in Thailand. Nevertheless, it might increase diet costs and affect the ability of lower-income groups to carry out recommendations that include a fortified infant cereal. Partially for this reason, a recommendation to feed 6- to 8-month-old and 9- to 11-month-old infants a special fortified infant cereal was not incorporated into the revised 2015 Thai CFGs. However, the revised 2015 Thai CFGs continue to provide examples of nutrient-rich complementary foods, such as liver, that can be fed to infants to increase the nutrient density of complementary feeding diets. The cost of one serving of a fortified commercial infant cereal is approximately three to six times higher than the cost of one serving of liver.

In this paper, we have described how a mathematical modeling approach was used to revise the 2012 Thai CFGs for 6- to 11-month-old infants in Thailand using nationally representative dietary data. The value of using mathematical modeling as one stage in a multistage process of revising national food guidelines is gaining global recognition.[8,25,29] However, when using diet modeling, the limitations must be kept in mind. Conclusions are dependent on the quality of the data used to define model parameters, such as the food composition values, NRVs, and food portion sizes (including breastmilk) used. The food composition table used in the current study was predominantly based on analyzed nutrient values of Thai foods; however, some values were derived from other food composition tables, which may not correspond with nutrient contents in Thai foods. Of greater concern is the nutrient content of breastmilk depends on maternal micronutrient status,[25] and it provided over 5% of 11 nutrients in the Module II nutritionally best diet. The sensitivity analyses showed the results, for problem nutrients, were not sensitive to the quantity of breastmilk modeled. However, the number of nutrients < 65% of their NRVs (Module III minimized analyses) increased from three to up to seven, especially when low breastmilk intakes were modeled. The nutrient content of the modeled breastmilk is presented in Table S5 (online only) for reference.

The NRVs for children less than 12 months of age are often based on AIs instead of estimated average requirements (EARs), which may overestimate nutrient needs.[30] The use of ≥65% NRV to interpret modeling results is arbitrary; however, when the lowest value in a nutrient intake distribution is ≥65% of an AI, the mean nutrient intake of the population would likely meet or exceed the AI, indicating dietary adequacy. In contrast, the iron and zinc NRVs are based on EARs, which means selecting 65% of the NRV is not simulating a zero percentage of the population at risk of inadequate intakes. In these analyses, however, minimized iron and zinc values were well below 65% of their NRVs, indicating that results would not change if a different %NRV had been chosen.

There are also uncertainties about the NRVs, which vary across authoritative bodies.[25] The NRVs used in these analyses for calcium and zinc are higher than the European Food Standards Authority Population Reference Intakes (PRIs)[31] and the American and Canadian Dietary Reference Intakes (DRIs)[32] (i.e., 400 mg/day versus 280 and 260 mg/day, respectively, for calcium, and 4.1 mg/day versus 2.9 and 3 mg/day, respectively, for zinc). Conversely, the NRV values modeled for iron were lower than those of these two authoritative bodies (i.e., 9.3 mg/day for our analyses versus 11 mg/day for the PRIs and DRIs). Nevertheless, reducing the calcium and zinc NRVs to the PRI or DRI values would not change the results for problem nutrients identified because the calcium and zinc contents of the Module II nutritionally best diet remained below them (i.e., nutritionally best diets for the 6- to 8-month and 9- to 11-month age groups had a Ca content of 210 and 218 mg/day and a Zn content of 1.9 and 2.4 mg/day, respectively). The PRI and DRI values for calcium in infants under 12 months of age are AIs based on the calcium intakes absorbed by a breastfed child, indicating the results are not sensitive to NRV assumptions regarding breastmilk/food sources of calcium and their differences in calcium bioavailability.

Finally, the analyses were also done at a national rather than a regional or socioeconomic group level, which may limit their applicability to different groups. It was also done using 2003–2005 National Survey data, which, given the rapid economic growth in Thailand, may not fully represent current dietary practices, especially in urban areas.

In conclusion, we have illustrated how diet modeling informed the most recent revisions of the Thai national CFGs for 6- to 12-month-old children. The benefits of using mathematical modeling to support revisions of national CFGs are that it objectively identifies unrealistic recommendations, provides insights into alternative revisions to strengthen CFGs, and indicates whether the CFGs, if adopted, will ensure dietary adequacy for most infants in the population. In countries such as Thailand, where quantitative national food consumption surveys are periodically done, the resources required to incorporate mathematical modeling into the process of national CFGs development or revision are minor. The evidence generated can also be used to guide policy decisions on ways to improve national food systems to support optimal nutrition in nutritionally vulnerable groups, such as infants.

Acknowledgments

We thank the European Union for funding the project (European Commission, FP7, GA-2896-16).

Author contributions

P.W. conceptualized the project. U.C., N.R., and E.F. conceptualized the analyses. U.C., N.R., and E.F. did the analyses. L.W., U.C., and E.F. wrote the first draft of the manuscript. All authors edited the manuscript and approved the final version.

Supporting information

Additional supporting information may be found in the online version of this article.

Table S1. A description of the analyses done in each of Module I, II, and III of Optifood, including the number of linear programming models run in each module, their objective functions, and model constraints.

Table S2. Foods, average serving sizes/day, constraint levels, and cost used in the models for each age group based on the food consumption reported in the 2003–2005 Thai National Food Consumption Survey.

Table S3. The low and high food group constraint levels used in the models for each age group based on observed patterns.

Table S4. The low and high food subgroup constraint levels used in the models for each target group based on observed patterns.

Table S5. The serving sizes and the energy and nutrient contents per 100 g of breastmilk and the special fortified infant complementary feeding product modeled.

Table S6. Comparison of the food serving sizes recommended in the original Thai complementary guidelines (CFGs) with those reported in the Thai 2003–2005 National Food Consumption survey presented by age group.

Table S7. The best food sources of nutrients in the Module II nutritionally best diet (only nutrient goals) modeled with and without a special fortified infant cereal, and the number of nutrients for which each food provided ≥5% of the nutrient content of this nutritionally best diet.

Table S8. Comparison of the original Thai complementary feeding guidelines (CFGs) modeled using all original individual recommendations and after deleting or reducing the number of selected individual recommendations and with or without a special fortified infant cereal.

Table S9. The sensitivity of Module III results to the model parameters of the diet energy content and the quantity of breastmilk modeled.

Competing interests

The authors declare no competing interests.

References

1. Tontisirin, K. & P. Winichagoon. 1999. Community-based programmes: success factors for public nutrition derived from the experience of Thailand. *Food Nutr. Bull.* **20:** 315–322.
2. Tontisirin, K., G.A. Attig & P. Winichagoon. 1995. An eight-stage process for national nutrition development. *Food Nutr. Bull.* **16:** 8–16.
3. Winichagoon, P. 2013. Thailand nutrition in transition: situation and challenges of maternal and child nutrition. *Asia Pac. J. Clin. Nutr.* **22:** 6–15.
4. Cohen, B. 2006. Urbanization in developing countries: current trends, future projections and key challenges for sustainability. *Tech. Soc.* **8:** 63–80.
5. Kosulwat, V. 2002. The nutrition and health transition in Thailand. *Public Health Nutr*. **5:** 183–189.
6. Rojroongwasinkul, N., K. Kijboonchoo, W. Wimonpeerapattana, *et al.* 2013. SEANUTS: the nutritional status and dietary intakes of 0.5–12-year-old Thai children. *Br. J. Nutr.* **110**(Suppl.): 36–44.
7. Victora, C.G., P. Christian, L.P. Vidaletti, *et al.* 2021. Revisiting maternal and child undernutrition in low-income and middle-income countries: variable progress towards an unfinished agenda. *Lancet* **397:** 1388–1399.
8. Murphy, S.P. & S.I. Barr. 2008. Food guides reflect similarities and differences in dietary guidance in three countries (Japan, Canada, and the United States). *Nutr. Rev.* **65:** 141–148.
9. Sirichakwal, P.P. & K. Sranacharoenpong. 2008. Practical experience in development and promotion of food-based dietary guidelines in Thailand. *Asia Pac. J. Clin. Nutr.* **17**(Suppl.): 63–65.
10. Sirichakwal, P.P., K. Sranacharoenpong & K. Tontisirin. 2011. Food based dietary guidelines (FBDGs) development and promotion in Thailand. *Asia Pac. J. Clin. Nutr.* **20:** 477–483.
11. Dewey, K.G. & K.H. Brown. 2003. Update on technical issues concerning complementary feeding of young children in developing countries and implications for intervention programs. *Food Nutr. Bull.* **24:** 5–28.
12. Pan American Health Organization, World Health Organization. 2003. *Guiding Principles for Complementary Feeding of the Breastfed Child*. Pan American Health Organization.
13. Chitpan, M., V. Chavasit & R. Kongkachuichai. 2005. Development of fortified dried broken rice as a complementary food. *Food Nutr. Bull.* **26:** 376–384.
14. Chavasit, V., S. Porasuphatana, U. Suthutvoravut, *et al.* 2015. Iron bioavailability in 8–24-month-old Thai children from a micronutrient-fortified quick-cooking rice containing ferric ammonium citrate or a mixture of ferrous sulphate and ferric sodium ethylenediaminetetraacetic acid. *Matern. Child Nutr.* **11**(Suppl.): 179–187.
15. Daelmans, B., E. Ferguson, C.K. Lutter, *et al.* 2013. Designing appropriate complementary feeding recommendations: tools for programmatic action. *Matern. Child Nutr.* **9**(Suppl.): 116–130.
16. Ferguson, E.L., N. Darmon, U. Fahmida, *et al.* 2006. Design of optimal food-based complementary feeding recommendations and identification of key "problem nutrients" using goal programming. *J. Nutr.* **136:** 2399–2404.
17. Food and Agricultural Organization. 2001. *Human Energy Requirements:* Report of a Joint FAO/WHO/UNU Expert Consultation. FAO Food and Nutrition Technical Report Series 1.
18. Joint FAO/WHO Report. 2004. *Vitamin and Mineral Requirements in Human Nutrition.* 2nd ed. World Health Organization and Food and Agricultural Organization.
19. Joint WHO/FAO/UNU Consultation Report. 2007. *Protein and Amino Acid Requirements in Human Nutrition*. World Health Organization. Technical Report Series. 935.

20. Santika, O., U. Fahmida & E.L. Ferguson. 2009. Development of food-based complementary feeding recommendations for 9- to 11-month-old peri-urban Indonesian infants using linear programming. *J. Nutr.* **139:** 135–141.
21. Vossenaar, M., F.A. Knight, A. Tumilowicz, *et al.* 2017. Context-specific complementary feeding recommendations developed using Optifood could improve the diets of breastfed infants and young children from diverse livelihood groups in northern Kenya. *Public Health Nutr*. **20:** 971–983.
22. Ferguson, E., P. Chege, J. Kimiywe, *et al*. 2015. Zinc, iron and calcium are major limiting nutrients in the complementary diets of rural Kenyan children. *Matern. Child Nutr.* **11:** 6–20.
23. Ferguson, E.L., L. Watson, J. Berger, *et al.* 2019. Realistic food-based approaches alone may not ensure dietary adequacy for women and young children in South-East Asia. *Matern. Child Health J*. **23:** 55–66.
24. Thurlow, R.A., P. Winichagoon, T. Pongcharoen, *et al.* 2006. Risk of zinc, iodine and other micronutrient deficiencies among school children in North-East Thailand. *Eur. J. Clin. Nutr.* **60:** 623–632.
25. Dewey, K.G., T. Pannucci, K.O. Casavale, *et al.* 2021. Development of food pattern recommendations for infants and toddlers 6–24 months of age to support the dietary guidelines for Americans, 2020–2025. *J. Nutr.* **151:** 3113–3124.
26. Black, R.E., C.G. Victora, S.P. Walker, *et al.* 2013. Maternal and child undernutrition and overweight in low-income and middle-income countries. *Lancet* **382:** 427–451.
27. Rocquelin, G., S. Tapsoba, M.C. Dop, *et al.* 1998. Lipid content and essential fatty acid (EFA) composition of mature Congolese breast milk are influenced by mothers' nutritional status: impact on infants' EFA supply. *Eur. J. Clin. Nutr.* **52:** 164–171.
28. Dewey, K.G. 2013. The challenge of meeting nutrient needs of infants and young children during the period of complementary feeding: an evolutionary perspective. *J. Nutr.* **143:** 2050–2054.
29. Bechthold, A., H. Boeing, I. Tetens, *et al*. 2018. Perspective: food-based dietary guidelines in Europe—scientific concepts, current status, and perspectives. *Adv. Nutr.* **9:** 544–560.
30. Gibson, R.S. 2005. *Principles of Nutritional Assessment*. 2nd ed. Oxford University Press.
31. European Food Standards Authority Population Reference Intakes (PRI). DRV Finder. Accessed November 20, 2021. https://multimedia.efsa.europa.eu/drvs/index.htm.
32. American and Canadian Dietary Reference Intakes (DRI). Accessed November 20, 2021. https://www.ncbi.nlm.nih.gov/books/NBK545442/table/.