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A Conflict Between Nutritionally Adequate Diets and Meeting the 2010 Dietary Guidelines for Sodium

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Abstract

Background—Compliance with dietary guidelines means incorporating multiple foods and nutrients into everyday diets, to be consumed in smaller or larger amounts. Feasibility studies can help determine whether one nutrient guideline comes into conflict with another. For one half of the U.S. population, the 2010 dietary guidelines for sodium were set at 1500 mg/d.

Purpose—To test the compatibility of the 1500mg/d sodium goal with nutrient-adequate diets.

Methods—Analyses, conducted in 2010, used U.S. federal nutrient composition and dietary intake databases to create modeled food patterns for six gender–age groups using linear programming techniques. The food patterns were designed to meet nutritional standards for 27 nutrients as the mean sodium content was progressively reduced from levels observed in the 2001–2002 National Health and Nutrition Examination Survey (NHANES) down to 1500 mg/day.

Results—For adults aged <50 years, the 2300 mg/day sodium goal was consistent with nutrient-adequate diets but required large deviations from current eating patterns. The 1500 mg/day goal was not feasible and no mathematical solution was obtained. The lowest-sodium food patterns that were nutrient-adequate and theoretically achievable were very high in fruit juices, nuts, and seeds but were low in grains and meats.

Conclusions—Compliance with the 2010 sodium guidelines will require large deviations from current eating behaviors and/or a profound modification of the U.S. food supply.

Introduction

Depending on gender and age, adult Americans consume between 2395 mg and 4476 mg of dietary sodium per day,¹ the lower amount corresponding to approximately 6 g of table salt. Bread, pizza, pasta, processed meats, chicken dishes, and condiments are among the top sources of sodium in the American diet.¹

The 2010 Dietary Guidelines¹ advised Americans to reduce daily sodium intake to less than 2300 milligrams (mg) per day, with an even lower goal of 1500 mg/day set for people who were aged ≥51 years and those of any age who were African-American or had hypertension, diabetes, or chronic kidney disease. The 2010 dietary guidelines for sodium make the 1500

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mg/day goal a concern for at least one half of the U.S. population, including children, and for the majority of adults.¹

The 1,500 mg/day sodium guideline is the same as the Adequate Intake level for this nutrient. The sodium Adequate Intake, set by the IOM, was intended to meet the sodium needs of healthy and moderately active people and to ensure that the recommended intake levels for other nutrients could also be met. The sodium Adequate Intake for individuals aged 9–50 years is 1500 mg/day. Lower-sodium Adequate Intake s were established for adults aged 51–70 years (1300 mg/day) and for those aged ≥ 71 years (1200 mg/day) because their energy intakes were lower.

Whether the recommended intake levels for multiple nutrients can, in fact, be met at very low sodium levels can be readily tested using linear programming models.^{2, 3} LINEAR PROGRAMMING methods take into account – simultaneously – population eating behaviors and nutritional goals at different energy requirements. In the present study, nutrient adequacy of the diet was iteratively tested at progressively lower levels of sodium.^{4–6} The goal was to determine at what point the low-sodium goal would begin to interfere with the model's ability to create food patterns that met adequacy standards for 27 nutrients. A food pattern can be declared to be infeasible when no mathematical solution is obtained.

The present study followed procedures used by Britten et al.⁷ to create low-sodium food patterns for six population subgroups by gender and age. The patterns were created using a mathematical diet optimization technique that was analogous to the one used by the U.S. Department of Agriculture to create the Thrifty Food Plan, a nutritious diet for least cost.^{8, 9} The present goal was to determine the lowest level of sodium that was compatible with nutrient-adequate diets for different age–gender groups.

Methods

Data analyses were conducted in 2010. Food patterns were created for men and women in three age groups: 20–30 years; 31–50 years, and >50 years. Observed energy intakes for gender–age groups were based on 24-hour recall data from the 2001–2002 National Health and Nutrition Examination Survey (NHANES).¹⁰ The NHANES sample of 4295 individuals excluded pregnant women and people with reported daily intakes of less than 600 kcal/day.¹¹ Theoretic energy requirements, based on previous work by the IOM¹² and the U.S. Department of Agriculture (USDA),¹³ ranged from 2,000 kcal to 2,400 kcal for men and from 1,600 kcal to 2,000 kcal for women, depending on age.

Input Data Sources

Food groupings—Nutrient composition of foods consumed by 2001–2002 NHANES participants was obtained from the USDA Food and Nutrient Database 1.0 (FNDDS 1.0). Baby foods, alcohol, medical foods and supplements, electrolyte solutions, chewing gum, and foods with an energy density < 10 kcal/100g (e.g., water, coffee, tea) were excluded.

The number of foods eaten varied with age and gender.¹⁴ For modeling purposes, individual foods consumed by each age–gender group were collapsed into 128 food categories, 39 food subgroups, and nine major food groups. The groupings largely followed the USDA system established for coding foods and amounts in What We Eat in America/NHANES 2001–2002. The number of food categories by age–gender subgroups varied from 85 to 128, whereas the number of food subgroups varied from 35 to 39. The nine major food groups were: fruits; vegetables; meat, poultry, and fish; eggs; dry beans, legumes, nuts and seeds;

milk, yogurt, and cheese; bread, cereal, rice, and pasta; fats and oils; and sugars, sweets, and beverages.

Nutrient profiles of food categories—Nutrient profiles were based on a weighted average of the nutrient contribution of each food, as derived from the FNDDS 1.0 nutrient composition data¹⁵ and frequency of occurrence in the 2001–2002 NHANES^{7-9, 16}. Values for solid fat and added sugar (g and kcal) were obtained from the MyPyramid Equivalents Database.¹⁷ The conversion factor for added sugar was 1 teaspoon = 4.2g.

Nutritional goals—Population-wide standards were used for protein, total carbohydrates, total lipids, saturated fatty acids, linoleic acid, linolenic acid, cholesterol, and added sugar (Table 1).¹² Age- and gender-specific DRI values¹⁸⁻²¹ were used for fiber, vitamins A, C, and E, thiamin, riboflavin, niacin, vitamin B6, folate, and vitamin B12 and for calcium, copper, iron, magnesium, phosphorus, selenium, zinc and potassium. Because potassium recommendations are typically hard to meet,⁷ potassium constraint was relaxed to 90% of Adequate Intake (i.e., 4230 mg/day) following the Thrifty Food Plan (TFP)⁹. The model also assumed the consumption of 2 mg/day of vitamin E for men aged 20–30 years, corresponding to 1 tablespoon of vegetable oil per day. The constraint for vitamin E was thereby reset to 13 mg/day.

Consumption constraints—Gender- and age-specific consumption constraints were placed on food groups and subgroups and on each food category. Modeled amounts for the 9 food groups were flanked by the 10th and 90th percentiles of the observed consumption in the referent gender–age group (Table 1). Upper bounds for food subgroups and food categories were set by the 75th percentile of observed consumption of the referent age–gender group (Table 1). Consumption criteria prevented the inclusion of unfamiliar or rarely consumed foods in modeled food patterns. Diet quality could not be improved by including food categories that were never consumed by that gender–age group.

Linear Programming Models

The previously described LINEAR PROGRAMMING model²² had an invariable objective function, energy constraint, a set of nutritional goals and a set of consumption constraints. The objective function measured the deviation from current eating behaviors as the model sought to reach the sodium target, while simultaneously satisfying both energy and nutrient requirements. All food pattern modeling analyses used the “proc optlp” procedure available in the Operational Research package of SAS version 9.2 (2009, SAS institute).

Food variables and objective function—The objective function (F) measured the deviation between a proposed food plan and the current average consumption pattern for the referent gender–age group. This function was the sum of the relative deviation expressed in absolute value (D_j) from each food subgroup j .

$$\text{Minimize } F = \sum_{j=1}^{j=J} D_j$$

$$\text{With } D_j = \left| \left(\sum_{i=1}^{i=I_j} Q_{ij} - Q_j^{obs} \right) / Q_j^{obs} \right|,$$

where J was the number of food subgroups, Q_{ij} was the amount of the food category i from food subgroup j in the modeled diet, Q_j^{obs} was the observed average amount of the food subgroup j in the referent gender–age group, and I_j was the number of food categories in

food subgroup j . To apply linear programming, F_i was transformed into a linear function using goal programming, as described elsewhere.^{5, 22, 23}

Fixed energy, nutritional, and consumption constraints—The energy constraint was the energy requirement for each group. Nutritional constraints (Table 1) ensured that each food pattern met 27 separate nutrition goals. Consumption constraints ensured that the food patterns respected American eating behaviors, a principle also espoused by the TFP and the DGAC report.

Variable sodium constraint—First, modeled food patterns were created without a sodium constraint. The upper bound for sodium was then progressively lowered by 100 mg/d decrements until no mathematical solution could be obtained.

Evaluation of modeled food patterns—In each gender–age group, the distance function (i.e., objective function) was graphically represented depending on the sodium amount in food patterns. When the distance function rises steeply, modeled food patterns depart from current eating behaviors. When no combination of food categories can satisfy model requirements, the food pattern can be declared to be infeasible.⁸

For each gender–age group, the modeled food patterns were analyzed for macronutrient composition, energy density, solid fats and added sugars (SoFAS), and MyPyramid (not FNDDS major food groups) servings for fruits, vegetables, whole grains, refined grains, meats and fish, beans and nuts, and dairy (i.e., milk and milk products).

Results

Impact of a Sodium Reduction on Current Consumption

The linear programming model generated food patterns for sodium levels ranging from the observed values down to the target goal of 1500 mg/day. Appendix A (available online at www.ajpmonline.org) shows that the diets of men aged >50 years were already close to the optimized food patterns, as indicated by the small distance function between current diets and modeled food patterns. By contrast, diets of younger men were farther away from optimum food patterns, as indicated by greater distance functions.

The changing shape of the distance function indicated when the need to comply with reduced sodium diets caused a major disruption in eating behaviors. Whenever the sodium constraint was not limiting, the distance functions were flat; by contrast, a sharply rising function indicated a deviation from existing diets⁸. For men, the distance curve was flat above 2,800–3,000 mg sodium per day, suggesting that sodium was not the limiting factor. However, to achieve the 2300mg/day sodium goal, younger men aged 20–30 years had to tolerate a substantial deviation from existing diets.

A failure to achieve a solution as the amount of sodium was lowered is indicated by the end of the line. For men, nutrient-adequate diets were no longer achievable at sodium levels below 2,000 mg/day for the 20–30 year age group and below 1600mg/day for the 30–50 year age group. The proposed sodium guideline of 1500 mg/day was compatible with nutrient-adequate diets only for men aged >50 years.

For women, the distance function increased as sodium was progressively reduced below 2,000 mg/d. For women aged 20–30 years, a nutritionally adequate food pattern could be obtained only above 1,700 mg/day of sodium. The 1,500 mg sodium guideline was compatible with a nutrient-adequate diet for women aged >50 years and was only just feasible for the 30–50 year age group.

Impact of a Sodium Reduction on the Composition of Modeled Food Patterns

Based on the NHANES data, the observed diet composition was 15% of energy from protein, 35% of energy from fat and 50% of energy from carbohydrate (Appendix B, available online at www.ajpmonline.org). The amount of proteins slightly decreased with the progressive restriction of sodium whereas in the same time amount of total carbohydrates slightly increased. The amounts of solid fats and added sugars (SoFAS) were much lower in modeled food patterns as compared to observed diets and remained stable depending on the sodium restriction.

The observed diets were high in meats and refined grains and were relatively low in vegetables, fruit, dairy, beans and nuts, and whole grains (Appendixes C and D, available online at www.ajpmonline.org). The sodium restriction in nutritionally adequate food patterns had a larger impact on foods than on macronutrients. Compared to the observed diets, modeled food patterns were sharply higher in vegetables, fruit, beans and whole grains, and were lower in meats and in refined grains.

Progressive reduction in the sodium content of modeled food patterns led to patterns that were lower in protein and higher in carbohydrates. As might be expected, reducing the allowed amount of sodium led to a precipitous drop in the meat group for all gender-age groups (Appendix C, available online at www.ajpmonline.org). Whole grains, refined grains, and vegetables dropped sharply for men and decreased slightly among women. The amounts of dairy products remained stable for men and women (Appendix D, available online at www.ajpmonline.org). The reduced-sodium food patterns were much higher in fruits, particularly fruit juices. The amounts of beans, nuts and seeds were much higher for men and women aged <50 years.

The USDA Food Patterns list the number of cups or ounce equivalents (oz eq) for each food group. For men, the lowest achievable sodium level that was associated with nutrient adequacy was provided by food patterns that had high levels of fruit (4.0–4.5 oz eq per cup) and nuts and seeds (3.0–5.5 oz eq per cup). For women, the lowest achievable sodium level associated with nutrient adequacy was provided by food patterns that were high in fruit (3–4 oz eq), vegetables (2.5–3.0 oz eq per cup), and in nuts and seeds (>1.5 oz eq per cup). The fruit in the lowest sodium food patterns was in the form of fruit juice (result not shown).

Discussion

The results of the present study suggest that compliance with the 2010 Dietary Guidelines for sodium may require large deviations from current eating behaviors; a profound modification of the U.S. food supply, or both. For people aged <50 years, the proposed guideline of 1,500 mg/day sodium was not feasible, being incompatible with nutrient-adequate diets.

This is the first feasibility analysis of sodium goals that is based on linear programming. The proposed guideline of 1,500 mg/day sodium was based, in part, on food pattern modeling of ideal diets, as determined by nutrition professionals.¹ Based on such modeling, the lowest-sodium food patterns that were nutritionally adequate contained from 500 to 1250 mg sodium, depending on energy needs.¹ The idealized “lowest sodium” patterns were created by replacing existing food choices with unsalted foods. For example, unsalted French fries and potato chips were substituted for salted versions, cooked fresh meats were substituted for processed meats, and unsalted cucumbers were substituted for olives.

Linear programming, a diet optimization technique analogous to the Thrifty Food Plan, provides an alternative means to create food patterns that meet multiple nutritional, food

group, consumption, and cost constraints.²⁴⁻²⁷ The present food patterns were created to meet 27 nutritional standards for macronutrients, fiber, vitamins and minerals. Separate analyses were conducted for 6 gender age-groups.

The shape of the linear programming objective function can usefully pinpoint when modeled food patterns begin to depart from the existing diets. At that point, substitutions within food groups are no longer sufficient to meet nutrient goals, so that shifts across food groups must be made. For example, the 2,300 mg/day sodium target could be achieved by most age-gender groups by selecting lower-sodium options within each major food group.

By contrast, reducing sodium to below 2,000 mg/d was associated with sharp deviations from existing food patterns. At that point, the amounts of meats, poultry and fish, eggs and grains had to be sharply reduced, whereas the amounts of fruit, beans, nuts and seeds were greatly increased. Vegetables remained in the model because of their very low energy density and because vegetables are among the most nutrient-dense foods.¹⁵ In past studies it was not possible to create a nutritionally adequate food pattern without vegetables²⁸ solid foods were replaced by liquids, particularly fruit juices (results not shown).

Consistent with previous studies, the modeled food patterns had lower energy density than the observed diets.^{5, 23, 29} Consistent with dietary guidelines,³⁰⁻³² the modeled food plans included more fruits and vegetables^{23, 25, 29} than the observed diets. The modeled diets were lower in SoFAS than the observed diets.²²

However, linear programming modeling also showed that sodium levels in the 1,500–2,000 mg/day range were associated with wrenching deviations from existing eating behaviors. The rise in the value of the objective function accurately pinpointed the sodium level at which the modeled food patterns became sharply different from current diets. The youngest age groups with the highest energy needs were affected the most by progressive sodium restriction. The nutrient-adequate food patterns that were achievable at lower levels of sodium were “fructivore” diets, largely composed of fruit juices, nuts, and seeds. By contrast, meats and grains were totally absent from the modeled food patterns because of their sodium content, as were many vegetables.

For age-gender groups aged <50 years, the proposed sodium goal of 1,500 mg/day was incompatible with nutrient-adequate diets. No combination of food categories satisfied the model requirements of a nutrient-adequate food pattern and no mathematical solution was obtained. In other words, at this low level of sodium, the requirements for multiple other nutrients could not be met. Based on the present linear programming modeling, the 1,500 mg sodium guidelines can be declared unfeasible for people aged <50 years and only theoretically feasible for people aged >50 years.

This study has some limitations. Dietary intakes were based on 24-hour recall, so that food patterns were developed for population subgroups rather than individuals, a procedure also followed by the USDA.⁷ An alternative and more robust method would be to base diet optimization on individual-level data.^{5, 29} The present model was very stringent in that as many as 26 nutrient recommendations had to be met as the level of sodium was progressively reduced from the observed values to 1,500 mg/d. Possibly, sodium targets would be easier to meet if guidelines for some additional nutrients were to be relaxed. However, in those cases, the lowest-sodium food pattern would no longer be compatible with the official nutrient goals.

The present analyses suggest that reducing dietary sodium down to the proposed goal of 1,500 mg/d may require a large deviation from current eating pattern for the majority of Americans. In addition to health benefit, the large deviation required by linear programming

models may also have advantageous effects on environmental issues (i.e., a reduction of meat product consumption and thus production would reduce greenhouse gas emissions from the food sector). Further analyses are needed to determine whether a 10% or a 20% reduction of sodium levels in the U.S. food supply will make the 2010 Dietary Guidelines easier to achieve for most age–gender groups. It is generally recognized that a 10%–20% reduction in sodium content is not perceived by most people and may not alter the hedonic profile of a food product.³³ Of course, sodium has multiple functions in food and issues of food chemistry and food safety will need to be considered as well. The use of dietary supplements and fortified foods may also help to change the proportion of sodium relative to other nutrients in the American diet.

The 2010 Dietary Guidelines specifically noted that sodium reduction was a long-term goal, both to allow the food industry to formulate new food products and to give consumers time to develop a liking for low-sodium foods. Given the current food supply and consumption patterns, compliance with sodium goals below 2300 mg/day will require some drastic shifts from a diet based on grains, meats and vegetables to a diet based on fruit juices, beans, nuts and seeds. Whether such a diet will be acceptable to consumers remains to be seen. Additional modeling of sodium-reduced foods will help decide whether a major reshaping of the American food supply is warranted as well.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Table 1

Summary of constraints applied in all linear programming models

List	Unit/day	Value
Energy constraint	kcal	= ER ^a
Macronutrient constraints ^{b,c}		
Proteins	% of TE	10 – 35
Total carbohydrates	% of TE	45 – 65
Total fats	% of TE	20 – 35
Linoleic acid	% of TE	5 – 10
Linolenic acid	% of TE	0.6 – 1.2
Saturated fatty acids	% of TE	≤ 10
Cholesterol	mg	≤ 300
Added sugar	% of TE	≤ 10
Micronutrient constraints ^b		
Fiber, vitamin A, thiamin, riboflavin, niacin, vitamin B-6, folate, vitamin B-12, vitamin C, vitamin E, calcium, copper, iron, magnesium, phosphorus, selenium, zinc, potassium, sodium ^e	g, mg, µg	≥ RDA ^d (or adequate intake) ≤ UL (when defined)
Consumption constraints		
Groups	g	> 10 th percentile
Groups	g	< 90 th percentile
Subgroups	g	< 75 th percentile
Categories	g	< 75 th percentile

^aEnergy requirement is 1600kcal, 1800kcal and 2000kcal for women and 2000kcal, 2200kcal and 2400kcal for men depending on the age class.

^bMacronutrient and micronutrient constraints based on DRIs as established by the IOM. For potassium, 90% of the adequate intake (i.e., 4.7 g/day) was used in constraint.

^cMacronutrient recommendations were the same for all gender–age groups

^dRDA were gender- and age-specific

^eSodium upper limits varied depending on the model. The minimum adequate intake for sodium was set at 1300mg for men and women aged >years and 1500mg for others.

ER, energy requirement; RDA, recommended dietary allowances, TE, total energy; UL, upper limit