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Dewey, Kathryn G

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The Challenge of Meeting Nutrient Needs of Infants and Young Children during the Period of Complementary Feeding: An Evolutionary Perspective[1–3]

Kathryn G. Dewey*

Department of Nutrition, Program in International and Community Nutrition, University of California, Davis, Davis, CA

Abstract

Breast-fed infants and young children need complementary foods with a very high nutrient density (particularly for iron and zinc), especially at ages 6–12 mo. However, in low-income countries, their diet is usually dominated by cereal-based porridges with low nutrient density and poor mineral bioavailability. Complementary feeding diets typically fall short in iron and zinc and sometimes in other nutrients. These gaps in nutritional adequacy of infant diets have likely been a characteristic of human diets since the agricultural revolution ~10,000 y ago. Estimates of nutrient intakes before then, based on hypothetical diets of preagricultural humans, suggest that infants had much higher intakes of key nutrients than is true today and would have been able to meet their nutrient needs from the combination of breast milk and premasticated foods provided by their mothers. Strategies for achieving adequate nutrition for infants and young children in modern times must address the challenge of meeting nutrient needs from largely cereal-based diets. J. Nutr. 143: 2050–2054, 2013.

Introduction

The period of transition from exclusive breastfeeding to consuming a wide range of foods in addition to breast milk is considered the period of complementary feeding, generally between 6 and 24 mo of age (1,2). This 18-mo interval is the largest part of the "1000 days" encompassing pregnancy and the first 2 years after birth, now viewed as the key window of opportunity for preventing undernutrition and its long-term adverse consequences (3). In disadvantaged populations, considerable growth faltering occurs between 6 and 24 mo of age (4–6), and there is often a high incidence of infection, which increases nutritional needs (7). Thus, ensuring adequate nutrition during the period of complementary feeding is a major global health priority. However, meeting nutritional needs during this age interval is challenging. The objective of this article is to provide an evolutionary perspective on why modern complementary food diets are often inadequate. Options for closing those nutrient gaps are discussed elsewhere (8).

Challenges to Ensuring Adequate Nutrition at 6–24 Months of Age

Children <2 y of age have high nutrient needs to support growth and development, yet breast-fed infants typically consume relatively small amounts of foods other than breast milk. As a result, complementary foods need to be high in nutrient density, i.e., the amount of each nutrient per 100 kcal of food. Iron and zinc are generally the most problematic nutrients during the period of complementary feeding (1,9), largely because their concentrations in human milk are low relative to needs. Because average expected energy intake from complementary foods is lowest at 6–8 mo [~200 kcal/d, assuming the average breast-milk intake observed in developing countries (2)], the minimum target nutrient densities in those foods tend to be highest for that age range (1) (e.g., 4.5 mg iron/100 kcal and 1.14 mg zinc/100 kcal). Target nutrient densities are lower for breast-fed infants at 9–11 mo than at 6–8 mo, because average expected intake from complementary foods increases to ~300 kcal/d at 9–11 mo. Expected energy intake from complementary foods increases further to ~550 kcal/d at 12–23 mo, while at the same time the need for iron is lower than during infancy and the need for zinc stays the same. As a result, the minimum iron and zinc densities of complementary foods are considerably lower in the second year of life (1.0 and 0.46 mg/100 kcal, respectively) than in the first year. Thus, the greatest challenge for meeting micronutrient needs of breast-fed children typically occurs during the second 6 mo of life.

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[3] Supplemental Table 1 is available from the ''Online Supporting Material'' link in the online posting of the article and from the same link in the online table of contents at http://jn.nutrition.org.

* To whom correspondence should be addressed. E-mail: kgdewey@ucdavis.edu.

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Infants need complementary foods with much higher nutrient density than is required for adult diets. For example, per 100 kcal of food, a breast-fed infant at 6–8 mo needs 9 times as much iron and 4 times as much zinc as an adult male [who needs 0.5 mg iron and 0.26 mg zinc/100 kcal based on 2700 kcal/d and recommended intakes of iron and zinc (10)]. Thus, infants should receive the most nutrient-rich foods available in the household, yet often the opposite is the case in low-income countries where infants are typically fed nutrient-poor, watery porridges.

Nutrient Gaps in Complementary Food Diets

When actual nutrient densities of typical complementary foods are compared with the target nutrient densities, protein density is generally adequate but several micronutrients are "problem nutrients" (1,11). In developing countries, the usual problem nutrients include iron and zinc, and other nutrients may also be low depending on the types of foods consumed (e.g., riboflavin, niacin, thiamin, folate, vitamin B-6, vitamin B-12, calcium, vitamin A, vitamin C, and vitamin E) or the water and/or soil content (e.g., iodine, selenium). If breast-fed infants are given family foods that are nutritionally adequate for the rest of the household, there is likely to be a shortfall in intake of certain key nutrients. For example, using "best case scenario family food menus" from low-income households in Guatemala, Vossenaar and Solomons (9) demonstrated that the nutrient density of the hypothetical infant diet would be far below the critical nutrient density (as defined by the authors) for iron, zinc, and calcium across the entire age range of 6–24 mo and below the critical nutrient density for some of the vitamins in certain age intervals. This illustrates that transitioning directly to "family foods" as the sole source of complementary foods may put the infant at risk of multiple micronutrient deficiencies. Even when "improved" complementary food recipes are developed, they usually fall short of providing adequate iron, zinc, and sometimes calcium (11).

Diets that are predominantly based on grains and legumes are of particular concern with regard to the amount of bioavailable iron and zinc provided. This is because these foods are usually high in phytate, which binds these minerals and limits their absorption by the child. Phytate concentration can be reduced via germination, fermentation, soaking, or pounding, but these techniques are probably not sufficient to compensate for the low iron and zinc content of typical plant-based complementary foods (11,12). The addition of phytase (the enzyme that breaks down phytate) to complementary foods may be a more effective option. This approach has been studied in school-aged children (13), but additional research is needed to demonstrate efficacy for children <2 y of age.

The high phytate content of grains and legumes may also limit the amount of bioavailable phosphorus, because up to 80% of the phosphorus in such diets is bound up in phytic acid (the storage form of phosphorus for the plant) and excreted unabsorbed (14). The adequacy of phosphorus intake has been largely ignored by nutrition researchers because *1*) there is no simple biomarker of phosphorus deficiency, *2*) most Western diets are rich in phosphorus due to high intakes of dairy products, and *3*) food composition tables present total phosphorus content without subtracting the phytate phosphorus, resulting in overestimates of bioavailable phosphorus intake. Even without subtracting the phytate phosphorus, the estimated intake of phosphorus from grain/legume-based diets used in emergency settings is only 57–68% of the recommended intake at 6–24 mo of age (15). Because phosphorus is a key constituent of body tissues (14), inadequate dietary intake of this nutrient may limit the deposition of lean body mass and linear growth of infants and young children in developing countries.

Another potentially limiting nutrient that has previously been neglected is potassium. Like phosphorus, potassium is a building block of body tissue and hence essential for growth (14). The estimated intake of potassium from grain/legume-based diets used in emergency settings is only 62–71% of the recommended intake at 6–11 mo of age, and even more deficient at 12–23 mo of age depending on which value for recommended intake is used (14,15).

Linear programming techniques have been used to determine whether micronutrient requirements can be met by using only unfortified local foods (regardless of cost or feasibility issues), and if they cannot, which micronutrients are most limiting in the diets of 6- to 11-mo-old breast-fed infants (16,17). Using information from Bangladesh, Ethiopia, and Vietnam (17), requirements could theoretically be met through unfortified foods alone (with some exceptions in Bangladesh), but this was possible only if liver were consumed daily, which is not likely to be feasible. A more realistic dietary scenario assessed was a "5 food group" unfortified diet (17), which included a minimum quantity of the typical staple food (30% of energy from complementary foods) as well as legumes, egg, fish or chicken, and green leafy vegetables every day to achieve a diverse, high-quality diet as recommended by WHO (18). These diets provided only 26–37% of iron needs (10) at 6–8 mo and 35–52% of iron needs at 9–11 mo. For zinc, the diets met 68–82% of needs (19) at 6–8 mo and 83–100% of needs at 9–11 mo.

The above findings raise the question of whether the estimated requirements for iron and zinc during infancy are too high. For these 2 nutrients, requirement estimates after 6 mo of age are based on the amounts needed to support daily maintenance needs and growth in body tissues (including an increase in blood volume) (19). These numbers are quite well understood. In fact, for infants 7–12 mo of age, iron and zinc are the only 2 "problem" micronutrients for which the Institute of Medicine has established an Estimated Average Requirement and a Recommended Dietary Allowance. However, although the estimates of absorbed iron and zinc required are quite solid because they can be easily quantified, there is more uncertainty about appropriate recommendations for iron and zinc intake because of incomplete understanding of iron and zinc bioavailability. The bioavailability assumptions for the hypothetical diets described above (17) were based on current evidence, but it is likely that infants with iron (although not zinc) deficiency are able to upregulate absorption (19). Thus, iron-deficient infants may be able to meet iron needs with smaller quantities of iron-rich foods than estimated, especially if those foods are high in heme iron.

An Evolutionary Perspective on Optimal Infant Diets

If it is so hard to meet nutrient needs during infancy with modern unfortified diets, have there always been nutrient gaps in the diets of infants? The answer is probably no, although micronutrient deficiencies have likely been a common feature of human diets for thousands of years, not just the past few centuries. Until the agricultural revolution ~10,000 y ago, humans relied on hunting, fishing, and gathering of wild plant and animal-source foods

(ASFs). Preagricultural humans consumed a wide variety of ASFs, including wild game, fish, shellfish, and insects. Based on economic subsistence data from 229 human hunter-gatherer societies, Cordain et al. (20) estimated that 45–65% of energy intake came from ASFs. Preagricultural humans also consumed a wide variety of wild plant foods such as leaves, flowers, roots and tubers, nuts, seeds, berries, and other fruits. Cereal grains were rarely consumed, probably because wild grains are tedious to collect and process. Similarly, legumes (e.g., dried beans) were not a major part of preagricultural diets.

The agricultural revolution brought about a profound change in human diets. Most notable was the shift to cereal grains such as wheat, rice, and maize to provide a large proportion of daily energy intake. This change was accompanied by a deterioration in nutritional status in most populations, including a reduction in adult height (21), probably due to a combination of poorer-quality diets and increased risk of infection associated with living in more crowded, settled communities. There is also evidence from skeletal markers that nutrient deficiencies such as iron deficiency anemia became more widespread in agricultural societies, which could be due to poor-quality diets but also certain infections or parasites that cause blood loss, such as hookworms (21,22). The decline in human nutritional status started with the shift to agriculture but worsened during the Industrial Revolution ~100–200 y ago (22). Archeological evidence indicates that the average height of preagricultural humans was similar to that of well-nourished modern populations (21). In high-income countries, average height has increased over the past ~100 y in parallel with improved nutrition (e.g., increased consumption of ASFs) and reduced infectious disease. In low-income populations, however, stunting in height remains widespread.

For infants, the shift to cereal-based diets would have been particularly problematic for several reasons. First, the porridges prepared from cereal flours tend to be very low in energy density, so the child has to consume a very large volume to meet energy needs. The child's stomach capacity limits how much can be consumed in a single feeding; thus, if meal frequency is low, the "bulkiness" of cereal-based diets can be a limiting factor (1). Second, if the infant consumes a typical amount of porridge (100–200 kcal/d), the amounts of other nutrient-rich foods that can be consumed are limited because total energy needs from complementary foods are only 200–300 kcal/d. Last, the inhibition of iron and zinc absorption by phytate in cereal and legume-based diets is of even greater importance to infants than to older children and adults because the needs for iron and zinc are so high during infancy.

Preagricultural diets also contained a moderate-to-high amount of fat (although low in saturated fat), with a favorable estimated ratio (1:1) of omega-6 (*ω*-6) to *ω*-3 fatty acids compared with modern diets, which generally have a much higher ratio (23,24). *ω*-3 Fatty acids are essential for adequate growth, immune function, and child development. Thus, the relatively poor quantity and quality of fat in predominantly cereal-based diets after the agricultural revolution may also have contributed to malnutrition among young children making the transition from breast milk (a good source of fat) to family foods (25).

What would the diets of infants in preagricultural societies have looked like? For most of human history, infants would have consumed breast milk and foods that were premasticated (prechewed) by their mothers. Pelto et al. (26) posit that premastication should be considered the "second arm of infant and young child feeding for health and survival," the first "arm" being breastfeeding. The authors argue that premastication was a "solution" to the dilemma that humans faced by virtue of giving birth to infants who develop more slowly than other primates (linked to evolution of brain size and upright posture) and whose tooth eruption is relatively delayed. Because of these characteristics, human infants are unable to consume foods in an unprocessed form, yet breast milk alone is not sufficient to meet all nutrient needs after 6–8 mo. Premastication allows infants to consume the same foods as consumed by their mothers and transfers various constituents of saliva (similar to those in breast milk) that may have health-promoting effects (26). Pelto et al. provide evidence to support their contention that premastication was practiced in all types of societies, and its disappearance as a usual practice is a recent phenomenon linked to modern, biomedical concepts that have labeled premastication as unhygienic and risky.

If one assumes that, in addition to breast milk, infants of hunter-gatherers received premasticated complementary foods in the same proportions as consumed by their mothers, it is possible to construct a hypothetical nutrient profile of this composite diet. Paleoanthropologists have estimated the nutrient content of hunter-gatherer diets on the basis of the nutrient content of wild game and uncultivated plant foods, evaluation of archeological remains, and the diets of recent hunter-gatherers (23,27). Their estimates suggest that preagricultural diets were very high in animal protein and much higher in vitamin and mineral content than modern diets, even current diets in high-income countries. If we assume that infants are provided with complementary foods that are similar in nutrient density to the diets consumed by their mothers, we can evaluate the likelihood of meeting infant nutrient needs.

Supplemental Table 1 shows the minimum target nutrient density of complementary food diets (accounting for the nutrients provided by breast milk) compared with the estimated nutrient density of the composite preagricultural diet. The hypothetical preagricultural diet appears to be more than adequate to meet the estimated nutrient needs of children under 2 y of age, with a few minor exceptions (see Supplemental Table 1). The iron density of the preagricultural diet (2.9 mg/100 kcal) is lower than the target density at 6–8 mo (4.5 mg/100 kcal) but very close to the target density at 9–11 mo (3.0 mg/100 kcal) and above the target density at 12–23 mo (1.0 mg/100 kcal).

The "shortfall" in iron content of the hypothetical preagricultural diet at 6–8 mo of age—compared with the target density—should be viewed in the context of the iron "endowment" at birth, which normally supports iron needs for several months. Total body iron just after birth is determined primarily by birth weight, maternal prenatal iron status, and the timing of clamping of the umbilical cord (28). Assuming normal birth weight, sufficient maternal prenatal iron intake, and a full transfer of placental blood after birth (with the umbilical cord tied off after blood flow ceases, the likely scenario in traditional societies), an infant's iron endowment combined with the small daily intake of iron from breast milk is adequate to meet iron needs for >8 mo, even with no additional iron coming from complementary foods (28). Under these conditions, the iron density of the preagricultural diet at 6–8 mo would have been sufficient to prevent development of iron deficiency before age 9 mo. By 9 mo, the iron density of the preagricultural diet (2.9 mg/100 kcal) matches almost exactly the target iron density (**Fig. 1**), which is remarkable given that typical modern-day (unfortified) complementary food diets have a much lower iron density [0.4–1.3 mg/100 kcal (1)].

It is reasonable to conclude that the complementary food diets of infants today, especially in low-income countries, are of much poorer nutritional quality than those typically consumed by infants during the vast majority of human evolution. Figure 1 illustrates the gaps in iron and zinc at 9–11 mo and the

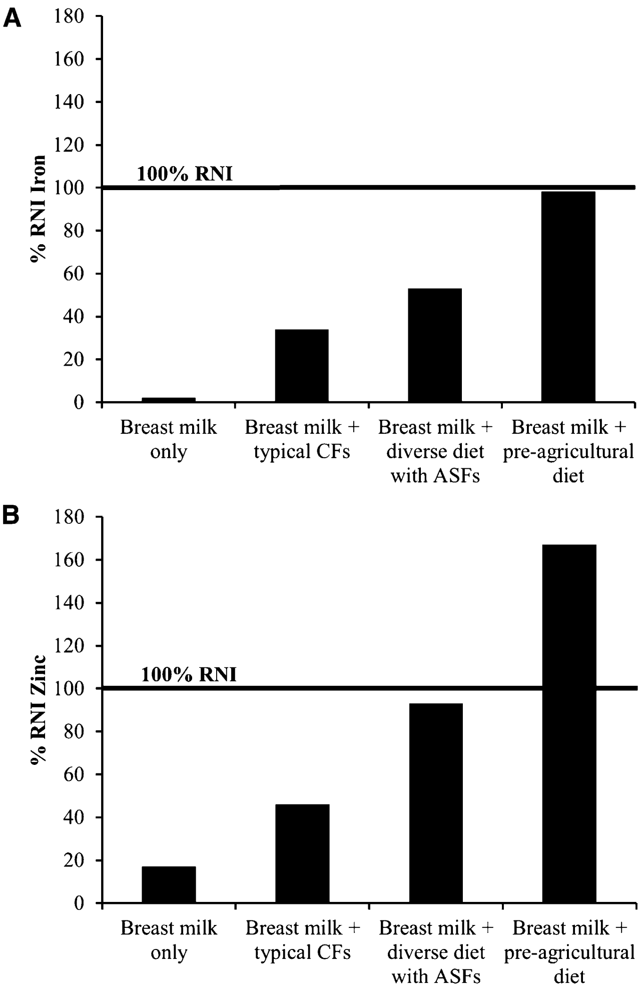

FIGURE 1 Estimated intakes of iron (*A*) and zinc (*B*) at ages 9–11 mo. Data sources: iron content of breast milk (2), zinc content of breast milk (30), iron and zinc content of typical complementary foods (15), iron and zinc content of diverse diet with animal-source foods (17), iron and zinc content of a preagricultural diet (23). ASF, animal-source food; CF, complementary food; diverse diet with ASFs, average of diets from Bangladesh, Ethiopia, and Vietnam consisting of the country's staple food, legumes, chicken egg, fish or chicken, and green leafy vegetables (17); preagricultural diet, average values for the nutrient content of the types of foods likely consumed by hunter-gatherers, as explained in footnotes 3 and 4 of Supplemental Table 1; RNI, recommended nutrient intake; Typical CFs, average of typical general food distribution rations provided by the World Food Program's Emergency Operations (15).

differences by comparison with the hypothetical preagricultural diet. The deterioration in dietary quality most likely began during the agricultural revolution, with the result that widespread nutritional deficiencies have been part of the human condition for thousands of years. The populations that have escaped from this condition are those whose economic status increased sufficiently to permit consumption of a more nutrient-rich diet, typically by increasing the proportion of ASFs. Even in those populations, such as in the United States, iron deficiency during infancy was common before the widespread use of iron-fortified infant foods (29). For low-income countries, the reality is that predominantly cereal-based diets are likely to be the mainstay for the foreseeable future. Returning to a preagricultural diet is not an option for populations that currently obtain more than half of their energy from cereal grains. Thus, other strategies for achieving adequate nutrition for infants and young children must be developed that are sustainable over the long term.

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