Is iron and zinc nutrition a concern for vegetarian infants and young children in industrialized countries?[1–3]

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ABSTRACT

Well-planned vegetarian diets are considered adequate for all stages of the life cycle, despite limited data on the zinc status of vegetarians during early childhood. The bioavailability of iron and zinc in vegetarian diets is poor because of their higher content of absorption inhibitors such as phytate and polyphenols and the absence of flesh foods. Consequently, children as well as adult vegetarians often have lower serum ferritin concentrations than omnivores, which is indicative of reduced iron stores, despite comparable intakes of total iron; hemoglobin differences are small and rarely associated with anemia. However, data on serum zinc concentrations, the recommended biomarker for identifying population groups at elevated risk of zinc deficiency, are sparse and difficult to interpret because recommended collection and analytic procedures have not always been followed. Existing data indicate no differences in serum zinc or growth between young vegetarian and omnivorous children, although there is some evidence of low serum zinc concentrations in vegetarian adolescents. Some vegetarian immigrants from underprivileged households may be predisposed to iron and zinc deficiency because of nondietary factors such as chronic inflammation, parasitic infections, overweight, and genetic hemoglobin disorders. To reduce the risk of deficiency, the content and bioavailability of iron and zinc should be enhanced in vegetarian diets by consumption of fortified cereals and milk, by consumption of leavened whole grains, by soaking dried legumes before cooking and discarding the soaking water, and by replacing tea and coffee at meals with vitamin C–rich drinks, fruit, or vegetables. Additional recommended practices include using fermented soy foods and sprouting at least some of the legumes consumed. Fortified foods can reduce iron deficiency, but whether they can also reduce zinc deficiency is less certain. Supplements may be necessary for vegetarian children following very restricted vegan diets. *Am J Clin Nutr* 2014;100(suppl):459S–68S.

INTRODUCTION

Interest in vegetarian diets has increased in industrialized countries, in part because of the health benefits of plant-based diets, as well as ethical, ecologic, and economic concerns. The arrival of immigrants who practice vegetarianism has also increased the number of vegetarians in many industrialized countries.

In general, a vegetarian dietary pattern that excludes animal products (ie, meat, poultry, and fish; and for vegans, eggs and dairy products), if well balanced, can be compatible with a healthy lifestyle and optimal nutritional status in adults and may offer some long-term health benefits (1). However, a vegetarian diet that supports the health of an adult may not necessarily be appropriate for infants and young children. Vegetarian diets for children are often bulky, with a low energy and nutrient density and a high content of inhibitors of iron and zinc absorption. This is of concern for infants and toddlers who have high physiologic requirements for iron and zinc to support their rapid growth and brain development (2). Even mild iron deficiency in this age group is important because if it progresses to iron deficiency anemia, impairments in cognitive function and behavioral problems arise, which may not be reversible with iron therapy (3). Similarly, zinc deficiency in early childhood is associated with anorexia, poor linear growth, and impaired immune competence, which can increase the risk of childhood illnesses and mortality, especially in low-income settings (4).

An emerging practice in industrialized countries is the use of nutrient-rich vegetarian foods and products fortified with iron and sometimes with zinc. The latter can reduce iron deficiency, but whether they can also reduce zinc deficiency is less certain. There has been no comprehensive review of the iron and zinc status of vegetarian infants and young children since these nutrient-rich and fortified foods became available. Here we examine the iron and zinc status of vegetarian infants and young children, discuss several dietary and nondietary factors that may exacerbate the risk of deficiency, and describe some dietary practices to reduce the risk of iron and zinc deficiency. Lactoovovegetarian, lactovegetarian, or vegan diets are considered, unless specified otherwise, and published data from 1995 on intakes and/or biomarkers of iron and zinc for children aged 0–11 y are included.

DIETARY IRON AND ZINC INTAKES OF YOUNG VEGETARIANS

Up to 6 mo of age, the iron and zinc requirements of exclusively breastfed full-term infants are likely to be met (2, 5). After 6 mo of age, additional sources of bioavailable iron and zinc are

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[2] Presented at the symposium “Sixth International Congress on Vegetarian Nutrition” held in Loma Linda, CA, 24–26 February 2013.

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First published online May 28, 2014; doi: 10.3945/ajcn.113.071241.

TABLE 1
Iron intakes and selected biomarkers of iron status in vegetarian and omnivorous children[1]

Study (reference)	Design; country (study period): sampling strategy	Target group	Dietary method	Iron intake	Biomarkers of iron status
Nathan et al (17)	Longitudinal; Merseyside, UK (January 1992–July 1993): self-selected; lactoovovegetarians or pescovegetarians; omnivores matched by age, sex, and ethnicity; all followed on 3 occasions every 6 mo	Vegetarians: 7–11 y (9.1 ± 1.5[2] y) (n = 50); omnivores: 7–11 y (9.4 ± 1.4 y) (n = 50)	3-d estimated diet records (1 weekend day) with in-home interviews with calibrated food models for portion sizes on 3 occasions	Vegetarians vs omnivores: 11.2 ± 0.42 vs 10.6 ± 0.34 mg/d, NS	Vegetarians vs omnivores: Hb: 118.6 (1.8)[3] vs 124.1 (2.0) g/L, $P < 0.05$; <3rd percentile: 47.5% vs 33%, NS
Leung et al (18)	Cross-sectional; Chinese Hong Kong: self-selected, lactoovovegetarian diet for ≥1 y only	Vegetarians: 4–6 y (n = 10), 4–11 y (n = 34), 7–11 y (n = 24); no omnivores	7-d consecutive estimated diet records followed by cross-check interview	Vegetarians only; 4–6 y: 10.3 (5.1–17.2)[4] mg/d; 7–11 y: 11.5 (8.3–19.0) mg/d	Vegetarians only; 4–6 y: Hb: 122 ± 13 g/L; ferritin: 27 ± 12 μg/L; 7–11 y: Hb: 135 ± 9 g/L; ferritin: 35 ± 20 μg/L
Yen et al (19)	Cross-sectional; Taiwan: recruitment method not described, vegetarians were children who had excluded meat or fish for ≥6 mo	Vegetarians: 2–6 y (n = 21); omnivores: 2–6 y (n = 28)	3-d consecutive estimated diet records (1 weekend day) by parents	Vegetarians vs omnivores: 10.1 ± 5.4 vs 8.8 ± 5.1 mg/d, NS	Vegetarians vs omnivores; Hb: 12.8 ± 1.0 vs 13.2 ± 1.1 g/L, NS; anemia: none; ferritin: 26.6 ± 13.7 vs 38.7 ± 24.9 μg/L, $P < 0.05$; low iron stores: none
Thane and Bates (15)	Cross-sectional; British National Diet and Nutrition Survey (July 1992–June 1993): nationally representative sample, children classified as vegetarians based on absence of meat and meat products from diet records, 44% of vegetarians were Asian	Vegetarians: 1.5–4.5 y (n = 44); omnivores: 1.5–4.5 y (n = 1307)	4-d weighed diet records (including 2 weekend days) recorded by mother or caregiver	Vegetarians vs omnivores; 1.5 to <3 y[5]**:** 5.0 ± 1.4 vs 5.2 ± 1.4 mg/d, NS; <LRNI: 20% vs 19%, NS; 3–4.5 y[5]: 6.0 ± 1.4 vs 6.0 ± 1.4 mg/d, NS; <LRNI: 10% vs 6%, NS	Vegetarians vs omnivores; 1.5 to <3 y: Hb: 11.8 ± 0.9 vs 12.1 ± 0.9 g/L, NS; Hb <110 g/L: 18% vs 10%, NS; ferritin: 8.0 (2, 29)[6] vs 16.0 (4, 67) μg/L, $P < 0.01$; ferritin <12 μg/L: 73% vs 34%, $P < 0.01$; ferritin <10 μg/L: 64% vs 24%, $P < 0.01$; 3–4.5 y: Hb: 12.1 ± 0.6 vs 12.3 ± 0.9 g/L, NS; Hb <110 g/L: 0% vs 6%, NS; ferritin: 13.0 (4, 44) vs 19.0 (5, 76) μg/L, NS; ferritin <12 μg/L: 40% vs 0.27%, NS; ferritin <10 μg/L: 20% vs 0.16%, NS

(Continued)

TABLE 1 (*Continued*)

Study (reference)	Design; country (study period): sampling strategy	Target group	Dietary method	Iron intake	Biomarkers of iron status
Taylor et al (20)	Longitudinal, observational; unspecified regions, UK (~1996): method of recruitment not specified, infants weighed ≥2500 g at birth	Non–meat eaters: infants from 4 mo (n = 15); meat eaters: infants from 4 mo (n = 49)	7-d consecutive weighed diet records by mother or caregiver for children at 4, 8, 12, 16, 20, and 24 mo	Non–meat eaters vs meat eaters; 4 mo: 3.3 ± 2.9 vs 4.8 ± 3.5 mg/d, NS; 8 mo: 6.3 ± 3.8 vs 8.1 ± 3.9 mg/d, NS; 12 mo: 7.9 ± 3.9 vs 6.5 ± 3.3 mg/d, NS; 16 mo: 6.9 ± 1.8 vs 4.8 ± 1.6 mg/d, $P < 0.02$; 20 mo: 6.7 ± 2.2 vs 4.9 ± 1.4 mg/d, $P < 0.01$; 24 mo: 6.4 ± 1.5 vs 5.2 ± 2.4 mg/d, $P < 0.01$	Non–meat eaters vs meat eaters; 4–5 mo—Hb: 120 ± 16 vs 117 ± 12 g/L, NS; ferritin: 49.5 ± 40.6 vs 37.7 ± 22.4 μg/L, NS; 12 mo—Hb: 119 ± 12 vs 120 ± 10 g/L, NS; ferritin: 24.9 ± 13.4 vs 27.0 ± 15.2 μg/L, NS; 24 mo—Hb: 124 ± 7 vs 121 ± 9 g/L, NS; ferritin: 21.9 ± 7.9 vs 23.3 ± 11.3 μg/L, NS

[1] Hb, hemoglobin; LRNI, Lower Reference Nutrient Intake.

[2] Mean ± SD (all such values).

[3] Mean; SE in parentheses (all such values)

[4] Median; 10th–90th percentile in parentheses (all such values).

[5] Values reported in the study are per 4.18 MJ. Values reported here have been adjusted by using data on mean energy intakes reported in the study.

[6] Geometric mean; 95% CI in parentheses (all such values).

needed to cover their requirements. In the predominantly plant-based complementary diets of low-income countries, intakes of energy, iron, and zinc from complementary foods are frequently below the WHO estimated needs for breastfed children aged 6–23 mo (6–11). Comparable data from industrialized countries on the adequacy of iron and zinc intakes of vegetarians during early childhood are sparse.

The US national surveys on feeding infants and toddlers (Feeding Infants and Toddlers Study) in 2002 and 2008 did not examine nutrient intakes in relation to an omnivorous or vegetarian dietary pattern (12, 13). In these surveys, the prevalence of inadequate intakes of iron and zinc for children (aged 12–47 mo) was very low (ie, <1%), although in 2008 there was a small subset of infants aged 7–11 mo whose iron (12%) and zinc (6%) intakes were considered inadequate (12) on the basis of the Estimated Average Requirement (EAR) cut-point method. These overall findings probably reflect the higher reported energy intakes, consumption of infant formulas and cereals fortified with iron and zinc, and use of supplements by US infants and young children (12, 14) compared with those from low-income countries. In the UK national survey of children aged 1.5–4.5 y in 1992–1993 (15), there were no significant differences between the vegetarian and omnivores in energy-adjusted intakes of iron and zinc or in the proportion with intakes below the UK lower reference nutrient intakes, although the latter ranged from 6% to 21%. Comparison of these data with the those from the United States is difficult because the UK survey did not apply the EAR cut-point method (16).

The data from industrialized countries on average iron and zinc intakes (mg/d) of young vegetarians are summarized in **Tables 1** and **2**, and they highlight that, for vegetarians up to 11 y of age, intakes are similar or even higher than those of omnivores (15, 17, 19, 20). This similarity may reflect both fortified and nonfortified cereal products being the major nonmilk source for iron and zinc during childhood, irrespective of dietary practices (12, 14, 15, 21–23). Intakes of meat, even among omnivores, are usually small during early childhood (24–26): for US infants aged 6–11 mo and toddlers aged 12–23 mo, meat contributed <1% and <8%, respectively, of dietary iron, although substantially more zinc (23).

Unfortunately, unlike the US Feeding Infants and Toddlers Study (12), none of the studies in Tables 1 and 2 applied the recommended method to assess the prevalence of inadequate intakes of iron and zinc (16), and most also failed to account for the lower mineral bioavailability in the vegetarian diet (27–29). To compensate for this lower bioavailability, the United States and Canada recommend that the EARs for iron and zinc for vegetarians be increased by 80% and 10%, respectively (2). Indeed, an even greater increase may be needed for zinc, because the inhibitory effect of phytate on zinc absorption may be larger than previously estimated (30). Without doubt, the poorer bioavailability of iron and zinc in vegetarian diets is likely to increase the risk of inadequate intakes of these trace minerals.

ASSESSMENT OF IRON AND ZINC STATUS IN YOUNG VEGETARIANS

There is also a paucity of data on biomarkers of iron and zinc status for vegetarians during childhood (Tables 1 and 2).

TABLE 2
Zinc intakes and serum zinc concentrations in vegetarian and omnivorous children[1]

Study (reference)	Design; country (study period): sampling strategy	Target group	Dietary method	Zinc intake	Serum zinc
Nathan et al (17)	Longitudinal; Merseyside, UK (January 1992–July 1993): self-selected; lactoovovegetarian or pescovegetarian; omnivores matched by age, sex, and ethnicity; all followed on 3 occasions every 6 mo	Vegetarians: 7–11 y (9.1 ± 1.5[2] y) (*n* = 50); omnivores: 7–11 y (9.4 ± 1.4 y) (*n* = 50)	3-d estimated diet records (1 weekend day) with in-home interviews with calibrated food models for portion sizes on 3 occasions	Vegetarians vs omnivores; 5.9 ± 0.20 vs 6.8 ± 0.22 mg/d, $P < 0.01$	ND
Thane and Bates (15)	Cross-sectional; British National Diet and Nutrition Survey (July 1992–June 1993): nationally representative sample, children classified as vegetarians based on absence of meat and meat products from diet records, 44% of vegetarians were Asian	Vegetarians: 1.5–4.5 y (*n* = 44); omnivores: 1.5–4.5 y (*n* = 1307)	4-d weighed diet records (including 2 weekend days) recorded by mother or caregiver	Vegetarians vs omnivores; 1.5 to <3 y[3]: 3.8 ± 1.0 vs 4.4 ± 1.0 mg/d, NS; <LRNI: 16% vs 14%, NS; 3–4.5 y[3]: 4.1 ± 0.7 vs 4.6 ± 1.1 mg/d, NS; <LRNI: 21% vs 18%, NS	Vegetarians vs omnivores; 1.5 to <3 y: 13.1 vs 13.0 μmol/L, NS; 3–4.5 y: 13.1 vs 13.0 μmol/L, NS
Taylor et al (20)	Longitudinal, observational; unspecified regions, UK (∼1996): method of recruitment not specified, infants weighed ≥2500 g at birth	Non–meat eaters: infants from 4 mo (*n* = 15); meat eaters: infants from 4 mo (*n* = 49)	7-d consecutive weighed diet records by mother or caregiver for children at 4, 8, 12, 16, 20, and 24 mo	Non–meat eaters vs meat eaters; 4 mo: 3.2 ± 0.8 vs 3.6 ± 1.3 mg/d, NS; 8 mo: 3.9 ± 1.5 vs 4.6 ± 1.5 mg/d, NS; 12 mo: 5.0 ± 1.8 vs 4.9 ± 1.5 mg/d, NS; 16 mo: 5.1 ± 2.4 vs 4.3 ± 1.0 mg/d, NS; 20 mo: 4.8 ± 2.0 vs 4.4 ± 1.1 mg/d, NS; 24 mo: 5.0 ± 1.6 vs 4.4 ± 1.1 mg/d, NS	Non–meat eaters vs meat eaters; 4–5 mo: 11.7 ± 1.1 vs 14.2 ± 2.3 μmol/L, NS; 12 mo: 13.6 ± 2.2 vs 15.4 ± 2.6 μmol/L, NS; 24 mo: 14.1 ± 2.2 vs 14.3 ± 2.3 μmol/L, NS

[1] LRNI, Lower Reference Nutrient Intake; ND, not determined.

[2] Mean ± SD (all such values).

[3] Values reported in study are per 4.18 MJ. Values reported here have been adjusted by using data on mean energy intakes reported in the study.

Assessment of iron status

A range of hematologic and biochemical indicators can be used to assess iron status and to detect iron deficiency. Of the hematologic indicators, the WHO (31) recommends hemoglobin concentration as a measure of anemia and mean cell volume to indicate the presence of abnormally small (microcytic) red blood cells, as occur in iron deficiency anemia, or abnormally large (macrocytic) red blood cells, as in vitamin B-12 or folate deficiency. The WHO also recommends the following 3 iron status biomarkers: serum ferritin as a measure of iron stores, soluble transferrin receptor (sTfR) to reflect tissue iron depletion, and zinc protoporphyrin as a measure of the severity of iron deficiency. By combining sTfR with ferritin, an estimate of body iron stores can be made with the use of appropriate formulas. For further justification for the selection of these indicators, the reader is referred to the WHO report (31).

In the studies summarized in Table 1, hemoglobin and serum ferritin were most commonly used. In some studies (17), low hemoglobin concentrations were assumed to reflect iron deficiency anemia, although their low specificity (31) probably results in an overestimate of iron deficiency anemia. In others, low serum ferritin concentrations were used to define storage iron depletion (15, 20) and, in combination with low hemoglobin, to define iron deficiency anemia (15, 20), even though a multivariable model that includes at least 2 biomarkers of iron status in addition to hemoglobin to minimize misclassification is preferred (31). Furthermore, most of the studies failed to account for the potential confounding effect of inflammation on serum ferritin concentrations. The latter increases in response to inflammation, irrespective of iron stores, because apoferritin is an acute-phase reactant protein (31). Increasingly, serum ferritin, sTfR, and hemoglobin are recommended as a useful combination to reflect storage iron depletion, tissue iron depletion, and functional impairment, respectively (32), although in the studies in Table 1 sTfR was not used.

In the studies shown in Table 1, most of the differences in hemoglobin concentrations between young vegetarians and omnivores were small (15, 19, 20), with the exception of the UK study in Merseyside children aged 7–11 y in whom mean hemoglobin concentrations in the vegetarians were significantly lower than in the omnivores (17). No iron biomarkers were measured, so whether there were any differences in rates of iron deficiency anemia among these Merseyside children is unknown. In contrast, serum ferritin was significantly lower in the vegetarian compared with the omnivorous children in some (15, 19) but not all (20) of the studies. The physiologic significance of low serum ferritin concentrations in the absence of anemia is uncertain.

The lower serum ferritin concentrations in vegetarian children are assumed to result from the absence of readily absorbable heme iron from flesh foods. None of the studies in Table 1 showed a positive relation between intakes of flesh foods or heme iron and serum ferritin (15, 19, 20), in contrast to other reports (33, 34). Several factors may have confounded such a relation, including a small sample size or a low intake of flesh foods, even among the omnivorous children. Alternatively, the impact of heme iron from flesh foods on serum ferritin may be important only when total iron intakes are low (20), which was not the case in the studies in vegetarian children shown in Table 1, as noted earlier. Several nondietary factors, such as failure to account for inflammation or infection (31) or day-to-day variation in serum ferritin (35), also have the potential to confound this relation but have rarely been considered.

Assessment of zinc status

Unlike iron, there is only one recommended biomarker, serum zinc, for identifying population groups at elevated risk of zinc deficiency [for further details, *see* Hess et al (36)]. Unfortunately, only 2 studies in young children consuming vegetarian dietary patterns have measured serum zinc (Table 2) (15, 20), and it is not clear whether the critically important International Zinc Nutrition Consultative Group procedures (4, 36) were used for the collection and analysis of the blood samples. In the UK 1992–1993 national preschool survey, there were no significant differences between plasma zinc concentrations of omnivores and vegetarians irrespective of age group, and no correlation with total zinc intake (15). Similar findings were observed in UK infants and toddlers who consumed diets with or without meat (20). Failure to observe a positive relation between serum zinc and meat intake in young children is not unexpected in view of the small portions of flesh foods consumed by this age group, as noted earlier (23, 25). Furthermore, serum zinc concentrations are influenced by numerous technical and biological factors, some of which are difficult to control in studies in young children. These factors include adventitious contamination, time of day, fasting status, the quantity and timing of the previous meal, age, and sex (4, 36). Inflammation is an additional confounding factor, because serum zinc concentrations decline during inflammation as a result of metabolic redistribution, so they do not accurately reflect zinc nutrition (4, 36).

In some adolescents and young women, lower serum zinc concentrations (based on fasting blood samples) were reported among those who excluded red meat from their diets compared with those who ate red meat (37, 38), and in some instances, serum zinc has been negatively associated with dietary phytate-to-zinc molar ratios (37, 38, 39). Such relations may be apparent in older age groups because they consume larger portions of flesh foods compared with young children. However, even in meat-based randomized controlled trials in young children, no positive response in serum zinc has been reported (40, 41).

The joint WHO/UNICEF/International Atomic Energy Agency/International Zinc Nutrition Consultative Group interagency meeting on zinc status indicators (42) recommended height- or length-for-age as the best available functional outcome associated with the risk of zinc deficiency in populations. Only 3 studies in Tables 1 and 2 reported on linear growth, which appeared to be normal in the young vegetarian children (18, 19, 43). This is consistent with the reports of most (44–47) but not all (48–50) studies in older children, depending in part on the age of the children and the extent of the vegetarianism.

Poor growth of some vegetarian children consuming very restricted diets was reported in some of the earlier studies (46, 51). It is possible that this may have been associated, at least in part, with suboptimal zinc status arising from inadequate intakes of bioavailable zinc. Unfortunately, serum zinc was not measured in these early studies, and neither of the 2 studies that measured serum zinc in Table 2 (15, 20) examined relations between serum zinc and linear growth.

DIETARY FACTORS AFFECTING IRON AND ZINC ABSORPTION IN YOUNG VEGETARIANS

The maintenance of whole-body iron homeostasis is regulated by absorption from the diet, whereas for zinc, both modulation of absorption of exogenous dietary zinc and reabsorption of endogenous zinc secreted in the intestinal lumen postprandially are involved (4, 32). These processes may be influenced by both diet and host-related factors.

Vegetarian diets are considered to have poor iron and zinc bioavailability because of their high content of unrefined cereals, legumes, nuts, and oleaginous seeds, which often replace flesh foods (ie, meat, poultry, and fish). These plant foods, although rich sources of nonheme iron and zinc, also contain high concentrations of phytate, which inhibits zinc and nonheme iron absorption by forming insoluble complexes in the gastrointestinal tract that cannot be digested or absorbed (2, 30, 52, 53). Some of these plant foods (52, 53), as well as beverages such as tea and coffee, are also rich in polyphenol compounds that inhibit nonheme iron absorption. In contrast, meat, poultry, and fish supply a source of well-absorbed heme iron and zinc and enhance nonheme iron and zinc absorption (2, 4, 32). The component of muscle tissue that enhances nonheme iron absorption is uncertain, although L-α-glycerophosphocholine is among the components that have been proposed (54), whereas zinc absorption is facilitated by the soluble ligands formed from L-amino acids and cysteine-containing peptides released during digestion (55).

The inhibitory effect of phytate on both iron and zinc absorption is dose-dependent (53, 56). Molar ratios of phytate-to-iron of <1.0 (57) and phytate-to-zinc of <15.0 (2) are said to improve the absorption of iron and zinc in adults, but whether these ratios apply to children's diets is uncertain. Likewise, the prediction equation of Miller et al (58) for calculating intakes of absorbable zinc from data on total intakes of zinc and phytate is based on adult data, and whether it is valid for children is unknown. Currently, data on the phytate content of diets of vegetarian children in industrialized countries are limited, in part because of the paucity of phytate values in nutrient databases.

Dietary fiber and calcium concentrations are often high in the diets of lactovegetarian children. High concentrations of dietary fiber appear to exert almost no influence on iron (59), or zinc (60) absorption on the basis of isotope studies using pure-fiber fractions. However, high-fiber diets frequently contain high concentrations of phytate. Despite earlier reports of adverse effects of high intakes of calcium on both iron and zinc absorption, most intervention studies based on whole-day diets failed to confirm this for iron (61), or zinc when zinc intakes are adequate (62). Whether calcium has an adverse effect on zinc absorption when zinc intakes are low is unclear.

The high consumption of fruit and vegetables by vegetarian children relative to nonvegetarians (19) may result in higher intakes of ascorbic acid. This increases nonheme iron (but not zinc) absorption by reducing Fe^{3+} to the more soluble Fe^{2+}, the form required for transport into mucosal cells (63). Whether this enhancing effect can counteract completely the absence of the "meat enhancing factor," the inhibitory effects of high intakes of phytic acid on nonheme iron absorption, or polyphenols on nonheme iron absorption in the diets of young vegetarian children is dependent on the amount of ascorbic acid consumed (53). It is conceivable that some adaptation to a vegetarian dietary pattern may occur, even during childhood. Some partial physiologic adaptive response in the absorption of nonheme iron was reported in adults by some (27, 64) but not all (65) investigators. For zinc, there is some increase in absorption in adults when diets have a low content of both zinc and phytate (66), but probably no adaptation in high-phytate vegetarian diets.

NONDIETARY FACTORS AFFECTING ABSORPTION OF IRON AND ZINC IN YOUNG VEGETARIANS

In general, overt iron and zinc deficiency do not appear to be common among vegetarian children in industrialized countries today, irrespective of the extent of their vegetarianism. Nevertheless, several nondietary factors summarized in **Table 3** may increase the risk of mild iron and zinc deficiency because they have a negative impact on iron and zinc absorption. These factors also have the potential to attenuate associations between dietary intakes and biomarkers of iron and zinc status and, although rarely considered, may be especially important for some recently arrived children of underprivileged vegetarian immigrants.

Inflammation can have a powerful effect on biomarkers of iron status both directly by influencing their production and release and indirectly because inflammation affects iron absorption. Hence, inflammation has the potential to confound the interpretation of some iron biomarkers in studies in vegetarian children. During inflammatory conditions accompanied by increased IL-6, hepcidin production is increased and iron absorption is reduced (67). At the same time, the release of iron from stores is restricted. Hence, in some of the studies in Table 1, children with inflammation may have been incorrectly diagnosed as iron replete on the basis of serum ferritin alone, emphasizing the importance of including a biomarker of inflammation such as C-reactive protein or α1-acid glycoprotein. In such cases, measurement of sTfR may also be helpful because sTfR is elevated in the presence of tissue iron deficiency and is less affected by inflammation than serum ferritin; thus, a raised sTfR suggests tissue iron deficiency even when the ferritin concentration may be falsely normal because of inflammation (31).

The inflammatory response can also be induced by bacterial and intestinal parasitic infections. Overweight and obesity can also induce an inflammatory response (68). In general, children following vegetarian diets tend to be leaner (43, 45, 46) than their omnivorous peers; although in the UK 1997 National Diet and Nutrition Survey, overweight was common among Asians, some of whom were almost certainly vegetarian (69).

Another factor that plays an important role in determining the amount of iron and zinc released from the food matrix and subsequently made available for absorption is gastric acid. Low gastric acid conditions, occurring, for example, as a result of *Helicobacter pylori*–induced hypochlorhydria, decrease solubilization of both iron and zinc and hence their absorption. The resultant hypochlorhydria also predisposes children to enteric infections that can result in diarrhea, and thus loss of zinc (4). In the US 1999–2000 NHANES, *Helicobacter pylori* infection was associated with both iron deficiency and iron deficiency anemia in participants aged ≥3 y (70).

Intestinal parasitic infections may increase the permeability of and reduce transit time in the gastrointestinal tract, causing

TABLE 3
Nondietary factors that affect absorption of iron and zinc

Factors	Mechanism
Inflammation/infection	Inflammatory response impairs iron absorption due to upregulation of hepcidin, resulting in functional iron deficiency. Also causes metabolic redistribution of zinc from plasma to liver. Infections may also increase urinary excretion of zinc.
Bacterial overgrowth and parasitic infections	May induce the inflammatory response, thus reducing iron absorption. Also alters the integrity of the intestinal mucosa, causing increases in intestinal permeability and transit time and a reduction in absorption of iron and zinc.
Overweight or obesity	Induces inflammatory response, which may lead to functional iron deficiency as well as low plasma zinc.
Helicobacter pylori–induced hypochlorhydria	Low gastric acid conditions decrease solubilization of iron and zinc and thus reduce absorption in gastrointestinal tract. Also predisposes children to enteric infections that result in diarrhea and hence loss of zinc.
Chronic diarrhea	Often accompanied by impaired absorption of fat that interferes with the normal conservation of endogenously secreted zinc, resulting in increased losses of zinc via stool.
Environmental enteropathy	Results in villus atrophy with infiltration of inflammatory T cells. Causes a decrease in absorption and perturbations in homeostasis of iron and zinc. May exist among recently arrived immigrants.
Hookworm, *Trichuris trichiura*, and *H. pylori* infections	Can progressively deplete iron stores via gastrointestinal blood loss, resulting in iron deficiency. Parasites can also induce anorexia and malabsorption.
Genetic hemoglobin disorders; results in abnormal hemoglobin chains (hemoglobinopathies) or inadequate production of hemoglobin chains (thalassemias)	Individuals may have asymptomatic or mildly symptomatic microcytic anemia, depending on the specific genetic and phenotypic condition. In sickle cell disease (hemoglobin S), excessive losses of urinary zinc may cause zinc deficiency.

malabsorption of iron and zinc and, in some cases (eg, hookworm), gastrointestinal blood loss that results in iron deficiency (71). Occult bleeding can also be provoked by the early introduction (ie, before 12 mo) of unmodified cow milk (72).

Finally, certain genetic disorders, some of which may be common among immigrant children of African, South Asian, or South-East Asian descent, can complicate the interpretation of hematologic and iron biomarkers (73). For example, the mild to severe anemia seen in thalassemias and sickle cell disease is unrelated to dietary practices and develops from ineffective erythropoiesis (ie, an increase in the number of immature red blood cells destroyed in the bone marrow) that stimulates an increase in iron absorption and elevated sTfR concentrations, even in the absence of low iron stores.

DIETARY PRACTICES TO ENHANCE THE ADEQUACY OF IRON AND ZINC IN THE DIETS OF YOUNG VEGETARIAN CHILDREN

Despite the limited epidemiologic data on biomarkers of zinc status, or longitudinal data on growth and development of vegetarian children, the Academy of Nutrition and Dietetics (formerly the American Dietetic Association) and Dietitians of Canada (1) consider that a well-planned vegetarian diet is adequate for all stages of the life cycle. Indeed, food guides have been designed to meet the nutrient needs of adult vegetarians in North America, with some suggested modifications to meet the needs of children aged 4–8 y (74). The guide, although highlighting the poorer bioavailability of calcium from nondairy foods, does not include practices to enhance the bioavailability of iron and zinc. Such practices include emphasizing the choice of leavened whole-grain breads and fermented soy foods such as miso and tempeh because during leavening and fermentation, phytate is hydrolyzed by microbial phytase enzymes to lower inositol phosphates, which no longer inhibit nonheme iron (75) or zinc (76) absorption. Legumes are high in phytates but often play a key role in vegetarian diets because of their contribution to protein and micronutrient intake, so it is preferable to improve the bioavailability of zinc and iron from these foods rather than to decrease their consumption. Techniques such as soaking dried beans and discarding the soaking water before cooking can be used because water-soluble phytates diffuse into the soaking water (77). The partial substitution of legumes with sprouted legumes, where possible, is also recommended because there is increased activity of endogenous phytase enzymes during germination, thus reducing the phytate content of the legumes. However, the increase in absorbable iron and zinc that might be achieved through these household phytate-reduction strategies has not yet been measured by in vivo stable isotope studies. The magnitude of the increase depends on the amount of phytate reduction, recent zinc intake (78), and the iron status of the target group (32). Avoiding tea and coffee during or after meals and consuming ascorbic acid–rich fruit juices, fruit, or vegetables with meals are other approaches to enhance nonheme iron absorption in vegetarian children's diets. In the UK National Diet and Nutrition Survey, tea consumption, even among young children aged 1.5–4.5 y who consume very little tea, was negatively associated with (log)ferritin ($r = -0.09$, $P < 0.007$) (21).

The use of cereals fortified with bioavailable iron and zinc can increase intakes of both total and absorbed iron and zinc (14, 79–81) and improve iron status of young children (21, 81). Whether fortified cereals also concomitantly enhance biochemical zinc status is less clear (81, 82).

Increasingly, fortified manufactured toddler milk drinks are being marketed in many industrialized countries. The substitution of cow milk with these fortified milk drinks is likely to be an acceptable practice for young children following lactoovovegetarian diets, because it does not require any behavior change, can be used concurrently with breastfeeding, and could increase their intakes of iron and zinc substantially, given the large amounts of milk often consumed (23, 82). Moreover, the consumption of fortified toddler milks has produced positive impacts on anemia rates and biomarkers of iron (83–85) but not zinc (41, 83) status. Evidence for improvements in functional health outcomes such as growth, morbidity, and cognitive function from the consumption of milk and cereal foods cofortified with zinc and iron is, however, inconclusive on the basis of a systematic review (81); more long-term studies examining these functional health outcomes are required.

For young vegetarian children following very restricted vegan diets, monitoring of iron (31) and zinc status, preferably by using a combination of the recommended indicators for zinc (42), may be advisable, and supplementation with iron and/or zinc should be undertaken if it is shown to be necessary (86). Consideration should be given to the routine inclusion (at a minimal cost) of zinc to existing iron supplements, preferably at low isomolar amounts to avoid any interference with absorption of either iron or zinc (87) and to prevent precipitating copper deficiency (2). Currently, the recommended dose for a zinc supplement is 5 mg Zn/d for children aged 6–36 mo and 10 mg Zn/d for older children (4). The WHO recommends a 2 mg Fe/kg per day dose for children aged 6–23 mo, and 20–60 mg Fe/d for older children (88). However, there is a need to review the supplement recommendations for children when a combination of iron and zinc supplements are prescribed, both in an effort to avoid any potential interference with iron or zinc absorption and to prevent excessive intakes, especially of zinc, because the current Upper Tolerable Intake Level for zinc for young children is less than twice the Recommended Dietary Allowance (2, 14). Of the supplements available, the chewable type tends to contain more micronutrients and in a greater amount, especially for zinc, than the gummy-type products for children (89).

CONCLUSIONS

There is an urgent need for more comprehensive studies on the iron and zinc status of young vegetarians. Many studies are based on a relatively small number of self-selected subjects and did not use the recommended procedures for evaluating dietary adequacy, identifying the stages in the development of iron deficiency anemia, or for collecting, analyzing, and interpreting serum zinc concentrations. More attention needs to be paid to the potential impact of nondietary factors on the iron and zinc status of immigrant vegetarian children from underprivileged households. Currently, there is insufficient evidence to conclude that a well-planned vegetarian diet cannot meet the needs for zinc for young children. However, for those following very restricted vegan diets, consideration should be given to monitoring their iron and zinc status with the recommended indicators and providing supplements, when necessary, with the recommended amounts of iron and/or zinc.

The authors' responsibilities were as follows—RSG: wrote the initial draft of the manuscript; and A-LMH and EAS-G: provided comments on and editing of the manuscript. All of the authors read and approved the final manuscript. None of the authors had a personal or financial conflict of interest.

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