May 2002: (I)127–134

Moving Toward a Plant-based Diet: Are Iron and Zinc at Risk?

Janet R. Hunt, Ph.D., R.D.

With reduced intake of meat and increased intake of phytate-containing legumes and whole grains, movement toward plant-based diets reduces dietary iron and zinc absorption. Although vegetarians have lower iron stores, adverse health effects of lower iron and zinc absorption have not been demonstrated with varied, plant-based diets consumed in developed countries. Improved assessment methods and monitoring are needed to detect and prevent possible iron and zinc deficiency with plant-based diets.

Key Words: phytate-containing legumes, whole grains, plant-based diet, iron, zinc

Introduction

A plant-based diet, containing predominately grains (especially whole grains), vegetables, fruits, and legumes, is currently emphasized by dietary recommendations from several government and health groups.[1–3] In addition, there is considerable popular promotion of "plant-based diets" for environmental, animal welfare, and religious, as well as health reasons.

However, movement toward a plant-based diet is not without some nutritional risk. The 2000 Dietary Guidelines for Americans[1] say to "use plant foods as the foundation of your meals," accompanied by the caution "if you choose to avoid all or most animal products, be sure to get enough iron, vitamin B_{12}, calcium, and zinc from other sources." As implied by this warning, the risk of nutrient inadequacy likely depends on one's definition of a "plant-based" diet; this can range on a continuum from a diet with small portions of lean meats, to replacement of red meats with chicken or fish, to predominately lacto-ovo vegetarian diets, to vegan diets that contain no animal products.

As suggested by the above quote, the minerals calcium, iron, and zinc merit special attention to safeguard nutritional adequacy when moving toward a plant-based diet. In part, this is because of the mineral composition of diets: the most recently available USDA food supply data[4] indicate that animal products provide 77% of the calcium and 56% of the zinc, but only 16% of the copper, 19% of the iron, and 29% of the magnesium content, in U.S. diets. However, at least as important as mineral content is mineral bioavailability, which may be inhibited by several factors in plant foods, and enhanced by other factors in plant and animal foods. Discussion of the content and bioavailability of calcium in foods, and implications for planning vegetarian diets, have been reviewed by Weaver et al.[5] This paper will mainly address these issues for iron and zinc.

Dr. Hunt is with the USDA-ARS Grand Forks Human Nutrition Research Center, P.O. Box 9034 University Station, Grand Forks, ND 58202, USA.

Iron

Intake Versus Bioavailability

Reducing or eliminating meat from the diet can be accomplished with minimal impact on the total dietary iron content. This is especially true with the increasing levels of iron fortification of grain products in the United States.[6] In countries without iron fortification of cereal and grain products, the iron content of the diet would be adversely affected by replacement of meat with refined, rather than whole-grain products. In Western countries, however, vegetarian diets can contain as much or more iron than omnivorous diets.[7–9] For example, as assessed with 3-day food records, daily iron intake was (mean ± SE) 18.01 ± 1.6 mg for vegan, 14.16 ± 0.81 mg for lacto-ovo vegetarian, and 14.40 ± 0.85 mg for non-vegetarian Seventh-Day Adventists; daily iron intake in a control group of non-vegetarians not associated with the Seventh-Day Adventist church was 16.08 ± 1.11 mg iron daily.[7]

But despite an iron content equivalent to an omnivorous diet, the iron from a plant-based diet is likely to be substantially less available for absorption because of differences in the chemical form of iron and the accompanying constituents that enhance or inhibit iron absorption. Dietary iron bioavailability is considerably influenced by food choices, and can vary tenfold from different meals with similar iron content.[10]

Heme and Nonheme Forms of Iron

The chemical form of iron is one important factor affecting dietary iron availability. Moving toward a plant-based diet alters the distribution of dietary iron between the efficiently absorbed heme form that is approximately 40% of the iron in meat, poultry, and fish,[11] and the less well absorbed nonheme form present in all foods. Absorption of nonheme iron is substantially affected by both body iron status and by dietary enhancers and inhibitors. Reducing meat consumption decreases dietary heme iron, which accounts for approximately 2 mg (10–12%) of the iron in a diet with substantial amounts of red meat.[12] Dietary heme iron is reduced when poultry or fish are substituted for red meat because these foods generally contain less total iron than red meat, although a similar proportion of the iron from these foods is in the heme form. Vegetarian diets contain no heme iron.

Although heme iron is very well absorbed, its absorption is much less affected by body iron status compared with nonheme iron absorption. The approximately 15 to 40% absorption of heme iron is substantially better than the 1 to 15% absorption of nonheme iron.[13–17] Yet, as earlier noted by Cook,[14] these ranges also reveal that the absorption of heme varies only two- to threefold, compared with a 10- to 15-fold cross-sectional variation in nonheme iron absorption across a range of body iron stores (Figure 1).[13,15–17] In omnivores with moderate iron stores, the fraction of the dietary iron in the heme form can account for nearly half of the iron absorbed from a diet with moderate to liberal amounts of red meat. In those with low body iron stores, however, nonheme iron contributes more than heme iron to the total amount of iron absorbed.[14] Accordingly, although plant-based diets contain a greater proportion of the generally less–well absorbed nonheme iron, this form is more responsive to differences in body iron status. This conveys the advantage that nonheme iron absorption can be more completely limited by those with high iron stores, while being nearly as well absorbed as heme iron by those with very low iron stores. However, the efficiency of nonheme iron absorption by those with low iron stores depends on the enhancing and inhibiting food constituents consumed concurrently.

Dietary Factors that Modify Iron Absorption

Movement toward a plant-based diet can substantially alter the dietary components that enhance or inhibit the intestinal solubility and absorption of nonheme iron. Hallberg reviewed human iron absorption, as it is affected by heme versus nonheme iron forms and by the enhancing or inhibiting effects of other dietary components; he proposed a mathematic algorithm for estimating dietary iron absorption.[10] The reader is referred to that paper for additional references concerning the dietary factors that enhance or inhibit iron absorption.

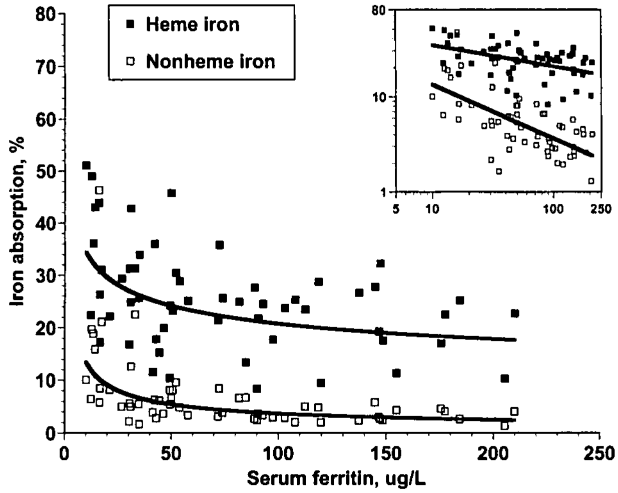

Figure 1. Both heme and nonheme iron absorption are greater in individuals with low iron stores, indicated by low serum ferritin, but the resulting difference in nonheme iron absorption is 10- to 15-fold, compared with a more limited 2- to 3-fold difference in heme iron absorption. Data are for healthy men and women consuming a high bioavailability, beef-based meal (modified from Roughead and Hunt).[17]

Briefly, absorption of both heme and nonheme iron is enhanced by unidentified factors in meat, poultry, and fish,[18,19] and inhibited by dietary calcium.[20,21] Other dietary components affect the absorption of only the nonheme form of iron. In addition to meat, poultry, and fish, ascorbic acid is the principal enhancing factor for nonheme iron absorption.[22–24] Other less investigated enhancing factors may include alcohol,[25] retinol, and carotenes.[26] Dietary factors or foods that inhibit nonheme iron absorption include phytic acid (6-phosphoinositol) in whole grains, legumes, lentils, and nuts; polyphenols, such as tannic and chlorogenic acids, in tea, coffee, red wines, and a variety of other cereals, vegetables, and spices;[10] soy protein (apparently independent of the phytic acid in soy); and eggs (unidentified factor). As people move toward plant-based diets, they are likely to consume more enhancers of iron absorption, such as ascorbic acid (and possibly carotene), but this enhancement is likely to be more than counteracted by the inhibitory effects of increased intake of phytic acid, polyphenols, and soy proteins, as well as the reduced intake of meat, poultry, or fish.

Single-meal, Whole-diet, and Adaptation Studies

In recent years, the long-term importance of dietary iron bioavailability, as measured in short-term, single-meal studies with radioiron tracers, has been questioned. In controlled trials of several weeks or months duration, serum ferritin was unresponsive to changes in dietary iron bioavailability, showing no increase with ascorbic acid[27–30] or meat[31] or decrease with calcium[32,33] intake. Using radiotracers, Cook and colleagues observed considerably less impact of calcium,[34] ascorbic acid,[35] or overall bioavailability[36] on iron absorption measurements when compared by modifying whole diets rather than single meals. However, the whole diets used by this research group were subject-selected according to investigator instructions, with intakes subsequently self-reported. By contrast, studies with single meals have been much more controlled, with weighed food items provided by the investigators. Thus, rather than concluding that whole diets provide different results than the sum of single meals, the data could be interpreted as indicating that there are less substantial differences in absorption when diets are tested under less controlled conditions.

Hunt and Roughead[12,37] demonstrated that differences in iron absorption measured from whole diets, when controlled by the investigators, were nearly as great as differences previously measured from single meals. Whereas Cook and colleagues[36] reported that a nearly sixfold difference in nonheme iron bioavailability observed with single meals was moderated to approximately twofold with whole diets, differences observed under more controlled whole-diet conditions were fourfold[12] and fivefold[37] for nonheme iron absorption, and six- and eightfold, respectively, for total iron absorption. In the first of these studies,[12] premenopausal women absorbed six times more iron from a nonvegetarian diet than from a lacto-ovo vegetarian diet that provided a similar amount of iron, but no meat, approximately 20% more ascorbic acid, and three times more fiber and phytic acid from whole grains and legumes. In the second study,[37] diets were planned to maximize differences in amounts of meat, ascorbic acid, dietary fiber, phytic acid, and tea, without changing total iron content, and to be acceptable to U.S. research volunteers for several weeks. Men initially absorbed eight times as much iron from the high- versus the low-bioavailability diet.[37] However, differences in iron bioavailability were reduced from eightfold to fourfold after 10 weeks of consuming the diets,[37] suggesting a moderation in bioavailability differences with long-term feeding. And despite the considerable differences in iron absorption in both studies, iron status (serum ferritin) of the subjects was unaltered after consuming these experimental diets for 8[12] or 12[37] weeks. These controlled diet studies suggest that even fairly large differences in dietary iron bioavailability do not change iron status within a few months. Although more rapid changes in serum ferritin have been predicted based on the cross-sectional relationship between serum ferritin and iron absorption,[38,39] such changes have not been supported by longitudinal studies of dietary iron bioavailability.

Iron Status of Vegetarians

In cross-sectional surveys, meat intake is the dietary factor most commonly associated with iron status or serum ferritin.[40–44] A 1989 Food and Nutrition Board publication stated, "Iron deficiency anemia appears to be no more prevalent among vegetarian women than among nonvegetarian women, but further study of iron bioavailability in vegetarian diets is needed."[45] That statement still seems to hold. Published comparisons evaluating the iron status of vegetarians and nonvegetarians indicate that vegetarians, especially female vegetarians, have lower iron stores, as indicated by serum ferritin (Table 1).[41,46–49] However, only three of eleven reports indicated that vegetarians had lower hematocrit or hemoglobin values. A 1988 report[52] described reduced serum ferritin, hemoglobin, and hematocrit, as well as greater iron-binding capacity in U.S. college women who consumed mainly fish and/or poultry or a lacto-ovo vegetarian diet, rather than diets containing red meat. However, hemoglobin and hematocrit levels were in the normal range for all groups. In Chinese adults with a generally greater incidence of anemia than in Western countries, twice as many female vegetarians (consuming a diet rich in soy products) as nonvegetarians were anemic.[56] Although vegetarian children in Great Britain had significantly lower hemoglobin concentrations than matched omnivores, the proportion with low values was similar in both groups.[57] Thus, the data from cross-sectional surveys indicate that vegetarians in Western societies have low iron stores, and may have lower hemoglobin, but do not have a greater incidence of iron deficiency anemia.

Recommendations to use iron cookware, to consume iron-containing foods concurrently with ascorbic acid–containing foods and limit inhibitory foods, and to use preparation methods that reduce the phytic acid in foods[60] may help improve the amount of iron absorbed from vegetarian diets. However, the hypothesized improvements in absorption have not been quantitatively tested. Considering that vegetarians have likely already taken such measures to some degree, as well as the limited improvement in iron absorption when research volunteers modified their self-selected meals to consume more ascorbate,[35] the impact of such modifications may be questionable.

Recommended Iron Intakes

Based on differences in iron absorption, the Food and Nutrition Board[61] recently recommended that iron intake for vegetarians should be adjusted upward by a factor of 80% compared with that for nonvegetarians. This adjustment results in recommended intakes of 14 and 33 mg iron daily for vegetarian adult men and premenopausal women, respectively.[61] By contrast with the recommendation of 14 mg for vegetarian men, the latter recommendation of 33 mg daily for vegetarian premenopausal

Table 1. Summary of Reports on the Iron Status of People Following Vegetarian Diets

Subjects	Hematocrit or Hemoglobin	Transferrin Saturation	Ferritin
Austrailian adults, >30 years[46]	NS	—	—
British children and adults[47]	NS	—	—
Canadian women, 52.9 ± 15.3 years[48]	NS	NS	—
U.S. college students[49]	NS	—	↓ *
U.S. adult males, 21–52 years[50]	NS	NS	—
U.S. adults, mean age 29.3 years[51]	—	—	↓
U.S. college women, mean age 28.9 years[52]	↓	—	↓
Australian adults, 17–65 years[41]	—	—	↓ *
British (Indian and Caucasian) women, 25–40 years[53]	NS	—	↓
New Zealand adults[54]	—	—	↓
Canadian young women, 14–19 years[55]	NS	NS	NS
Chinese men and women, mean ages 20–24 years[56]	↓ *	NS	↓
British children, 7–11 years[57]	↓	—	—
Australian women, 18–45 years[58]	NS	—	↓
U.S. and German adults, females-to-male ratio 2:1[59]	—	—	↓

*In females only. NS = not significant.

women is unlikely to be obtained from only dietary sources, and thus implies a recommendation for iron supplementation. However, the health benefits of routine iron supplementation of vegetarian women have not been demonstrated. Iron supplementation must be continuous to have a long-term influence on serum ferritin of women with low iron stores,[17] and iron supplementation may be associated with increased oxidative stress to the lower bowel.[62] Even though they are likely to have lower iron stores than omnivores, the majority of vegetarian women do not have serum ferritin less than 15 μg/L, and routine iron supplementation of this majority is not likely to offer any benefit. It may be better to base iron supplementation on routine hemoglobin screening of women with risk factors for iron deficiency, as recommended by the U.S. Centers for Disease Control.[63] The listing of low iron intake as one such risk factor[63] could be extended to women who consume vegetarian diets or who avoid red meat, based on the iron absorption and cross-sectional survey data reviewed above.

It should be noted that lowering serum ferritin, without increasing iron deficiency anemia, might confer a health advantage from plant-based diets for many consumers of Western diets. Although it will not be reviewed extensively here, the data are insufficient to conclude that there is a health disadvantage of low iron stores without anemia. Likewise, the data are insufficient to definitely conclude that high iron stores are not associated with an increased risk of cardiovascular disease and cancer. (These questions have recently been reviewed in the Institute of Medicine publication on Dietary Reference Intakes.[61]) Worth noting is a recent report of enhanced insulin sensitivity in lacto-ovo vegetarians, compared with their meat-eating counterparts with similar body mass (BMI <23 kg/m^2), and an improvement in insulin sensitivity of the latter group following phlebotomy to lower their serum ferritin.[59] A partial swing of the dietary pendulum to plant-based diets appears to confer many advantages for Western societies, possibly including reduced iron stores. At the same time, it should be acknowledged that extreme changes toward plant-based diets will reduce iron status, with potential disadvantage to those most vulnerable to iron deficiency: infants and women of childbearing age. Monitoring for a possible increased incidence of iron deficiency seems desirable when large public nutrition programs that serve women or children move further toward plant-based diets. A possible example is the recent modification of the U.S. National School Lunch Program,[64] allowing complete replacement of meat, poultry, and fish products with alternate plant protein products, and removing requirements for iron and zinc fortification of such products. Such monitoring may confirm that a moderate application of these new guidelines can increase school lunch flexibility without increasing the risk of iron (or zinc) undernutrition.

Zinc

Intake Versus Bioavailability

The impact of moving toward a plant-based diet is more difficult to evaluate for zinc than for iron nutrition. Because isotopic methods are generally more difficult or resource-intensive, considerably less data are available regarding dietary zinc bioavailability. Unlike iron, there is no clinical indicator of adequate versus marginal zinc nutritional status in humans. More than half of the zinc in U.S. diets is derived from animal foods, and one-quarter of the zinc comes from beef.[65] Although vegetarian diets can be planned with zinc contents similar to omnivorous diets, this diet planning may be more difficult.[66]

Plant foods rich in zinc, such as legumes, whole grains, seeds, and nuts, are also high in phytic acid, a main inhibitor of zinc bioavailability[67] (phytic acid is now hypothesized to be a phytochemical with anticarcinogenic health benefits).[68] Bioavailability of zinc is enhanced by dietary protein, but plant sources of protein are also generally high in phytic acid.

Despite high phytate content that lowers the fraction of zinc absorbed from unrefined foods, the higher zinc content of these foods may make these foods preferable to more refined products lower in zinc. For example, comparing whole wheat to white bread, the lower fractional absorption from whole wheat bread (16.6% compared with 38.2%) was less influential than the greater zinc content (1.3 compared with 0.4 mg), resulting in more absolute zinc absorbed (0.22 versus 0.15 mg) from whole wheat than from white bread.[69] This nearly 50% greater zinc absorption from whole grain, versus a more refined grain product, could substantially influence the zinc absorbed from a diet that emphasizes grain products as a foundation.

A World Health Organization publication[70] describes diets with high zinc bioavailability (50–55% absorption) as refined, low in cereal fiber, with a phytate/zinc molar ratio of <5, and with adequate protein principally from animal sources. Diets with moderate zinc bioavailability (30–35% absorption) are mixed diets, including lacto and/or ovo vegetarian and vegan diets, not primarily based on unrefined cereal grains, and with phytate/zinc molar ratios of 5 to 15. Low zinc bioavailability diets (15% absorption) are high in unrefined cereal grains, with a phytate/zinc ratio >15, low amounts of animal protein, and the majority of energy supplied by high-phytate foods, with soy products as the main protein source. Bioavailability of these diets may be especially low with high fortification levels of calcium.[70]

Unless meat is replaced with plant foods rich in zinc, which also tend to be rich in phytic acid, lower meat intakes can substantially reduce dietary zinc content. Replacement of meat intake with simple carbohydrates reduced dietary zinc content (from 13 to 6.7 mg/day), and considerably reduced the amount of zinc absorbed (from 3.6 to 2.0 mg/day) by postmenopausal women, even though the fractional zinc absorption (29%) was unaffected.[31] It may be noteworthy that simply fortifying the low-meat diet with minerals from meat was ineffective in making up the difference in absorbed zinc; this "fortification" reduced fractional zinc absorption, so that the amount of zinc absorbed was no greater than from the unfortified low-meat diet.[31]

A more practical replacement of meat with legumes, whole grains, seeds, and nuts was tested with women consuming an experimental lacto-ovo vegetarian diet, compared with an omnivorous diet with phytate/zinc molar ratios of 14 and 5, respectively. Even after 4 weeks of dietary adaptation, the women absorbed zinc less efficiently from the vegetarian diet (26 versus 33%), which contained somewhat less zinc; this resulted in only two-thirds as much zinc absorbed from the vegetarian diet (2.4 versus 3.7 mg zinc/day, respectively).[66] This difference was considerably less than that predicted by the WHO model,[70] or than that observed when formula diets were modified with purified phytic acid to achieve phytate/zinc molar ratios of <1 and 15, which resulted in 34 and 18% fractional zinc absorption by men.[71] Thus, less zinc may be absorbed from a vegetarian compared with an omnivorous diet because of both reduced zinc content and bioavailability. However, current models predicting zinc absorption from human diets have not been sufficiently verified by research with practical, whole diets consumed for extended periods.

Adaptation in Zinc Absorption

As noted for iron absorption, the negative effects of plant-based diets on zinc bioavailability may be overestimated by studies with single meals or short-term feeding. Adaptation in zinc absorption was recently demonstrated with infant rhesus monkeys that absorbed significantly less zinc from a regular soy formula, compared with a low-phytate soy formula (22 ± 4 vs. 36 ± 9%) when tested at 1 month of age; when tested at 4 months the monkeys absorbed significantly more zinc (33 ± 7 vs. 18 ± 4).[72] Thus, homeostatic adaptation may considerably modify zinc absorption from low bioavailability diets, and long-term assessments are necessary to fully determine the impact of plant-based diets on zinc absorption and nutrition.

Effects of Bioavailability on Zinc Status

Effective evaluation of vegetarian diets and zinc nutriture has been hindered by the lack of a sensitive clinical measure of marginal zinc status. Cross-sectional plasma zinc measurements have not usually differed between vegetarians and nonvegetarians.[48,50,73] In longitudinal studies, changing to a vegetarian diet did not affect plasma zinc after 22 days,[74] but did reduce plasma zinc concentrations (within a normal range) in one study after 8 weeks,[66] and in another study after 3 months, with no further reduction after 6 and 12 months;[75] the latter observation suggests that the participants had reached a new equilibrium on the vegetarian diet. Together, these studies suggest that as a result of consuming a vegetarian diet, plasma zinc concentrations are reduced within a normal range, and this reduction is detectable after several weeks when compared with concentrations in the same individuals consuming a nonvegetarian diet. Compared with baseline values, vegetarian diets have also been associated with reduced hair zinc,[75] increased 3-hour plasma zinc response to an oral zinc load, and reduced zinc concentration in the salivary sediment.[74] Unfortunately, assessment of the long-term effects of plant-based diets will continue to be difficult while there is no generally-accepted, sensitive clinical criteria for marginal zinc nutritional status.

Because of their high variability, zinc balance measurements provide a relatively insensitive assessment of zinc nutrition associated with different diets. Zinc balance was positive with an experimental vegetarian diet containing 40 g dietary fiber and a phytate/zinc molar ratio of 14,[66] as well as with lower dietary fiber (18–20 g).[76] Zinc balance was greater when the latter vegetarian diet was modified to contain beef, but the balance results suggested that there was no advantage in zinc balance by adding six or nine, compared with three ounces of beef.[76] However, negative zinc balance was reported for adults consuming an animal protein–based diet characterized as high in fiber and phytic acid (with a phytate/zinc molar ratio of 7), despite 29% zinc absorption of the 9 mg zinc contained in the diet.[77] These mixed results with the zinc balance method emphasize the need for more sensitive measures of zinc status.

The Food and Nutrition Board committee setting Dietary Reference Intakes for zinc[61] concluded that, because of lower absorption of zinc, those consuming vegetarian diets, especially with phytate/zinc molar ratios exceeding 15, may require as much as 50% more zinc than nonvegetarians. More research is required to develop criteria for accurately estimating zinc absorption from Western, plant-based diets, and to develop sensitive indices to assess zinc status in humans consuming such diets.

Conclusion

The amounts of both iron and zinc absorbed from Western diets are negatively affected by reducing meat, especially red meat, and by increasing plant sources of phytic acid such as whole grains, legumes, seeds, and nuts. In developing countries, deficiencies of both these nutrients are associated with plant-based diets of limited variety with little or no animal protein. As we seek to improve Western diets and reduce problems related to overconsumption of energy and saturated fat, we must define a moderate balance to obtain maximum benefit from moving toward a plant-based diet, with appropriate precautions to protect children and women of child-bearing age who may be vulnerable to iron or zinc deficiency.

1. U.S. Departments of Agriculture and Health and Human Services. Nutrition and your health: dietary guidelines for Americans, 5th ed. Washington, DC: USDA, 2000
2. Krauss RM, Eckel RH, Howard B, et al. AHA dietary guidelines revision 2000: a statement for healthcare professionals from the Nutrition Committee of the American Heart Association. Circulation 2000;102: 2296–311
3. World Cancer Research Fund/American Institute for Cancer Research. Food, nutrition and the prevention of cancer: a global perspective. Menasha, WI: Banta Book Group, 1997
4. U.S. Department of Agriculture Center for Nutrition Policy and Promotion. Food supply database (1909–1997). Available at: http://www.ers.usda.gov/Data/FoodConsumption. Accessed 4/15/02
5. Weaver CM, Proulx WR, Heaney R. Choices for achieving adequate dietary calcium with a vegetarian diet. Am J Clin Nutr 1999;70:543S–8S
6. Gerrior S, Bente L. Nutrient content of the U.S. food supply, 1909–1997. U.S. Department of Agriculture, Center for Nutrition Policy and Promotion, Home Economics Research Report No. 54. Washington, DC: USDA, 2001
7. Calkins BM, Whittaker DJ, Nair PP, et al. Diet, nutrition intake, and metabolism in populations at high and low risk for colon cancer. Nutrient intake. Am J Clin Nutr 1984;40:896–905
8. Craig WJ. Iron status of vegetarians. Am J Clin Nutr 1994;59:1233s–7s
9. American Dietetic Association. Position of the American Dietetic Association: vegetarian diets. J Am Diet Assoc 1997;97:1317–21
10. Hallberg L, Hulthen L. Prediction of dietary iron absorption: an algorithm for calculating absorption and bioavailability of dietary iron (erratum Am J Clin Nutr 2000;72:1242). Am J Clin Nutr 2000;71:1147–60
11. Monsen ER, Hallberg L, Layrisse M, et al. Estimation of available dietary iron. Am J Clin Nutr 1978;31: 134–41
12. Hunt JR, Roughead ZK. Nonheme iron absorption, fecal ferritin excretion, and blood indexes of iron status in women consuming controlled lacto-ovovegetarian diets for 8 wk. Am J Clin Nutr 1999; 69:944–52
13. Lynch SR, Skikne BS, Cook JD. Food iron absorption in idiopathic hemochromatosis. Blood 1989;74: 2187–93
14. Cook JD. Adaptation in iron metabolism. Am J Clin Nutr 1990;51:301–8
15. Taylor P, Martinez-Torres C, Leets I, et al. Relationships among iron absorption, percent saturation of plasma transferrin and serum ferritin concentration in humans. J Nutr 1988;118:1110–5
16. Hallberg L, Hulten L, Gramatkovski E. Iron absorption from the whole diet in men: how effective is the regulation of iron absorption? Am J Clin Nutr 1997; 66:347–56
17. Roughead ZK, Hunt JR. Adaptation in iron absorption: iron supplementation reduces nonheme-iron but not heme-iron absorption from food. Am J Clin Nutr 2000;72:982–9
18. Martinez-Torres C, Layrisse M. Iron absorption from veal muscle. Am J Clin Nutr 1971;24:531–40

19. Hallberg L, Bjorn-Rasmussen E, Howard L, Rossander L. Dietary heme iron absorption. A discussion of possible mechanisms for the absorption-promoting effect of meat and for the regulation of iron absorption. Scand J Gastroenterol 1979;14: 769–79
20. Hallberg L, Brune M, Erlandsson M, et al. Calcium: effect of different amounts on nonheme- and heme-iron absorption in humans. Am J Clin Nutr 1991;53: 112–9
21. Cook JD, Dassenko SA, Whittaker P. Calcium supplementation: effect on iron absorption. Am J Clin Nutr 1991;53:106–11
22. Gillooly M, Bothwell TH, Torrance JD, et al. The effects of organic acids, phytates and polyphenols on the absorption of iron from vegetables. Br J Nutr 1983;49:331–42
23. Cook JD, Monsen ER. Vitamin C, the common cold, and iron absorption. Am J Clin Nutr 1977;30:235–41
24. Hallberg L, Brune M, Rossander L. Effect of ascorbic acid on iron absorption from different types of meals. Studies with ascorbate rich foods and synthetic ascorbic acid given in different amounts with different meals. Human Nutr Appl Nutr 1986;40A: 97–113
25. Charlton RW, Jacobs P, Seftel HC, Bothwell TH. Effect of alcohol on iron absorption. BMJ 1964;2: 1427–9
26. Garcia-Casal MN, Layrisse M, Solano L, et al. Vitamin A and beta-carotene can improve nonheme iron absorption from rice, wheat, and corn by humans. J Nutr 1998;128:646–50
27. Cook JD, Watson SS, Simpson KM, et al. The effect of high ascorbic acid supplementation on body iron stores. Blood 1984;64:721–6
28. Malone HE, Kevany JP, Scott JM, et al. Ascorbic acid supplementation: its effects on body iron stores and white blood cells. Ir J Med Sci 1986;155: 74–9
29. Monsen ER, Labbe RF, Lee W, Finch CA. Iron balance in healthy menstruating women: effect of diet and ascorbate supplementation. In: Momcilovic B, ed. Trace elements in man and animals (TEMA-7). Dubrovnic, Yugoslavia: Institute for Medical Research and Occupational Health, University of Zagreb, 1991:6.2–6.3
30. Hunt JR, Gallagher SK, Johnson LK. Effect of ascorbic acid on apparent iron absorption by women with low iron stores. Am J Clin Nutr 1994;59:1381–5
31. Hunt JR, Gallagher SK, Johnson LK, Lykken GI. High- versus low-meat diets: effects on zinc absorption, iron status, and calcium, copper, iron, magnesium, manganese, nitrogen, phosphorus, and zinc balance in postmenopausal women. Am J Clin Nutr 1995;62:621–32
32. Minihane AM, Fairweather-Tait SJ. Effect of calcium supplementation on daily nonheme-iron absorption and long-term iron status. Am J Clin Nutr 1998;68: 96–102
33. Sokoll LJ, Dawson-Hughes B. Calcium supplementation and plasma ferritin concentrations in premenopausal women. Am J Clin Nutr 1992;56:1045–8
34. Reddy MB, Cook JD. Effect of calcium intake on nonheme-iron absorption from a complete diet. Am J Clin Nutr 1997;65:1820–5
35. Cook JD, Reddy MB. Effect of ascorbic acid intake on nonheme-iron absorption from a complete diet. Am J Clin Nutr 2001;73:93–8
36. Cook JD, Dassenko SA, Lynch SR. Assessment of the role of nonheme-iron availability in iron balance. Am J Clin Nutr 1991;54:717–22
37. Hunt JR, Roughead ZK. Adaptation of iron absorption in men consuming diets with high or low iron bioavailability. Am J Clin Nutr 2000;71:94–102
38. Hallberg L, Hulthen L, Garby L. Iron stores and haemoglobin iron deficits in menstruating women. Calculations based on variations in iron requirements and bioavailability of dietary iron. Eur J Clin Nutr 2000;54:650–7
39. Hallberg L. Perspectives on nutritional iron deficiency. Annu Rev Nutr 2001;21:1–21
40. Bergstrom E, Hernell O, Lonnerdal B, Persson LA. Sex differences in iron stores of adolescents: what is normal? J Pediatr Gastroenterol Nutr 1995;20: 215–24
41. Leggett BA, Brown NN, Bryant S, et al. Factors affecting the concentration of ferritin in serum in a healthy Australian population. Clin Chem 1990;36: 1350–55
42. Salonen JT, Nyyssonen K, Korpela H, et al. High stored iron levels are associated with excess risk of myocardial infarction in Eastern Finnish men. Circulation 1992;86:803–11
43. Takkunen H, Seppanen R. Iron deficiency and dietary factors in Finland. Am J Clin Nutr 1975;28: 1141–7
44. Fleming DJ, Jacques PF, Dallal GE, et al. Dietary determinants of iron stores in a free-living elderly population: the Framingham Heart Study. Am J Clin Nutr 1998;67:722–33
45. Food and Nutrition Board, National Research Council. Diet and health: implications for reducing chronic disease risk. Washington, DC: National Academy Press, 1989
46. Armstrong BK, Davis RE, Nicol DJ, et al. Hematological, vitamin B-12, and folate studies on Seventh-day Adventist vegetarians. Am J Clin Nutr 1974;27: 712–8
47. Sanders TAB, Ellis FR, Dickerson JWT. Haematological studies on vegans. Br J Nutr 1978;40:9–15
48. Anderson BM, Gibson RS, Sabry JH. The iron and zinc status of long-term vegetarian women. Am J Clin Nutr 1981;34:1042–8
49. McEndree LS, Kies CV, Fox HM. Iron intake and iron nutritional status of lacto-ovo-vegetarian and omnivore students eating in a lacto-ovo-vegetarian food service. Nutrition Reports International 1983;27:199–206
50. Latta D, Liebman M. Iron and zinc status of vegetarian and nonvegetarian males. Nutrition Reports International 1984;30:141–9
51. Helman AD, Darnton-Hill I. Vitamin and iron status in *new* vegetarians. Am J Clin Nutr 1987;45:785–9
52. Worthington-Roberts BS, Breskin MW, Monsen ER. Iron status of premenopausal women in a university community and its relationship to habitual dietary sources of protein. Am J Clin Nutr 1988;47:275–9
53. Reddy S, Sander TAB. Haematological studies on pre-menopausal Indian and Caucasian vegetarians

compared with Caucasian omnivores. Br J Nutr 1990;64:331-8
54. Alexander D, Ball MJ, Mann J. Nutrient intake and haematological status of vegetarians and age-sex matched omnivores. Eur J Clin Nutr 1994;48:538-46
55. Donovan UM, Gibson RS. Iron and zinc status of young women aged 14 to 19 years consuming vegetarian and omnivorous diets. J Am Coll Nutr 1995; 14:463-72
56. Shaw NS, Chin CJ, Pan WH. A vegetarian diet rich in soybean products compromises iron status in young students. J Nutr 1995;125:212-9
57. Nathan I, Hackett AF, Kirby S. The dietary intake of a group of vegetarian children aged 7-11 years compared with matched omnivores. Br J Nutr 1996; 75:533-44
58. Ball MJ, Bartlett MA. Dietary intake and iron status of Australian vegetarian women. Am J Clin Nutr 1999;70:353-8
59. Hua NW, Stoohs RA, Facchini FS. Low iron status and enhanced insulin sensitivity in lacto-ovo vegetarians. Br J Nutr 2001;86:515-9
60. Gibson RS, Donovan UM, Heath AL. Dietary strategies to improve the iron and zinc nutriture of young women following a vegetarian diet. Plant Foods Hum Nutr 1997;51:1-16
61. Food and Nutrition Board, Institute of Medicine. Dietary reference intakes for vitamin A, vitamin K, arsenic, boron, chromium, copper, iodine, iron, manganese, molybdenum, nickel, silicon, vanadium, and zinc. Washington, DC: National Academy Press, 2001
62. Lund EK, Wharf SG, Fairweather-Tait SJ, Johnson IT. Oral ferrous sulfate supplements increase the free radical-generating capacity of feces from healthy volunteers. Am J Clin Nutr 1999;69:250-5
63. Centers for Disease Control and Prevention. Recommendations to prevent and control iron deficiency in the United States. MMWR Morb Mortal Wkly Rep 1998;47(RR-3):1-29
64. U.S. Department of Agriculture. Modification of the "vegetable protein products" requirements for the National School Lunch Program, School Breakfast Program, Summer Food Service Program and Child and Adult Care Food Program. Federal Register, March 9, 2000:12429-42
65. Subar AF, Krebs-Smith SM, Cook A, Kahle LL. Dietary sources of nutrients among US adults, 1989 to 1991. J Am Diet Assoc 1998;98:537-47
66. Hunt JR, Matthys LA, Johnson LK. Zinc absorption, mineral balance, and blood lipids in women consuming controlled lactoovovegetarian and omnivorous diets for 8 wk. Am J Clin Nutr 1998;67:421-30
67. Harland BF, Oberleas D. Phytate in foods. World Rev Nutr Diet 1987;52:235-59
68. Harland BF, Morris ER. Phytate: a good or bad food component? Nutr Res 1995;15:733-54
69. Sandström B, Arvidsson B, Cederblad A, Bjorn-Rasmussen E. Zinc absorption from composite meals I. The significance of wheat extraction rate, zinc, calcium, and protein content in meals based on bread. Am J Clin Nutr 1980;33:739-45
70. World Health Organization. Trace elements in human nutrition and health. Geneva, Switzerland: WHO, 1996:72-104
71. Turnlund JR, King JC, Keyes WR, et al. A stable isotope study of zinc absorption in young men: effects of phytate and alpha-cellulose. Am J Clin Nutr 1984;40:1071-7
72. Lonnerdal B, Jayawickrama L, Lien EL. Effect of reducing the phytate content and of partially hydrolyzing the protein in soy formula on zinc and copper absorption and status in infant rhesus monkeys and rat pups. Am J Clin Nutr 1999;69:490-6
73. Kies C, Young E, McEndree L. Zinc bioavailability from vegetarian diets. Influence of dietary fiber, ascorbic acid, and past dietary practices. In: Inglett GE, ed. Nutritional bioavailability of zinc. Washington, DC: American Chemical Society, 1983:115-26
74. Freeland-Graves J. Alterations in zinc absorption and salivary sediment zinc after a lacto-ovo-vegetarian diet. Am J Clin Nutr 1980;33:1757-66
75. Srikumar TS, Johansson GK, Öckerman P, et al. Trace element status in healthy subjects switching from a mixed to a lactovegetarian diet for 12 mo. Am J Clin Nutr 1992;55:885-90
76. Johnson JM, Walker PM. Zinc and iron utilization in young women consuming a beef-based diet. J Am Diet Assoc 1992;92:1474-8
77. Knudsen E, Sandstrom B, Solgaard P. Zinc, copper and magnesium absorption from a fibre-rich diet. J Trace Elem Med Biol 1996;10:68-76