Vegetarian Diets Across the Lifecycle: Impact on Zinc Intake and Status

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Abstract

Optimal zinc status is an important consideration when evaluating the nutritional adequacy of vegetarian diets. In the absence of animal tissue sources of zinc and with increased intake of inhibitors of zinc absorption, phytic acid in particular, the bioavailability of zinc is thought to be lower from vegetarian as compared to omnivorous diets. The aim of this chapter is to review the research that examines the effects of vegetarian compared to omnivorous diets on zinc intake and zinc status in the elderly, adults, children, pregnancy, and lactation. A narrative review of the published literature was undertaken, focusing on observational studies in humans that reported zinc intake and biomarkers of zinc status at various stages of the life cycle. Compared to their respective nonvegetarian control groups, adult male and female vegetarians have lower dietary zinc intakes and serum zinc concentrations. However in the elderly, children, and in women during pregnancy and lactation, there is insufficient evidence to determine whether zinc intake and status are lower in vegetarians compared to omnivores. Inconsistencies in study findings reflect variations inherent in the definition of vegetarian diets, and in many instances compromised statistical power due to a small sample size. Improved methods for the assessment of zinc status are required to determine whether homeostatic responses are sufficient to maintain an adequate zinc status in vegetarians, particularly during times of increased requirement. Appropriate dietary advice to increase the zinc content and bioavailability of vegetarian diets throughout the life cycle is prudent.

1. INTRODUCTION

A considerable body of scientific information reports on the health implications of observing a vegetarian diet. The American Dietetic Association and Dietitians of Canada (2003) have concluded that "appropriately planned" vegetarian diets are healthful and may provide benefits in the prevention and treatment of certain diseases. Plant-based diets are reported to contain less saturated fatty acids and cholesterol, and more folate, fiber, and phytochemicals than omnivorous diets (Bingham, 1999; Phillips, 2005). Vegetarian diets have been associated with a reduction in several of the established risk factors for cardiovascular disease, including more favorable blood lipid profiles, lower body mass index, and lower systolic and diastolic blood pressures (Phillips, 2005), which is consistent with the lower mortality rate from coronary heart disease reported for vegetarians compared with meat eaters (Key et al., 1998). There are several nutrients that require particular consideration in the planning of a nutritionally adequate vegetarian diet including vitamin B_{12}, iron, and zinc: the latter have poorer bioavailability when obtained from plant-derived compared to animal food sources.

Zinc is an essential trace element and is involved in many biological processes that include enzyme action, stabilization of cell membranes, regulation of gene expression, and cell signaling (Foster & Samman, 2010; Samman, 2012); hence, the effects of zinc deficiency have the potential to be wide-ranging. Deficiencies associated with low intakes of absorbable zinc may be exacerbated during times of increased requirement, including growth, pregnancy and lactation, and physiologic changes associated with aging. The aim of this chapter is to review the observational studies that compare the effects of vegetarian and omnivorous diets on zinc intake and serum/plasma zinc concentrations at various stages of the life cycle.

2. DEFINITIONS OF VEGETARIAN DIETS

In classic terms (Table 1), an individual is considered a vegetarian if he/she abstains from eating all flesh foods (meat, poultry, fish, shellfish); those who follow a total vegetarian or "vegan" diet consume only plant-derived foods, excluding all foods of animal origin including eggs and dairy products. Eating patterns that are similar to a vegetarian diet include the macrobiotic diet, which is low in meat and dairy products, and the pescetarian diet, in which fish/shellfish is the only animal flesh consumed. Motivations for following a vegetarian diet in Western cultures commonly include a combination of animal rights and welfare, environmental, religious, and health considerations. In Western societies, women are more

Table 1 Classifications of vegetarian eating patterns

Type of vegetarian	Definition
Classic	
Ovo-lacto-/lacto-ovo-, ovo-, lacto-vegetarian	Diet is devoid of all flesh foods, but includes egg (ovo) and/or dairy (lacto) products
Vegan	Diet excludes all animal products
New	
Meat reductionist	Diet includes only limited amounts of animal flesh
Semi-vegetarian	Fish/shellfish and poultry are the only animal flesh consumed
Pesco-vegetarian	Fish/shellfish is the only animal flesh consumed
Pollo-vegetarian	Poultry is the only animal flesh consumed

likely to be vegetarian than men (Beardsworth & Bryman, 1999; McLennan & Podger, 1995; White & Frank, 1994), which is consistent with findings that some nonvegetarian women avoid eating meat and poultry (Fayet, Flood, Petocz, & Samman, 2013), eat less meat than their male counterparts (Beardsworth et al., 2002), and are more likely than men to be decreasing their meat consumption (Beardsworth et al., 2002; Fargerli & Wandel, 1999; Ruby, 2012).

3. ZINC INTAKE AND BIOAVAILABILITY

Zinc is widely distributed in foods. Meat, fish, and poultry are the major contributors of zinc in the adult omnivorous diet; however, dairy products and many staple vegetable foods provide amounts of zinc similar to those found in animal tissues. Vegetarians obtain a substantial amount of zinc from dairy foods, cereals, grains, legumes, pulses, nuts, and seeds. Green leafy vegetables and fruits are only moderate sources of zinc because of their high water content. In addition to the total zinc content of the diet, a range of other dietary components influences the amount of zinc that is absorbed from food (Fig. 1). Factors that have a positive effect on zinc absorption include the amount of protein in a meal, individual amino acids, and other low-molecular-weight ions, such as the organic acid citrate (Lönnerdal, 2000; Sandström, 1997). The primary dietary factor that decreases the bioavailability of zinc is inositol phosphate, also known as phytic acid, or phytate when in salt form (Oberleas, 1983; Sandberg, Hasselblad, Hasselblad, & Hultén, 1982). There is evidence that zinc absorption is reduced by the chronic provision of iron supplements (McArthur, Petocz, Caterson, & Samman, 2012; O'Brien, Zavaleta, Caulfield, Wen, & Abrams, 2000; Solomons, 1986) and conflicting evidence that zinc absorption is affected by folate (Butterworth & Tamura, 1989; Hansen et al., 2001).

3.1. Phytate, zinc, and calcium

Phytic acid is the principal storage form of phosphorus in cereals, legumes, and oleaginous seeds and hence is abundant in plant-based diets. Inositol hexaphosphates and pentaphosphates form poorly soluble complexes with zinc in the gastrointestinal tract, resulting in reduced zinc absorption or reabsorption. In contrast, tetra- and lower phosphate derivatives, which result from the hydrolysis of phytate by phytases, have little influence on zinc availability (Sandström & Sandberg, 1989). Although phytase is not present

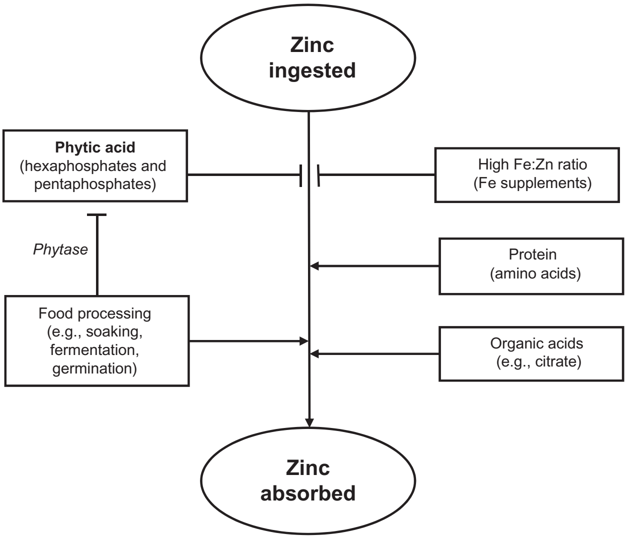

Figure 1 Dietary factors that influence the amount of zinc absorbed from food. The principal dietary factor that has a positive effect on zinc absorption is the total amount of zinc ingested from food; other beneficial factors include the amount of protein in a meal, and organic acids such as citrate. The primary dietary factor that decreases the bioavailability of zinc is phytic acid, unless it has been degraded to its tetra- or lower derivatives by phytase during food processing. Chronic provision of iron supplements, especially in aqueous form, may inhibit zinc absorption due to the induction of an iron/-zinc imbalance.

in the gastrointestinal tract of humans, microbial phytases produce lower inositol phosphates during certain food preparation and processing practices, such as fermentation and germination (Gibson, Perlas, & Hotz, 2006). The ability of food-processing methods to degrade phytate to its lower derivatives is absent in extrusion cooking, which denatures intrinsic phytase activity (Sandberg, Anderson, Carlson, & Sandström, 1987). Although the nutritional significance of phytate on zinc utilization is likely to be modified by other dietary constituents in the food matrix (World Health Organization, 1996), an independently validated multivariate saturation model of zinc absorption suggests that phytate, along with ingested dietary zinc, accounts for more than 80% of the variability in the quantity of zinc absorbed (Hunt, Beiseigel, & Johnson, 2008; Miller, Krebs, & Hambidge, 2007).

The World Health Organization (1996) has identified three grades of zinc bioavailability based on the phytic acid:zinc molar ratio, with ratios less than 5 being indicative of "high" zinc bioavailability (corresponding to 50%

zinc absorption), ratios in the range 5–15 being of "moderate" zinc bioavailability (30% absorption), and ratios greater than 15 being of "low" zinc bioavailability (15% absorption). Vegetarian and vegan diets are described as being of moderate zinc availability provided they are not based primarily on unrefined, unfermented, and ungerminated cereal grains or high extraction rate flours. In 2004, the International Zinc Nutrition Consultative Group classified diets into two diet types based on phytate:zinc molar ratios derived from total diet studies: mixed diets or refined vegetarian diets characterized by phytate:zinc molar ratios of 4–18 and unrefined cereal-based diets with phytate:zinc molar ratios greater than 18 (International Zinc Nutrition Consultative Group et al., 2004).

Calcium may potentiate the inhibitory effect of phytate on zinc bioavailability. Zinc has been shown *in vitro* to bind strongly to precipitates of phytic acid with calcium (Simpson & Wise, 1990), and the (calcium)(phytic acid):zinc molar ratio has been proposed as a more useful predictor of zinc bioavailability than the ratio of phytic acid:zinc (World Health Organization, 1996). Studies that utilized isotopic tracer methods in humans have not confirmed an effect of dietary calcium or of a phytate × calcium interaction on zinc absorption in participants consuming conventional diets containing adequate levels of zinc (Hunt & Beiseigel, 2009). There is some evidence, however, that high calcium levels may adversely affect zinc bioavailability in diets that are high in phytate and low in readily available zinc (Bindra, Gibson, & Thompson, 1986; Simpson & Wise, 1990), which would make the (calcium)(phytic acid):zinc ratio relevant to some lacto-ovo vegetarian diets and vegan diets that are fortified with calcium.

4. MECHANISMS OF ZINC HOMEOSTASIS

At the whole-body level, synergistic adaptations in zinc absorption, resorption, and excretion along the gastrointestinal tract are the primary means of maintaining zinc homeostasis. The cellular mechanisms of zinc homeostasis are multifaceted and appear to include interactions between zinc sensors, such as metal-responsive element-binding transcription factor-1, and cell signaling machinery; the trafficking of zinc through the cell by metallothionein, which has the ability to bind up to seven zinc ions in multiple zinc containing clusters; and the transcriptional and/or posttranslational regulation of two classes of zinc transporters, the ZnT (SLC30) and Zip (SLC39) transporter families, which facilitate the movement of zinc across the gastrointestinal tract and its distribution in tissues

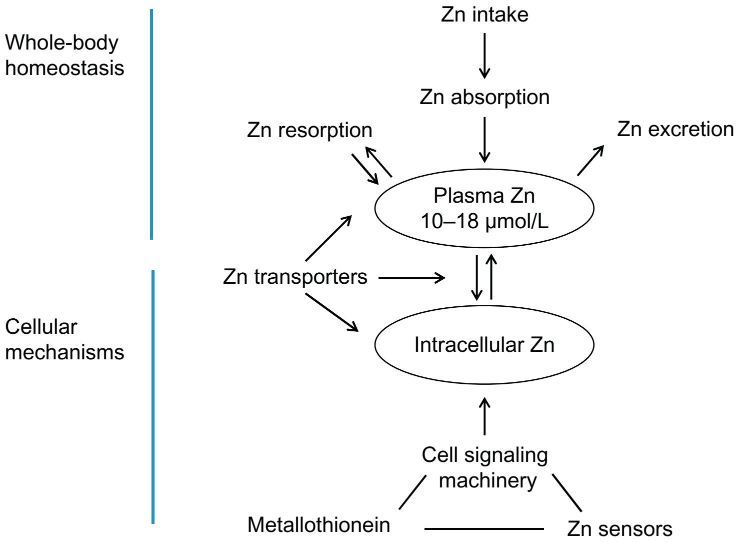

Figure 2 Zinc homeostasis. At the whole-body level, synergistic adaptations in zinc absorption, resorption, and excretion along the gastrointestinal tract are the primary means of maintaining a constant zinc state. The cellular mechanisms of zinc homeostasis are complex, but appear to include interactions between zinc sensors and cell signaling machinery; the trafficking of zinc through the cell by metallothionein; and the regulation of zinc transporters, which facilitate the movement of zinc across the gastrointestinal tract and its distribution in tissues.

(Foster & Samman, 2010; Fig. 2). As there is no recognized storage site for zinc, cells are dependent on plasma to provide them with a constant supply of zinc to sustain normal function. In humans, homeostatic mechanisms maintain plasma zinc within a concentration range of approximately 10–18 μmol/L. Although at any one time it comprises only a minor fraction of the total body zinc, plasma zinc constitutes a highly mobile pool. In addition to the zinc that is moved in and out of the tissues daily, all absorbed zinc passes through the plasma compartment (King, Shames, & Woodhouse, 2000), with the total zinc flux being in the order of 130 times/day (King & Cousins, 2006).

5. DETERMINATION OF ZINC STATUS

Early manifestations of zinc deficiency are nonspecific. Given that the rapid efflux of zinc from the plasma is essential in supplying constant amounts of zinc to the tissues, a fall in plasma zinc may be the first line of homeostatic response to an inadequate zinc intake, operating to maintain zinc at critical levels in those tissues most susceptible to zinc depletion (King et al., 2000). While clinical symptoms of zinc deficiency do not become evident until after the plasma zinc concentration has fallen substantially (King et al., 2000), the effects of zinc deficiency on specific cellular functions appear to occur before plasma zinc falls below the normal range (Prasad, 1998). The effectiveness of homeostatic mechanisms in maintaining plasma zinc concentrations within defined limits, even in the presence of dietary zinc restriction (Milne, Canfield, Mahalko, & Sandstead, 1983), renders it an insensitive marker of the zinc status of an individual. At the population level, however, the serum or plasma zinc concentration is useful for identifying subgroups at risk of zinc deficiency, particularly if it is used to evaluate zinc status in combination with dietary and functional physiological indices (Gibson, 2005; International Zinc Nutrition Consultative Group et al., 2004). In a meta-analysis of observational studies and randomized controlled trials aimed at describing the relationship between zinc intake and status in adults (Lowe et al., 2012), the overall effect of zinc supplementation on serum/plasma zinc concentrations was statistically significant, indicating that for every doubling in zinc intake the difference in serum/plasma zinc concentration is increased by approximately 6%. Whether this relationship could be used to identify the optimal zinc intake and be applied to vegetarian populations remain a matter for further investigation.

6. VEGETARIAN DIETS AND ZINC STATUS IN HEALTHY ADULTS

The recommended dietary intake for zinc varies between countries, being 14 mg/day for men and 8 mg/day for women in Australia (National Health and Medical Research Council, 2006) and 9.5 mg/day for men and 7.0 mg/day for women in the United Kingdom (Committee on Medical Aspects of Food Policy, 1991). The Institute of Medicine has cautioned that for vegetarians, and particularly for strict vegetarians with phytate:zinc ratios greater than 15, the dietary zinc requirement may be as much as 50% greater than that of individuals consuming an omnivorous diet containing low levels of phytate (Institute of Medicine, 2001).

6.1. Prevalence of vegetarian diets in adults

National nutrition surveys in the United Kingdom (Department of Health and Food Standards Agency (FSA), 2011) and Australia (McLennan & Podger,

1995) estimate that 2–3% of adults are vegetarian. In unadjusted frequency data from the 2008/09 New Zealand Adult Nutrition Survey, 1% of participants had not consumed meat, chicken, or seafood in the 4 weeks prior to the survey (University of Otago and Ministry of Health, 2011). In the United States, 6% of participants from the National Health and Nutrition Examination Survey (NHANES) 1999–2004 did not report eating meat, poultry, or fish on the day of the survey (Farmer, Larson, Fulgoni, Rainville, & Liepa, 2011); however, unadjusted data from NHANES 2009, which assessed self-perceived vegetarian status, suggest a lower frequency of vegetarians in the population (Centers for Disease Control and Prevention [CDC], 2012). Marketing research and polling results of self-reported vegetarians indicate that 3.2% of the population in the United States follow a vegetarian diet (Vegetarian Times, 2008), with higher prevalence rates in Israel (8.5%), Germany (9%) (European Vegetarian Union, 2007), and India (40%) (Yadav & Kumar, 2006). Vegetarian prevalence data are confounded by those who self-identify as vegetarian despite consuming limited amounts of animal flesh foods (Weinsier, 2000), and by changes in attitudes toward meat eating and the range of foods that are eaten over time (Ruby, 2012).

6.2. Adaptations to a vegetarian diet

In order to ensure an adequate intake of essential nutrients, the planning of a vegetarian diet requires emphasis on the use of whole grains, legumes, nuts, and seeds. Despite the high phytate content in these foods, their higher zinc content compared to more refined products may compensate for the less efficient absorption of zinc, resulting in a greater amount of total zinc absorbed (Hunt, 2003). The relationships between zinc intake, bioavailability, and absorption are confounded further by the finding in a number of studies that humans absorb a higher fraction of dietary zinc from low-zinc diets compared to when zinc intake is adequate (King et al., 2001; Taylor, Bacon, Aggett, & Bremner, 1991; Wada, Turnlund, & King, 1985). Beyond the immediate influence of a low zinc dose, fractional absorption has been shown to be upregulated further (from 49% to 70%) after several weeks of equilibration to a diet low in zinc and of high bioavailability (Hunt et al., 2008). This longer-term adaptation was not seen with low-zinc diets of poor bioavailability (phytic acid:zinc ratio >15), suggesting that the amount of zinc available for transport may have been insufficient for further biological upregulation to increase zinc absorption (Hunt et al., 2008).

Despite the reported increases in the fraction of zinc absorbed when dietary zinc intake is restricted, the total amount of absorbed zinc is likely to lessen (Wada et al., 1985). In addition, increases in zinc absorption efficiency may not be sustained where exposure to diets low in zinc is chronic (Lee, Prasad, Hydrick-Adair, Brewer, & Johnson, 1993). Adjustments in gastrointestinal zinc excretion, on the other hand, have the potential to conserve substantially greater quantities of endogenous zinc in response to habitually low zinc intakes (Sian et al., 1996). The two mechanisms work concomitantly, with shifts in endogenous fecal zinc excretion occurring in response to changes in zinc absorption (Jackson, Jones, Edwards, Swainbank, & Coleman, 1984). The changes in excretion are sustained in the presence of habitually low zinc intakes and are likely to reflect both a reduction in the amount of zinc secreted into the intestinal lumen and increased distal reabsorption of endogenous zinc (Hambidge & Krebs, 2001; King et al., 2000). In instances where homeostatic adjustments to a marginal zinc intake are insufficient to maintain zinc equilibrium, zinc will be lost from the tissues with a concomitant increase in the risk of zinc deficiency.

6.3. Comparative studies of zinc status in adults

The effects of a vegetarian diet on zinc status in healthy adult populations that habitually consume vegetarian diets have been explored by the present authors in a recent systematic review and meta-analysis (Foster, Chu, Petocz, & Samman, 2013). Thirty-four studies qualified for inclusion in the systematic review, of which 26 compared measures of zinc status in males and/or females consuming vegetarian diets with those of omnivorous control groups (Tables 2 and 5). Zinc intake and serum/plasma zinc were the most common outcomes to be investigated, although they were reported together only in six papers. The studies explored vegan, lacto-vegetarian, ovo-vegetarian, and ovo-lacto-vegetarian dietary patterns. Due to inconsistencies of definition among studies, two further categories of diet were included: vegetarian undefined and low meat. Vegetarian populations were defined as "low meat" if study participants were described as consuming limited amounts of meat, fish, or poultry (less than once per month, for example).

Vegetarians overall were found to have lower dietary zinc intakes (Fig. 3A) and serum zinc concentrations (Fig. 3B) compared to their respective nonvegetarian control groups (Foster, Chu, et al., 2013). When

Table 2 Zinc status in healthy adult populations that habitually consume a vegetarian diet compared to nonvegetarian controls

Study (author, year)	Diet groups (VN, V-L, V-OL, VU, LoM, NV)	Gender (F/M)	Age[a] (years)	Biomarkers of Zn status	Main outcomes
Alexander, Ball, and Mann (1994)	LoM (including 5 VN)	F & M	26 (F)[b]; 28 (M)	Intake	No difference in Zn intake between LoM and NV control
	NV	F & M	±1[c]		
Ball and Ackland (2000)	LoM (including 2 VN)	F	25.2	Intake, serum	Zn intake lower in LoM compared to NV females, no difference in serum Zn; no difference in Zn intake among male diet groups, serum Zn higher in LoM compared to VN and NV
	NV	F	25.3		
	LoM	M	20–50		
	VN	M	20–50		
	NV	M	Age matched		
Davey et al. (2003)	V-OL	F	35[d]	Intake	Zn intakes lower in female and male V-OL and VN compared to NV but no indication of statistical significance given
	VN	F	32[d]		
	NV (meat group)	F	48[d]		
	V-OL	M	39[d]		
	VN	M	35[d]		
	NV (meat group)	M	51[d]		

Continued

Table 2 Zinc status in healthy adult populations that habitually consume a vegetarian diet compared to nonvegetarian controls—cont'd

Study (author, year)	Diet groups (VN, V-L, V-OL, VU, LoM, NV)	Gender (F/M)	Age (years)	Biomarkers of Zn status	Main outcomes
Deriemaeker et al. (2010)	V-OL	F	35 ± 12	Intake	Zn intakes higher in female and male V-OL compared to NV controls
	NV	F	36 ± 12		
	V-OL	M	23 ± 4		
	NV	M	24 ± 3		
Faber, Gouws, Benade, and Labadarios (1986)	V-OL	F	29[e]	Intake	No difference in Zn intake between female V-OL and NV; Zn intake lower in male V-OL compared to NV control
	NV	F	27[e]		
	V-OL	M	29[e]		
	NV	M	27[e]		
Freeland-Graves, Bodzy, and Eppright (1980)	V-L	F & M	18–40	Intake, serum, hair, salivary sediment	No differences in Zn intake or serum Zn in vegetarian groups compared to NV control; hair and salivary sediment Zn lower in all vegetarian groups compared to control
	V-OL	F & M	18–40		
	VN	F & M	18–40		
	NV	F & M	18–40		
Haddad, Berk, Kettering, Hubbard, and Peters (1999)	VN	F	36.0 ± 8.1[e]	Intake, plasma	No differences in Zn intake or plasma Zn in female or male VN compared to NV controls
	NV	F	33.5 ± 8.2[e]		
	VN	M	36.0 ± 8.1[e]		
	NV	M	33.5 ± 8.2[e]		

Janelle and Barr (1995)	V-L (including 8 VN)	F	26.6 ± 4.3	Intake	Zn intake lower in V-L compared to NV control
	NV	F	27.9 ± 5.9		
Kadrabova, Madaric, Kovacikova, and Ginter (1995)	VU	F	35[e]	Plasma	Plasma Zn lower in female and male VU compared to respective NV controls
	NV	F	Age matched		
	VU	M	35[e]		
	NV	M	Age matched		
Kelsay et al. (1988)	V-OL (including 2? VN)	F	34	Intake	No differences in Zn intake among female or male vegetarian groups
	VU	F	36		
	NV	F	34		
	V-OL (including 1? VN)	M	34		
	VU	M	37		
	NV	M	35		

Continued

Table 2 Zinc status in healthy adult populations that habitually consume a vegetarian diet compared to nonvegetarian controls—cont'd

Study (author, year)	Diet groups (VN, V-L, V-OL, VU, LoM, NV)	Gender (F/M)	Age (years)	Biomarkers of Zn status	Main outcomes
Krajcovicová-Kudlácková et al. (1995)	V-OL	F	46.1 ± 4.3	Plasma	No differences in plasma Zn between groups
	NV	F	45.1 ± 3.6		
	V-OL	M	42.6 ± 5.4		
	NV	M	51.6 ± 3.7		
Krajcovicová-Kudlácková et al. (1996)	V-OL	F	45.4 ± 3.9	Plasma	No differences in plasma Zn between groups
	NV	F	47.9 ± 3.6		
	V-OL	M	46.3 ± 4.2		
	NV	M	41.9 ± 3.6		
Krajčovičová-Kudláčková et al. (2003)	V-OL	F & M	37.5 ± 3.1	Plasma	No difference in plasma Zn between groups
	NV	F & M	35.0 ± 4.0		
Latta and Liebman (1984)	LoM	M	30.6 ± 6.0	Plasma, RBC	No difference in plasma or RBC Zn between groups
	NV	M	30.7 ± 5.3		
Levin, Rattan, and Gilat (1986)	V-OL	F	50.5 ± 16.8	Intake, serum	No differences in Zn intake or serum Zn in female or male V-OL compared to NV controls
	NV	F	51.7 ± 12.4		
	V-OL	M	55.4 ± 15.2		
	NV	M	50.3 ± 12.2		

Li, Sinclair, Mann, Turner, and Ball (2000)	V-OL	M	34.9 ± 9.0	Intake	Zn intake lower in V-OL but not VN compared to NV control
	VN	M	33.0 ± 7.7		
	NV (meat <285 g/day)	M	38.3 ± 7.3		
Pohit and Pal (1985)	VU	M	30–50	Intake	No difference in Zn intake between VU and NV control
	NV	M	30–50		
Raghunath et al. (2006)	VU	F & M	20–40	Intake	Zn intake lower in VU compared to NV control
	NV	F & M	20–40		
Rattan, Levin, and Graff (1981)	VU	F & M	54 ± 15	Serum	No difference in serum Zn between VU and NV control
	NV	F & M	51 ± 12		
Rauma, Torronen, Hanninen, Verhagen, and Mykkanen (1995)	VN (raw)	F	46 ± 11	Intake	No difference in Zn intake between VN and NV control
	NV	F	44 ± 10		
Srikumar, Ockerman, and Akesson (1992)	VN	F	23–68[e]	Plasma, hair	Plasma Zn lower but no difference in hair Zn in male and female VN compared to respective NV controls
	NV	F	25–62[e]		
	VN	M	23–68[e]		
	NV	M	25–62[e]		

Continued

Table 2 Zinc status in healthy adult populations that habitually consume a vegetarian diet compared to nonvegetarian controls—cont'd

Study (author, year)	Diet groups (VN, V-L, V-OL, VU, LoM, NV)	Gender (F/M)	Age (years)	Biomarkers of Zn status	Main outcomes
Wilson and Ball (1999)	LoM	M	33.3 ± 8.2	Intake	No difference in Zn intake between groups
	VN	M	31.0 ± 5.6		
	NV	M	32.7 ± 8.8		
Wójciak, Krejpcio, Czlapka-Matyasik, & Jeszka (2004)	V-OL	F	18–24	Hair	No difference in hair Zn between V-OL and NV control
	NV	F	18–22		

[a] Mean ± SD where available, otherwise mean alone or range unless otherwise stated.

[b] Mean age of VN = 30 years.

[c] NV controls described as being within 1 year of LoM.

[d] Median age given.

[e] M & F combined in determination of age.

F, female; LoM, low meat; M, male; NV, nonvegetarian; RBC, red blood cell; V-L, lacto-vegetarian; VN, vegan; V-O, ovo-vegetarian; V-OL, ovo-lacto vegetarian; VU, vegetarian undefined.

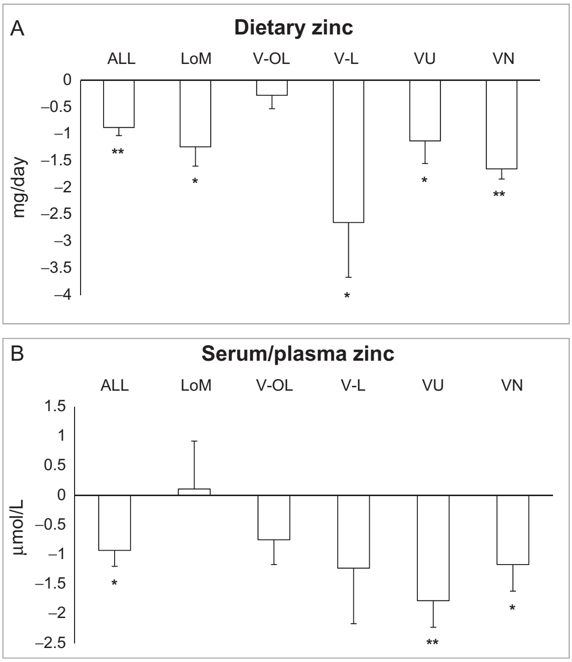

Figure 3 Meta-analyses of dietary zinc intake and serum zinc concentration in vegetarian adults overall and according to category of vegetarian diet. In a random-effects meta-analysis of observational studies, dietary zinc intake (A) and serum zinc concentration (B) were found to be lower in adult populations that follow habitual vegetarian diets compared to NV control groups, but not all vegetarian diets impacted zinc status to the same extent (Foster, Chu, et al., 2013). Results are expressed as mean difference ± SE. $*P<0.01$, $**P<0.001$. LoM, low meat; V-OL, ovo-lacto-vegetarian; V-L, lacto-vegetarian; VU, vegetarian undefined; VN, vegan.

analyzed according to dietary pattern, no differences were observed in the zinc intake or serum/plasma zinc of ovo-lacto-vegetarians compared to nonvegetarians, while the differences compared to controls were greater in vegans and vegetarians (undefined), suggesting that not all vegetarian categories impact zinc status to the same extent. Vegans exclude all animal products from their diet which, in the absence of careful nutritional planning or the consumption of zinc-fortified foods or supplements, may increase their likelihood of having a low zinc status. A high amount of ingested phytate may have contributed to the low zinc status in the vegetarian (undefined) category, which included populations from India, South Korea, and Slovakia; dietary phytate levels have been shown to be high in Indian (Khokhar, Pushpanjali, & Fenwick, 1994) and South Korean (Kwun & Kwon, 2000) populations, in particular, compared to Western populations (Foster et al., 2012).

Despite the reduced zinc bioavailability of many plant-based diets, there do not appear to be any adverse health consequences in adult vegetarians that are attributable to a lower zinc status, supporting suggestions that there is an increase in the efficiency with which zinc is utilized in those following long-term vegetarian diets. An important consideration is whether homeostatic adjustments to a vegetarian diet are sufficient to maintain an adequate zinc status during times of increased zinc requirement.

7. VEGETARIAN DIETS AND ZINC STATUS IN PREGNANCY AND LACTATION

Pregnant and lactating women are vulnerable to a low zinc status due to the additional zinc demands associated with pregnancy and infant growth and development. Estimates of dietary zinc requirements in pregnancy take into account zinc accumulation in late pregnancy, the period of greatest need (National Health and Medical Research Council, 2006). The marked increase in physiological demands for zinc during lactation is believed to be counterbalanced by a systemic redistribution of tissue zinc during postnatal readaptation to the nonpregnant state (World Health Organization, 1996); currently, the recommendation for zinc intake in lactation considers the additional needs for milk production together with estimates of zinc released for use as a consequence of decreasing maternal blood volume after parturition (National Health and Medical Research Council, 2006). The extent of adaptive responses to zinc utilization during pregnancy in the human female is unknown, and as with vegetarians generally, it is suggested that pregnant and lactating vegetarians need to consume as much as 50% higher intakes of zinc than their omnivorous counterparts.

7.1. Comparative studies of zinc intake in pregnancy

A number of studies (Table 3), predominantly conducted in the United Kingdom and the United States in the 1980s, have explored the effects of an habitual vegetarian compared to an omnivorous diet on zinc status in pregnancy. Three studies (Abraham et al., 1985; Campbell-Brown et al., 1985; Drake et al., 1998) reported a lower zinc intake in pregnant vegetarians compared to nonvegetarian control groups; one of these examined the zinc intake of three vegetarian categories and found that the amount of ingested zinc reflected differences in animal protein intake, with the lacto-vegetarian group having a lower zinc intake than the ovo-lacto-vegetarian and low

Table 3 Zinc status in pregnant women who habitually consume a vegetarian diet compared to nonvegetarian controls

Study (author, year)	Diet groups (V-L, V-OL, VU, LoM, NV)	Age[a] (years)	Biomarkers of Zn status [stage of pregnancy when measured[b]]	Main outcomes
Abraham et al. (1985)	V-L		Intake [trimester 1 (30%)[c]]	Lower Zn intake in all vegetarian groups compared to NV control; lower Zn intake in V-L compared to V-OL and LoM
	V-OL			
	LoM			
	NV			
Abu-Assal and Craig (1984)	LoM	28 ± 3	Intake [≥32] Plasma [37 ± 2[a]] PP plasma [11 ± 7[a]]	No difference in Zn status measures between LoM and NV control
	NV	29 ± 3		
Campbell-Brown et al. (1985)	VU		Intake [1st antenatal visit] Plasma [booking, 20, 28, 36] Urine [booking, 20, 36] Hair [booking, 36]	Zn intake lower in VU compared to NV; plasma Zn decreased during pregnancy with no differences between VU compared to NV; urinary Zn increased during pregnancy and was lower in VU compared to NV; no differences in hair Zn
	NV			
Drake, Reddy, and Davies (1998)	V-OL	28.5 ± 3.9	Intake [V-OL: 25.0 ± 9.6[a]; NV: 24.3 ± 8.2[a]]	Zn intake lower in V-OL compared to NV control
	NV	29.8 ± 4.2		
King, Stein, and Doyle (1981)	V-OL	25 ± 3	Intake [trimester 3] Plasma [trimester 3] Urine [trimester 3] Hair [trimester 3]	No differences in Zn intake, plasma Zn, urinary Zn, hair Zn between V-OL and NV control
	NV	27 ± 4		
Ward et al. (1988)	VU		Intake [28] Plasma [28]	No differences in Zn intake or plasma Zn between VU and NV control
	NV			

[a] Mean ± SD, where available.

[b] Expressed as trimester 1, 2, 3 or weeks of gestational age, unless otherwise stated.

[c] Further information not provided.

LoM, low meat; NV, nonvegetarian; PP, postpartum; RBC, red blood cell; V-L, lacto-vegetarian; V-O, ovo-vegetarian; V-OL, ovo-lacto vegetarian; VU, vegetarian undefined.

meat groups (Abraham et al., 1985). In contrast, three studies (Abu-Assal & Craig, 1984; King et al., 1981; Ward et al., 1988) that evaluated zinc intake in the third trimester of pregnancy found no differences in the zinc intake of vegetarians compared to omnivorous control groups. Although there is little evidence that pregnant women increase their zinc intake as pregnancy progresses, these studies suggest that the stage of pregnancy at which dietary intake is measured is an important consideration when comparing zinc intake results among studies.

In all but one study (King et al., 1981), the mean zinc intake was lower than amounts recommended for pregnancy (Health Canada, 2005) in both the vegetarian and nonvegetarian populations; concerns that zinc intakes are insufficient to provide the minimum requirement for adequate fetal growth therefore apply to both groups. Whether vegetarians need higher zinc intakes than omnivores to meet physiologic requirements depends on the zinc bioavailability of the diet. None of the studies investigating zinc status in pregnant vegetarian compared to omnivorous women reported data on phytate intake or the phytic acid:zinc ratio, although five studies did report fiber intake (Abraham et al., 1985; Campbell-Brown et al., 1985; Drake et al., 1998; King et al., 1981; Ward et al., 1988), which may give some indication of the amount of phytate that has been ingested (Foster et al., 2012). The results were mixed, with the fiber intake of vegetarians compared to omnivores found to be higher in one study (Abraham et al., 1985), lower in one study (Ward et al., 1988), and not significantly different in the others (Campbell-Brown et al., 1985; Drake et al., 1998; King et al., 1981). Overall, there is insufficient evidence that zinc intake and status during pregnancy are lower in vegetarians as compared to omnivores.

7.2. Comparative studies of zinc biomarkers in pregnancy

The use of biochemical indices in the assessment of zinc status during pregnancy is influenced by physiologic adjustments in zinc metabolism during gestation. It is well documented that the plasma zinc concentration declines during pregnancy, perhaps as early as the first trimester (Hambidge & Droegemueller, 1974). The mechanisms of this phenomenon remain to be elucidated but may include hemodilution, hormonal changes (Jameson, 1976a), and active transport of zinc from the mother to the fetus (Tamura & Goldenberg, 1996). Conversely, the concentration of urinary zinc increases during pregnancy, often reaching a value nearly twice that of preconception (King, 2000). The three studies that found no difference in third trimester zinc intake (as discussed above) additionally found no differences in zinc concentrations in plasma (Abu-Assal & Craig, 1984; King et al., 1981; Ward et al., 1988), postprandial plasma (Abu-Assal & Craig, 1984), urine, or hair (King et al., 1981) between vegetarians and controls, suggesting that zinc status in pregnancy is not compromised by a vegetarian diet. A different conclusion can be inferred from a study that investigated the zinc status of vegetarian pregnant women compared to controls at multiple time points (Campbell-Brown et al., 1985). Vegetarians and nonvegetarians both demonstrated the pregnancy-associated fall in the plasma zinc concentration and an increase in urinary zinc levels during the study. Although no differences were found between vegetarians and NV in plasma zinc measurements, the urinary zinc concentration was lower in vegetarians than nonvegetarians at all time points. Taken together with the lower zinc intake reported at the first antenatal visit (Campbell-Brown et al., 1985), this finding may signify a lower zinc status in the vegetarian group that necessitated a degree of renal zinc conservation during pregnancy.

7.3. Zinc status and functional outcome in pregnancy

Early prospective studies investigating maternal zinc status and pregnancy outcome in healthy primigravidae (Jameson, 1976c) and women with a history of pregnancy complications (Jameson, 1976b) reported a significantly lower serum zinc concentration in women who had complications at delivery and/or gave birth to abnormally formed infants compared to women with normal deliveries. The findings of later observational studies, including numerous surveys of the association between maternal zinc status and the birth weight of infants, have been mixed (King, 2000). Of the studies of zinc status in pregnant vegetarian women, four studies assessed one or more pregnancy outcome variable. No differences were found in period of gestation (Drake et al., 1998), delivery characteristics (Drake et al., 1998), or birth weight (Abu-Assal & Craig, 1984; Campbell-Brown et al., 1985; Drake et al., 1998; Ward et al., 1988) between vegetarian populations and their respective control groups.

7.4. Zinc status during lactation

The concentration of zinc in breast milk is highest in colostrum and progressively declines with the duration of lactation (Institute of Medicine, 1992).

In healthy term infants, zinc requirements to support the very rapid growth of early infancy generally are met by exclusive feeding of human milk; however after the first 5 or 6 months of life, it becomes necessary to introduce complementary foods to meet infant zinc requirements, which continue to be high in relation to body weight.

The zinc concentration of human milk is relatively resistant to changes in maternal zinc intake (Krebs, 2000), even in women with intakes that are chronically inadequate (Simmer, Ahmed, Carlsson, & Thompson, 1990), suggesting that homeostatic mechanisms rather than an increase in ingested zinc compensate for the maternal contribution of zinc that is secreted into breast milk. Fractional zinc absorption has been shown to increase (Fung, Ritchie, Woodhouse, Roehl, & King, 1997) and urinary zinc to decrease (Klein, Moser-Veillon, Douglas, Ruben, & Trocki, 1995) during lactation. Endogenous fecal zinc and zinc mobilized from bone resorption also are likely to contribute to the maintenance of zinc status (Moser-Veillon, 1995). The effects of a vegetarian diet on zinc nutriture and homeostatic adaptations during lactation are little studied. In one study of pregnant women, biochemical assessment at 11 weeks postpartum showed no difference in the plasma zinc concentration between vegetarians and non-vegetarians, with all but one of the participants breastfeeding (Abu-Assal & Craig, 1984). Studies that specifically investigate the zinc status of lactating vegetarians compared to omnivores are needed.

8. VEGETARIAN DIETS AND ZINC STATUS IN CHILDREN

Human zinc deficiency was first recognized in the Middle East in young men and adolescent boys consuming diets high in wheat and low in animal protein, who showed signs of severe growth retardation and developmental delays (Prasad, Halsted, & Nadimi, 1961; Prasad, Mial, Farid, Schulert, & Sandstead, 1963). Other consequences of zinc deficiency that have been identified in children from developing countries include stunting and increased rates of infectious diseases. It is estimated that more than 4% of deaths from diarrhea, malaria, and pneumonia among children aged between 6 months and 5 years in Latin America, Africa, and Asia are attributable to zinc deficiency (Fischer Walker, Ezzati, & Black, 2009). Low zinc concentrations in serum (Cavan et al., 1993) and hair (Cavan et al., 1993; Ferguson, Gibson, Thompson, & Ounpuu, 1989) in children from developing countries have been associated with impairment in linear growth (Cavan et al., 1993; Ferguson et al., 1989) and taste acuity (Cavan et al., 1993). Zinc supplementation trials show improvements in health outcomes, such as growth (Chen et al., 1985) and the reduced duration and severity of acute diarrhea (Sazawal et al., 1995), further confirming the existence of zinc deficiency in these populations of children. Suboptimal zinc status in developing countries is attributed to traditional dietary patterns that, although not strictly vegetarian, are predominantly plant-based with limited intakes of meat and/or fish and high phytate:zinc molar ratios. Zinc deficiency, in a mild form, has been demonstrated also in developed countries in apparently healthy children who were selected for study based on the results of anthropometric screening for suboptimal zinc nutriture (Gibson et al., 1989; Hambidge, Hambidge, Jacobs, & Baum, 1972; Smit Vanderkooy & Gibson, 1987; Walravens, Krebs, & Hambidge, 1983).

8.1. Prevalence of vegetarian diets in children

National surveys in the United States estimate that 0.7% and 1.3% of children aged 6–12 and 12–19 years, respectively, are vegetarian (Haddad & Tanzman, 2003). In the region of Minnesota, USA, vegetarians comprised 6% of the teenage population and were more likely that nonvegetarians to be female (Perry, Mcguire, Neumark-Sztainer, & Story, 2001). In New Zealand, the 2002 Children's Nutrition Survey reported that 1% of children aged 5–14 years followed a vegetarian diet (Ministry of Health, 2012), and data from the 2008–2009 Nutrition Survey reported 0.2% and 1.7% of males and females aged 15–18 years, respectively, had not consumed meat, chicken, or seafood in the past 4 weeks (University of Otago and Ministry of Health, 2011). Similar prevalence data are reported for the United Kingdom, with approximately 2% of children surveyed during the years 2010–2012 reporting that they are vegetarian (Vegetarian Society, 2014).

There are limited prevalence data on vegetarian children in Australia. In the 2007 Australian National Children's Nutrition and Physical Activity Survey, 2% of the children surveyed ($n = 4487$) were classified as vegetarian (M. Riley, Commonwealth Scientific and Industrial Research Organisation, unpublished results, 17 February 2014). An examination of the adequacy of zinc intakes of all survey participants showed that most children met the estimated average requirement (EAR) for zinc except for 29% of boys aged 14–16 years. Zinc intakes were higher than reported in the previous national survey, especially from "cereals and cereal products," while remaining similar for other major food groups (Rangan & Samman, 2012). In the small percentage of children who consumed a vegetarian diet, 13.3% used zinc supplements as compared to 8.6% in those who consumed an omnivorous diet (Rangan, Jones, & Samman, 2014).

8.2. Comparative studies of zinc status in children

Children are particularly vulnerable to suboptimal zinc status during periods of rapid growth that increase requirements for zinc. The effects of habitual vegetarian compared to omnivorous diets on zinc status in children have been explored in a limited number of observational studies (Table 4). The studies were conducted principally in developed countries and canvass populations from infancy to adolescence.

8.3. Infants

As with adults, higher zinc intakes are recommended for vegetarian compared to nonvegetarian infants to account for differences in bioavailability between plant and meat sources of zinc (National Health and Medical Research Council, 2006). Data from the United States suggest, however, that the inclusion of meats as part of daily complementary feeding regimes is not common (Siega-Riz et al., 2010), raising concerns that zinc requirements in infants are not being met. In a recent experimental diet study that compared the capacity of three different complementary feeding strategies (commercially available pureed meats, iron-and-zinc-fortified infant cereal, or whole-grain, iron-fortified infant cereal) to meet infant zinc requirements (Krebs et al., 2012), only the meat and zinc-fortified cereal groups met the EAR for zinc intake at 9 months of age. The mean zinc intake of the group consuming the whole-grain cereal fortified only with iron was approximately 50% of the EAR, and despite a higher fractional zinc absorption compared to the other groups, the total amount of absorbed zinc was significantly lower than the estimated amount required to replace losses and support optimal growth. In contrast, one longitudinal observational study (Taylor et al., 2004) that investigated the zinc status of infants consuming no meat with those consuming varying amounts of mixed red and white meat reported no differences among groups in zinc intake, which was assessed at 4-monthly intervals between the ages of 4 months and 2 years. Mean zinc intakes were marginally lower than the reference nutrient intake (RNI) for age at each time point in all groups, except at 12 and 16 months when the nonmeat group met the RNI. Zinc bioavailability and absorption were not considered so it is not clear whether the nonmeat group required intakes higher than the RNI to meet estimated physiologic requirements.

Table 4 Zinc status in children who habitually consume a vegetarian diet compared to nonvegetarian controls

Study (author, year)	Diet groups (V-OL, VU, LoM, NV)	Gender (M/F)	Age[a] (years)	Biomarkers of Zn status	Main outcomes
Donovan and Gibson (1995, 1996)	LoM	F	17.7 ± 1.4	Intake, serum, hair	No differences in Zn intake, serum Zn, hair Zn between LoM and NV control
	NV	F	18.2 ± 1.4		
Gorczyca, Prescha, and Szeremeta (2013)	VU	F & M	1–17.6	Intake	No difference in Zn intake between VU and NV control
	NV	F & M	2.3–17.8		
Nathan, Hackett, and Kirby (1996)	LoM	F & M	9.1 ± 1.5	Intake	Zn intake lower in LoM compared to NV control
	NV	F & M	9.4 ± 1.4		
Taylor, Redworth, and Morgan (2004)[b]	V-OL[c]	F & M	24 months[d]	Intake[e], serum[f]	No differences in Zn intake or serum Zn among groups at any time point
	NV (low)[c]	F & M	24 months[d]		
	NV (medium)[c]	F & M	24 months[d]		
	NV (high)[c]	F & M	24 months[d]		
Thane and Bates (2000)	LoM	F & M	2.3 ± 0.4[g]	Intake, plasma	No differences in Zn intake[h] or plasma Zn between LoM and NV control in either age group
	NV	F & M	2.3 ± 0.4[g]		
	LoM	F & M	3.7 ± 0.4[g]		
	NV	F & M	3.7 ± 0.4[g]		
Treuherz (1982)	VU	F & M	10–16	Intake, hair	Trend toward higher Zn intake in VU compared to NV control that was significant when expressed per 1000 kcal energy; hair Zn lower in VU
	NV	F & M	Age matched		

Continued

Table 4 Zinc status in children who habitually consume a vegetarian diet compared to nonvegetarian controls—cont'd

Study (author, year)	Diet groups (V-OL, VU, LoM, NV)	Gender (M/F)	Age (years)	Biomarkers of Zn status	Main outcomes
Yen, Yen, Huang, Cheng, and Huang (2008)	V-OL	F & M	5.2 ± 1.5	Intake	No differences in Zn intake between V-OL and NV control
	NV	F & M	5.0 ± 1.1		

[a] Mean ± SD where available, otherwise range unless otherwise stated.
[b] Longitudinal study.
[c] Diet groups correspond to study definitions, as follows: V-OL (nonmeat eaters), NV (low, middle, and upper tertile meat eaters).
[d] Participants were recruited before they were 4 months of age and were followed up until 24 months of age.
[e] Measured at 4, 8, 12, 16, 20, 24 months of age.
[f] Measured at 4–5, 12, 24 months of age.
[g] LoM and NV combined in determination of each age group.
[h] Expressed as mg/4.18 MJ.
F, female; LoM, low meat; M, male; NV, nonvegetarian; V-OL, ovo-lacto vegetarian; VU, vegetarian undefined.

Neither the experimental nor the observational study demonstrated differences in serum zinc concentrations between nonmeat and meat-eating infant groups. Zinc-related functional outcomes, such as growth, neurocognitive development, and infectious morbidity, were not measured. In the absence of evidence of adverse health effects of a vegetarian diet, the studies suggest that zinc status is maintained in vegetarian and nonvegetarian infants to a similar degree.

8.4. Young children

The British National Diet and Nutrition Survey 1992–1993 of children aged 1.5–4.5 years demonstrated no significant differences in energy-adjusted zinc intake or plasma zinc concentrations in younger (1.5 to <3 years) or older (3–4.5 years) participants who consumed no meat during the 4-day period of dietary record keeping compared to those who ate meat. No difference was observed between percentages of omnivores and vegetarians with intakes below the lower RNI threshold (Thane & Bates, 2000). Consistent results were obtained in a study of preschool children conducted in Taiwan; no differences between vegetarians and omnivores were found in zinc intake or in weight, height, or the weight-for-height index (Yen et al., 2008). As in infants, the results in young children indicate that zinc status is maintained to the same extent in vegetarians and omnivores. The absence of a relationship between zinc intake and meat consumption suggests that other food sources, such as milk and cereal products, dominate the supply of zinc from the diet. Further comparisons of zinc status in vegetarian and nonvegetarian children are needed that focus on those individuals within each dietary pattern who are at risk of suboptimal zinc status at key stages of growth and development.

8.5. Adolescents

Physiological requirements for zinc peak at the onset of the growth spurt in early puberty and at the age of peak height velocity during late puberty, which occur respectively at approximately 10 and 12 years of age in girls and 12 and 14 years of age in boys (Aksglaede, Olsen, Sorensen, & Juul, 2008). In England, comparative studies suggest that the zinc status of children who are approaching or have reached adolescence is lower in vegetarians than nonvegetarians. In one study, the zinc intake of vegetarian children with a mean age of 9 years was found to be lower than that of age-matched omnivores although both groups had mean intakes below the RNI (Nathan et al., 1996). In an earlier study (Treuherz, 1982), there was a contrary trend toward a higher zinc intake in a small number of vegetarian children aged 10–16 years compared to age- and sex-matched omnivores, which was significant when zinc intake was expressed as nutrient density (mg zinc per 1000 kcal of energy intake); however, despite the higher zinc intake, the concentration of zinc in hair was lower in the vegetarian group. The intake of dietary fiber also was significantly higher in the vegetarian population, which implies that the lower hair zinc concentrations reflect a lower zinc bioavailability of the vegetarian compared to the omnivorous diet.

Not all observational studies support a difference in zinc status between vegetarian and nonvegetarian adolescents. In a recent study in Poland that included adolescent children (Gorczyca et al., 2013), zinc intakes were reported to be lower but not significantly different in male and female vegetarians compared to omnivores, and no differences in height, weight, infectious disease morbidity, or serum immunoglobulin levels were observed between groups; however, the study was conducted in a small number of participants and the age range was wide, which limits the generalizability of the findings. In a Canadian study, no differences in zinc intake, serum zinc, or hair zinc concentrations were found in young vegetarian, semi-vegetarian, and nonvegetarian women aged 14–19 years (Donovan & Gibson, 1995). Although the median phytate:zinc molar ratio was higher in vegetarians, with a higher proportion of vegetarians than semi-vegetarians and omnivores having ratios above 15, similar proportions of each group were observed to have serum and hair zinc concentrations below lower threshold levels. The study authors note that cereal products were the major source of zinc for all groups of adolescents, suggesting that the low zinc status identified in many of the participants was attributable to inadequate intakes of readily available zinc from flesh foods in all dietary groups (Donovan & Gibson, 1995). Zinc status in both vegetarian and NV adolescents may be enhanced by strategies that increase the total amount of zinc in the diet, promote the intake of enhancers of zinc absorption, and reduce the intake of antagonists of zinc absorption (Gibson, Donovan, & Heath, 1997; Harland, Smith, Howard, Ellis, & Smith, 1988).

9. VEGETARIAN DIETS AND ZINC STATUS IN THE ELDERLY

Elderly individuals, particularly if housebound (Bunker & Clayton, 1989), often experience a decline in their intake of zinc (Briefel et al., 2000; Prasad et al., 1993). It has been suggested that a reduction in zinc intake may occur in response to reduced energy requirements or age-related sensory impairment (Stewart-Knox et al., 2005). Factors such as inadequate mastication, reduction in appetite, and physiologic changes associated with aging that affect zinc metabolism may increase the risk of suboptimal zinc status in elderly individuals (Mocchegiani et al., 2013). The risk is compounded with the onset of age-related diseases and concomitant use of medications that may interact with zinc (Braun & Rosenfeldt, 2013). Zinc supplementation in elderly participants has been shown to improve immunological competence, supporting indications that marginal zinc status can occur in old age (Haase & Rink, 2009).

9.1. Comparative studies of zinc status in the elderly

Few studies (Table 5) have explored the zinc status of healthy elderly ($\geq$60 years) vegetarian compared to omnivorous adults. A comparison of elderly male and female ovo-lacto-vegetarian and nonvegetarian residents of senior citizens homes in the Netherlands and Belgium (Deriemaeker et al., 2011) reported no differences in dietary zinc intake or serum zinc

Table 5 Zinc status in healthy elderly (≥60 years) populations that habitually consume a vegetarian diet compared to nonvegetarian controls

Study (author, year)	Diet groups (VN, V-L, V-OL, VU, LoM, NV)	Gender (F/M)	Age[a] (years)	Biomarkers of Zn status	Main outcomes
Deriemaeker, Aerenhouts, De Ridder, Hebbelinck, and Clarys (2011)	V-OL	F	84.1 ± 5.1	Intake, serum	No differences in Zn intake or serum Zn between V-OL and NV controls
	NV	F	84.3 ± 5.0		
	V-OL	M	80.5 ± 7.5		
	NV	M	80.6 ± 7.3		
Kim, Choi, and Sung (2007)	VU	F	60.7 ± 6.9	Intake, serum	Zn intake and serum Zn lower in VU compared to NV control
	NV	F	60.8 ± 6.7		
Nieman et al. (1989)	V-OL	F	72.2 ± 1.3	Intake	No difference in Zn intake between V-OL and NV control
	NV	F	71.1 ± 1.4		

[a] Mean ± SD.
F, female; M, male; NV, nonvegetarian; V-OL, ovo-lacto vegetarian; VU, vegetarian undefined.

concentration among groups. Serum zinc values were within the reference range and mean zinc intakes of males and females exceeded the recommended intake in both the ovo-lacto-vegetarian and nonvegetarian groups, which suggests that participants consumed an adequate variety of micronutrient-dense foods regardless of dietary pattern or gender. In contrast, although again no differences were shown between the two groups, zinc intakes were found to be less than half of recommended intakes in an earlier study of Seventh-Day Adventist ovo-lacto-vegetarian and nonvegetarian women (Nieman et al., 1989). A study in South Korea reported similarly low dietary zinc intakes in postmenopausal women, but in this instance both zinc intake and serum zinc levels were lower in vegetarian (undefined) compared to nonvegetarian controls (Kim et al., 2007), which may reflect a difference in the zinc bioavailability of a South Korean vegetarian diet. The lower zinc status was not associated with any difference in bone mineral density in the postmenopausal women; however, no other functional outcomes were measured.

The three comparative studies in elderly vegetarians were included in the meta-analysis of zinc status in healthy adults, described above, which reported lower dietary zinc intakes and serum zinc concentrations in vegetarians compared to omnivores (Foster, Chu, et al., 2013). The data in elderly participants were insufficient to allow secondary analyses by age to be conducted. Further evidence is needed to determine whether zinc status is lower in vegetarian compared to NV elderly populations.

10. LIMITATIONS AND FURTHER RESEARCH

There is insufficient evidence to determine whether the zinc status of vegetarians during pregnancy and lactation, childhood, and old age is lower than that of respective omnivorous populations. Inconsistencies in study findings may reflect disparities in statistical power, with the small sample size in many studies being potentially insufficient to detect differences in measures of zinc status between groups, as well as variations inherent in the different categories of vegetarian diet. A more complete understanding is required of the relationships in vegetarian populations among zinc nutriture, physiological adaptations in zinc metabolism during periods of increased requirement, and functional outcomes to elucidate the effects of a vegetarian diet on zinc status and the prevalence of zinc deficiency across the life cycle.

More generally, a key limitation of the existing literature on vegetarian nutriture is the lack of specificity in describing vegetarian populations. Variations inherent in the different categories of vegetarian diet impact study results, indicating the need for detailed dietary intakes, supplement use, and other lifestyle-related practices to be ascertained and reported using appropriate methodologies. In addition, few recent studies have been conducted. Updated information on zinc bioavailability from vegetarian and omnivorous diets is required, particularly in developed countries. Changes in dietary patterns, such as a reduction in meat consumption and an increase in the availability of fortified foods, are likely to have altered the average content and bioavailability of zinc in contemporary diets (Gibson, 1994). Data on the amounts of zinc in plant foods should be sourced from locally grown produce as trace element content is affected by cultivar, soil type, harvest conditions, and potentially small differences that are introduced due to variations in agricultural methods such as organic farming (Hunter et al., 2011). Modern methods of food processing may have altered the phytate content of foods, suggesting the need also for revised phytate data. At the least, dietary analyses of phytate consumption in particular populations should rely on data obtained using methodologies that separate and quantify the individual inositol phosphate esters, such as the high-performance liquid chromatography method (Lehrfeld, 1989); less sensitive methods of phytic acid analysis will tend to overestimate phytate content.

As with all zinc research, the identification of a specific and reliable biomarker of zinc status would be invaluable in the assessment of zinc nutriture in vegetarian populations. The discovery of zinc transporters provides new insight into the maintenance of human zinc homeostasis; the coordinated control of zinc transporters in humans (Foster, Hancock, Petocz, & Samman, 2011; Foster, Petocz, & Samman, 2013) represents a promising direction in biomarker research that should continue to be explored.

11. CONCLUSION

Compared to their respective nonvegetarian control groups, adult men and women have lower dietary zinc intakes and serum zinc concentrations. Nonetheless, there do not appear to be any adverse health consequences in adult vegetarians that are attributable to a lower zinc status, presumably because of homeostatic mechanisms that allow adults to adapt to a vegetarian diet (Gibson, 1994). There is a need for updated and additional studies of vegetarian nutriture in the elderly, in children and adolescents, and in women during pregnancy and lactation to determine whether zinc intakes and status are adequate in these populations. In both vegetarians and omnivores, research that targets individuals below critical zinc intake and biomarker thresholds may assist in the determination of mild zinc deficiency, particularly in children during phases of rapid growth when additional zinc requirements increase their susceptibility to suboptimal zinc status. Although there is insufficient evidence to suggest that zinc deficiency is more prevalent in vegetarians than omnivores in developed countries, appropriate dietary advice to increase the zinc content and bioavailability of vegetarian diets during times of increased requirement is prudent.

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