Vegetarian diets and bone status\textsuperscript{1–3}

Katherine L Tucker

ABSTRACT

Osteoporosis is a common chronic condition associated with progressive loss of bone mineral density (BMD)\textsuperscript{4} and compromised bone strength, with increasing risk of fracture over time. Vegetarian diets have been shown to contain lower amounts of calcium, vitamin D, vitamin B-12, protein, and n–3 (\(\omega-3\)) fatty acids, all of which have important roles in maintaining bone health. Although zinc intakes are not necessarily lower quantitatively, they are considerably less bioavailable in vegetarian diets, which suggests the need for even higher intakes to maintain adequate status. At the same time, healthy vegetarian diets tend to contain more of several protective nutrients, including magnesium, potassium, vitamin K, and antioxidant and anti-inflammatory phytonutrients. On balance, there is evidence that vegetarians, and particularly vegans, may be at greater risk of lower BMD and fracture. Attention to potential shortfall nutrients through the careful selection of foods or fortified foods or the use of supplements can help ensure healthy bone status to reduce fracture risk in individuals who adhere to vegetarian diets. \textit{Am J Clin Nutr} doi: 10.3945/ajcn.113.071621.

INTRODUCTION

Osteoporosis is a common chronic condition associated with progressive loss of bone mineral density (BMD)\textsuperscript{4} and compromised bone strength, with increasing risk of fracture. Recent prevalence data from the National Osteoporosis Foundation suggest that 9 million adults in the United States have osteoporosis and 48 million have low bone mass, placing them at risk of fracture (1). For the US population \(\geq 50\) y of age in 2005, incident fractures were estimated at \(>2\) million, with the majority of these in women (2). It has been estimated that 1 in 3 women and 1 in 5 men aged \(>50\) y will experience a fracture in their lifetime (3). In addition to the inconvenience, pain, and medical costs associated with fracture, there are important associated subsequent risks: up to 50% of older hip fracture patients do not regain the ability to walk independently; for many, this moves them into long-term care; and for \(10\%–20\%\), the fracture begins a downward spiral leading to excess mortality during the following year (4). Total BMD is the result of a delicate balance between bone resorption by osteoclasts and bone formation by osteoblasts during continuous remodeling. With aging, osteoclast activity progressively exceeds osteoblast activity and leads to bone loss (5). This is particularly true for postmenopausal women, because bone loss accelerates to 2–6 times the premenopausal rates soon after menopause and then slows to \(\sim 1\%\) annually over approximately the next 10 y (6, 7).

In older men, there is a slower, but consistent, bone loss over time of \(\sim 1\%/y\) (7).

BONE STATUS IN VEGETARIANS

Although studies remain limited, there is evidence that vegetarians may be at greater risk of lower BMD and greater risk of fracture. A 2009 meta-analysis of 9 studies comparing vegetarians and omnivores, which included 1880 women and 869 men aged 20–79 y, showed 4% lower BMD (95% CI: 2%, 7%) at both the femoral neck and lumbar spine in vegetarians relative to omnivores. Subgroup analysis showed that the difference was greater for vegans, who had 6% lower BMD relative to omnivores (95% CI: 2%, 9%) (8). A study in Taiwanese women showed that long-term vegan practice was associated with almost 4 times the risk of osteopenia of the femoral neck (adjusted OR: 3.9; 95% CI: 1.2, 12.8) relative to lactoovo vegetarians or omnivores (9).

Few studies are available that examine vegetarian diets with fracture outcome. A prospective study of fracture risk in the United Kingdom that used data from the European Prospective Investigation into Cancer and Nutrition–Oxford cohort, with 7947 men and 26,749 women aged 20–89 y of age, found that fracture risk was higher in vegans with low (<525 mg/d) calcium intakes but did not differ between meat eaters, fish eaters, or lactoovo vegetarians (10).

Together, the evidence suggests that there is some increased risk of osteoporosis and fracture with vegetarian, and particularly with vegan, diets. It is therefore important to take a closer look at these diets to better understand what may be contributing to this risk in order to advise vegetarians on optimal practices to ensure long-term protection of the skeleton.

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\textsuperscript{3}Abbreviations used: ALA, \(\alpha\)-linoleic acid; BMD, bone mineral density; MMA, methylmalonic acid; 25(OH)D, 25-hydroxyvitamin D.


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DIET AND BONE HEALTH

Much has been learned in recent decades with regard to the importance of diverse foods and nutrients to the maintenance of BMD and prevention of fracture. Bone is exquisitely sensitive to its microenvironment, and small imbalances over time can lead to considerable bone loss over years of exposure. In addition to the well-known importance of calcium and vitamin D, many nutrients affect BMD and/or fracture status.

Vegetarian diets differ in the probability of meeting nutrient requirements from diets that contain animal products. One large study identified lower intakes of protein, vitamin B-12, vitamin D, and retinol in both lactoovovegetarians and vegans relative to meat eaters, with these nutrients being particularly low in vegans (11). In addition, calcium was lower in vegans than in lactoovovegetarians or in meat eaters. Although total milligrams of zinc intake did not appear to vary greatly, its dietary sources differed, and these minerals become important when bioavailability is considered. Sources of these at-risk nutrients for lactoovovegetarians and vegans, along with their nutrient content, are provided in Table 1. As long as vitamin A is sufficient from carotenoid intakes, the lower intake of retinol may be a positive factor for bone health, because higher intakes of retinol in the US diet have been associated with greater fracture risk (13). In addition, it should be noted that healthy vegetarian diets might often have higher intakes of protective anti-inflammatory and antioxidant nutrients that protect against loss of BMD. In this study, vegans had higher intakes of folate, vitamin C, vitamin E, and magnesium than did the other groups (11). They also tended to have higher intakes of vitamin K, which is found in green leafy vegetables and vegetable oil, and this nutrient has been associated with protection against fracture risk (14, 15).

TABLE 1

<table>
<thead>
<tr>
<th>Nutrient, adult RDA/AI</th>
<th>Lactoovovegetarian sources</th>
<th>Serving</th>
<th>Nutrient content</th>
<th>Vegan sources</th>
<th>Serving</th>
<th>Nutrient content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium, 1000–1200 mg</td>
<td>Yogurt</td>
<td>244 g (1 c)</td>
<td>368 mg</td>
<td>Fortified soy milk</td>
<td>245 g (1 c)</td>
<td>299 mg</td>
</tr>
<tr>
<td></td>
<td>Milk</td>
<td>244 g (1 c)</td>
<td>293 mg</td>
<td>Firm calcium-set tofu</td>
<td>100 g (3.5 oz)</td>
<td>683 mg</td>
</tr>
<tr>
<td></td>
<td>Cheese</td>
<td>28 g (1 oz)</td>
<td>191 mg</td>
<td>Fortified breakfast cereal¹</td>
<td>15 g (0.5 c)</td>
<td>500 mg</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Blackstrap molasses</td>
<td>20 g (1 Tb)</td>
<td>120 mg</td>
</tr>
<tr>
<td>Vitamin D, 600 IU</td>
<td>Fortified milk</td>
<td>244 g (1 c)</td>
<td>120 IU</td>
<td>Fortified soy milk</td>
<td>245 g (1 c)</td>
<td>105 IU</td>
</tr>
<tr>
<td></td>
<td>Fortified yogurt</td>
<td>245 g (1 c)</td>
<td>107 IU</td>
<td>Fortified breakfast cereal¹</td>
<td>15 g (0.5 c)</td>
<td>50 IU</td>
</tr>
<tr>
<td></td>
<td>Egg</td>
<td>11 g</td>
<td>41 IU</td>
<td>UV-light-exposed mushrooms²</td>
<td>0.5 c</td>
<td>316 IU</td>
</tr>
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<td>Vitamin B-12, 2.4 µg</td>
<td>Milk</td>
<td>244 g (1 c)</td>
<td>1.3 µg</td>
<td>Fortified breakfast cereal¹</td>
<td>15 g (0.5 c)</td>
<td>3.0 µg</td>
</tr>
<tr>
<td></td>
<td>Yogurt</td>
<td>244 g (1 c)</td>
<td>1.2 µg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Egg</td>
<td>11 g</td>
<td>0.4 µg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc, 8–11 mg</td>
<td>—</td>
<td></td>
<td></td>
<td>Fortified breakfast cereal¹</td>
<td>15 g (0.5 c)</td>
<td>7.5 µg</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pumpkin seeds</td>
<td>28 g (1 oz)</td>
<td>2.2 µg</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tofu, tempeh³</td>
<td>100 g (3.5 oz)</td>
<td>1.6 µg</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nuts</td>
<td>28 g (1 oz)</td>
<td>1.3 µg</td>
</tr>
<tr>
<td>Protein, 46–56 g</td>
<td>Yogurt</td>
<td>244 g (1 c)</td>
<td>11.2 g</td>
<td>Dried beans, peas, cooked</td>
<td>89 g (0.5 c)</td>
<td>7.7 g</td>
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<td>Milk</td>
<td>244 g (1 c)</td>
<td>8.1 g</td>
<td>Soy milk</td>
<td>245 g (1 c)</td>
<td>6.3 g</td>
</tr>
<tr>
<td></td>
<td>Egg</td>
<td>11 g</td>
<td>6.3 g</td>
<td>Tofu, tempeh³</td>
<td>100 g (3.5 oz)</td>
<td>15–18 g</td>
</tr>
<tr>
<td></td>
<td>Cheese</td>
<td>28 g (1 oz)</td>
<td>6.6 g</td>
<td>Nuts</td>
<td>28 g (1 oz)</td>
<td>4.4 g</td>
</tr>
<tr>
<td>n-3 Fatty acids, 1.1–1.6 g</td>
<td>—</td>
<td></td>
<td></td>
<td>Walnuts</td>
<td>28 g (1 oz)</td>
<td>2.6 g</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Walnut oil</td>
<td>14 g (1 Tb)</td>
<td>1.4 g</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Flaxseeds/flaxseed oil</td>
<td>14 g (1 Tb)</td>
<td>2.4 g</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Canola oil</td>
<td>14 g (1 Tb)</td>
<td>7.2 g</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14 g (1 Tb)</td>
<td>1.3 g</td>
</tr>
</tbody>
</table>

¹AI, Adequate Intake; c, cup; oz, ounce; RDA, Recommended Dietary Allowance; Tb, tablespoon.
²From the USDA National Nutrient Database for Standard Reference, Release 26 (12).
³Content from cereal with 100% of the daily value for added zinc.
⁴Content from cooked spinach.
⁵Sunlight exposure is a good source of vitamin D, depending on latitude and season.
⁶Content from cooked portabella mushrooms; UV-exposed mushrooms are usually labeled.
⁷Lactoovovegetarian foods are not good sources of zinc or of n-3 fatty acids.
⁸Zinc in fermented products (tempeh, miso) is more bioavailable.
supplementation may not be sufficient to prevent fracture risk and emphasize the importance of a diet with adequate calcium.

Studies of dietary calcium intake support its importance for bone status and fracture prevention. An NHANES III follow-up analysis found twice the fracture risk among women ≥50 y of age who recalled low milk intake during childhood and adolescence (19). Women with baseline calcium intakes <525 compared with ≥1200 mg/d had a 75% higher fracture risk in the United Kingdom (20). Intervention studies with food have shown benefit; when dairy foods were added to the diets of postmenopausal women to raise calcium intake from 900 to 1500 mg (22.5–37.5 mmol)/d, the intervention group had significantly lower bone loss relative to controls (21); in another study, 3 servings of yogurt/d showed a significant reduction in urinary excretion of bone turnover markers in older women (22).

Calcium in foods such as milk and yogurt may be used more effectively than supplements because it comes packaged with other important nutrients that work together, including vitamin D, protein, potassium, and magnesium. These foods may be used by lactoovovegetarians in even higher amounts than by non-vegetarians, thereby offering protection for bone status. However, among vegans not using dairy foods, low calcium intakes are a key area of concern. Although several vegetables contain calcium, including leafy green vegetables and legumes, the calcium from these sources is not very bioavailable. Vegan populations may obtain calcium from tofu, fortified soy products, or fortified orange juice, but careful attention is required to ensure adequacy.

**VITAMIN D**

After calcium, vitamin D (cholecalciferol) is the next most well-known nutrient to protect bone health. Activated vitamin D [1,25(OH)₂D (calcitriol)] enhances mineralization and bone formation (23). Vitamin D is obtained from the diet as cholecalciferol (vitamin D₃) from animal sources (mainly from fatty fish, egg yolk, and fortified milk) and to a much lesser extent as ergocalciferol (vitamin D₂) from plant sources (notably mushrooms that have been exposed to UV light) (24). Most vegan diets contain very little vitamin D. Importantly, vitamin D₃ is also synthesized cutaneously from 7-dehydrocholesterol with sunlight (UVB) exposure. However, synthesis is low in the winter season in upper latitudes, and sun exposure has been increasingly limited with widespread use of air conditioning and sunscreens, making food sources an important consideration.

A 2007 systematic review (25) of circulating 25-hydroxyvitamin D [25(OH)D] concentration with bone health outcomes concluded that the evidence showed inverse associations between serum 25(OH)D and serum parathyroid hormone, BMD, and change in BMD, but that the evidence remained inconsistent with respect to fracture. Consequently, the subsequently published prospective National Osteoporosis Risk Assessment Study in 76,507 postmenopausal women found that vitamin D intakes >600 IU (15 μg) compared with <200 IU (5 μg) were associated with 27% lower odds of osteoporosis (95% CI: 0.66, 0.81) but not with 3-y fracture risk (26). However, several other studies showed associations between vitamin D and fracture. In one US study, elderly women with 1,25(OH)₂D ≥ 23 pg/mL (60 pmol/L) compared with those with higher concentrations had twice the risk of hip fracture over 4 y (27); in the NHANES III follow-up in elderly adults, serum 25(OH)D concentrations ≥24 ng/mL (60 nmol/L) compared with lower concentrations were associated with a 36% lower risk of hip fracture, as identified with Medicare records (28); and in the Netherlands, serum 25(OH)D concentrations ≤12 ng/mL (30 nmol/L) compared with higher concentrations were associated with 3 times the fracture risk over 6 y of follow-up (29).

Although vitamin D status is clearly important, the role of dietary intake has been less clear, given the availability of sun exposure to make vitamin D. Several studies showed that dietary intake of vitamin D was associated with serum vitamin D status and with bone health. For example, in an 18-y prospective analysis in 72,337 postmenopausal women, intakes of ≥500 IU vitamin D (12.5 μg)/d compared with <140 IU vitamin D (3.5 μg)/d were associated with a 37% lower risk of hip fracture (30). The results of clinical trials of vitamin D supplementation have been mixed. However, a recent meta-analyses of 12 trials in elderly adults for nonvertebral fracture and 8 trials for hip fracture concluded that doses >400 IU (10 μg)/d resulted in an 18% reduction in hip fracture and a 20% reduction in nonvertebral fracture (31).

With large proportions of the population showing low vitamin D status, and vegetarians at greater risk of low vitamin D, it is important to focus on adequate intake. Although lactoovovegetarians may obtain vitamin D from fortified milk and egg yolk, vegans need to be especially careful to include vitamin D sources in their diet. Many soy products as well as orange juice and breakfast cereals are now fortified with vitamin D, and these may offer protection against deficiency. Regular exposure to sunlight for 10 min before applying sunscreen is helpful. However, those with low sun exposure and limited dietary sources as well as older adults, who have lower efficiency vitamin D production in the skin (32), may want to consider the use of vitamin D supplements, particularly in winter months in northern latitudes.

**VITAMIN B-12**

Vitamin B-12 is a known high-risk nutrient for vegetarians, because it is available almost exclusively from animal products. It is less well known that it is important for protecting bone status. A recent meta-analysis in 7475 individuals in 4 prospective studies showed a 4% lower fracture risk for each 50-pmol/L increase in vitamin B-12 concentration (RR: 0.96, 95% CI: 0.92, 1.00) (33). Among older adults in the Framingham Osteoporosis Study, plasma vitamin B-12 concentrations <200 pg/mL (148 pmol/L) compared with higher concentrations were significantly associated with lower BMD (34). In NHANES III participants, BMD was lower and osteoporosis significantly more likely (P < 0.01) with increasing serum methylmalonic acid (MMA), a functional indicator of vitamin B-12 inadequacy; and serum vitamin B-12 was associated with BMD, in a dose-response manner, up to ~200 pmol/L. Furthermore, osteoporosis or osteopenia was twice as prevalent among participants with serum vitamin B-12 concentrations less than the 25th percentile than among those with serum vitamin B-12 above this cutoff (95% CI: 1.0, 3.9) (35). In the Netherlands, the prevalence of osteoporosis was reported to be almost 7 times higher in women with serum vitamin B-12 concentrations <285 pg/mL (210 pmol/L) compared with those with concentrations ≥343 pg/mL (320 pmol/L) (36). Longitudinally, a 42-mo study in US elderly women showed...
cysteine significantly lower BMD than did subjects with serum homocysteine, which has been independently associated with bone status, low vitamin B-12 may lead to an elevation in homocysteine concentration. One study, specifically among vegetarians, showed that low vitamin B-12 concentration was associated with greater bone remodeling, which may accelerate bone loss.

In addition to likely direct effects of vitamin B-12 on bone status, low vitamin B-12 may lead to an elevation in homocysteine, which has been independently associated with fracture risk, possibly by weakening collagen crosslinking. A meta-analysis in 11,511 individuals in 8 studies showed a 4% greater fracture risk for each μmol/L increase in homocysteine concentration (RR: 1.04; 95% CI: 1.02, 1.07). In the Framingham Osteoporosis Study, age-adjusted incidence rates for fracture in the highest quartile of homocysteine compared with the lowest quartile were approximately twice as high for women and 4 times as high for men (39). The NHANES III study also found that individuals with serum homocysteine ≥20 μmol/L had significantly lower BMD than did subjects with serum homocysteine <10 μmol/L (35).

Vegetarians have been shown to have lower vitamin B-12 and higher homocysteine concentrations relative to nonvegetarians (40). A European study that directly compared lactoovovegetarians and vegans with omnivores found that the prevalence of low vitamin B-12 status (holotranscobalamin II <35 pmol/L) was 11% in omnivores, 77% in lactoovovegetarians, and 92% in vegans. Similarly, elevated MMA was observed in 5% of omnivores, 68% of lactoovovegetarians, and 83% of vegans; and high homocysteine was observed in 16% of omnivores, 38% of lactoovo vegetarians, and 67% of vegans (41). It is therefore clear that ensuring adequacy of vitamin B-12 is of paramount importance for vegetarians. Nonanimal sources of vitamin B-12 include fortified breakfast cereals, nutritional yeast, and vitamin B-12–fortified soy products. Because vitamin B-12 deficiency is highly prevalent among vegetarians, it is recommended that serum vitamin B-12 concentrations be checked periodically, with follow-up testing for MMA if serum vitamin B-12 is <258 pg/mL (350 pg/mL) (42). However, even without testing, vegans may be advised to take vitamin B-12 supplements to ensure adequacy.

ZINC

Another mineral associated with meat intake, and which is frequently inadequate in vegetarian diets, is zinc (43). Lower serum and bone zinc have been noted in patients with osteoporosis (44). In a 2-y controlled trial, postmenopausal women randomly assigned to treatment with calcium plus copper and zinc compared with calcium plus corn starch, with usual daily zinc intakes <8.0 mg, benefited from the copper and zinc supplements (45). Although zinc is found in nuts, beans, and whole grains, the phytate in these foods makes it less bioavailable than it is from animal-based sources. Higher total zinc intakes may be needed from these foods than from animal products to meet requirements. The Food and Nutrition Board recommends at least 50% more zinc for those who obtain it from vegetarian sources (46). Soaking, heating, sprouting, fermenting, and leavening processes assist in limiting the effects of phytates on zinc availability, so foods such as tempeh and sourdough breads may be a good choice, as are practices such as soaking dried beans before cooking (47). Another source is fortified breakfast cereals. Consideration of zinc intake should be included in the review of any vegetarian diet.

PROTEIN

Protein has only recently been appreciated for its positive role in bone health, and protein intake can be compromised with some vegetarian diets. Because metabolic studies showed that high protein intakes lead to calcium losses, it has often been assumed protein has a negative effect on BMD (48). However, relatively recent epidemiologic studies showed that higher, not lower, protein intakes were associated with greater BMD and lower risk of fracture. In the Framingham Osteoporosis Study in older adults, for example, 4-y bone loss was lowest among those with the highest protein intakes (49) and those in the lowest quartile of protein intake had a significantly greater risk of hip fracture compared with those with higher protein intakes (50). Similarly, an inverse relation was observed for protein intake and risk of hip fracture in the Iowa Women’s Health Study (51). In contrast, no association between protein intake and hip fracture was identified in the Nurse’s Health Study (52).

The balance of animal to plant protein intake on bone status remains unclear, as does the possibility of conditional effects of protein intake on bone, depending on other nutrients. In one US study, dietary protein appeared to be most protective against bone loss only among those with high calcium intakes (17). The overall acid-base balance of the diet may also affect the response to protein, with better results in the presence of alkaline-forming foods. Adequate protein intake is clearly important for bone status, but more research is needed to understand possible interactions with other nutrients. Because vegetarian diets tend to be more base producing, whereas omnivorous diets are more acid producing, this may modify protein requirements in relation to effects on bone in vegetarians.

Finally, it is important to note that adequate protein intake is important for maintenance of muscle mass with aging, thereby protecting against falls and fracture beyond its direct effect on bone (53).

n–3 FATTY ACIDS

Fatty acids are important in numerous aspects of metabolism, and PUFA’s may influence bone health through several complex mechanisms, including effects on inflammatory cytokines (54, 55), modulation of prostaglandin E2 production (56, 57), and enhancement of calcium transport and retention (58, 59). Essential n–3 and n–6 fatty acids and their derivatives also act as ligands for peroxisome proliferator–activator receptors (60). These are involved in the differentiation of mesenchymal stem cells to adipocytes or osteoblasts (61–63). Lipoxins, synthesized from arachidonic acid, and resolvins, from EPA and DHA (64, 65), have anti-inflammatory effects that are thought to protect bone on the basis of animal studies (66–68). Whereas vegetarian diets tend to be high in n–6 fatty acids, the exclusion of fish diets means that many vegetarians have low intakes of n–3 fatty acids, particularly of DHA and EPA, which are the most biologically active forms. They may, however, obtain n–3 fatty acids from plant sources, such as α-linoleic acid (ALA), which is found in walnuts, flaxseeds, and canola oil.
In the Rancho Bernardo Study, higher intake ratios of n–6 to n–3 fatty acids were associated with lower hip BMD (69). In the Framingham Osteoporosis Study, ≥3 servings of fatty fish/wk were protective against 4-yr loss of femoral neck BMD (70), and dietary ALA was associated with lower risk of hip fracture (71). Existing studies of fatty acid intakes and fracture have reported contradictory findings (71–74). Supplementation with fish oil was shown to be protective in postmenopausal women (75, 76), but another study found no effect in women given fish oil and calcium compared with calcium alone for 12 mo (77).

More research is needed to better understand the effects of fatty acids on bone health. However, it is clear that n–3 fatty acids are important, and that they tend to be low in large segments of the population. Vegetarian sources of n–3 fatty acids include certain algae, walnuts, flaxseeds, canola oil, and avocado. Most vegetarian sources are in the form of ALA. Although ALA intakes have been shown to protect against hip fracture, it remains unclear which balance of long-chain fatty acids is optimal. ALA can be converted to EPA and DHA in the body, but this conversion is inefficient. Supplements from algae can provide direct sources of DHA.

**PROTECTIVE NUTRIENTS IN VEGETARIAN DIETS**

Although many nutrients, as discussed above, require particular attention for vegetarians to achieve adequacy and protection of bone health, good-quality vegetarian diets often include many healthful properties and may contain higher intakes of several important nutrients that also protect bone. These nutrients include magnesium, potassium, vitamin K, antioxidants including vitamins C and E and carotenoids, and anti-inflammatory phytonutrients in fruit, vegetables, nuts, beans, tea, and herbs.

Diets rich in nuts, legumes, and whole grains tend to be high in magnesium, which is low in the typical US diet (78). Magnesium enhances bone strength (79) and regulates active intestinal calcium transport. Several studies have documented protective effects of magnesium intake against bone loss (80–82), and serum magnesium concentrations have been shown to be significantly lower in women with osteoporosis than in those with normal BMD (83).

Diets high in fruit and vegetables are usually relatively high in potassium. Potassium promotes renal calcium retention and neutralizes dietary acid load, thereby protecting against calcium loss. In premenopausal women, a difference of 8% in femoral neck BMD was noted between the highest and lowest quartiles of potassium intake (84); in perimenopausal women, potassium intake was associated with greater BMD and lower bone resorption (85). In the Framingham Osteoporosis Study, potassium intake was associated with greater BMD in men and women at baseline and with lower BMD loss over time in men (80).

A vegetarian diet with high intakes of fruit and vegetables, including soy products, also tends to provide higher intakes of vitamin C, carotenoids, flavonoids, and other phytonutrients. These antioxidant and anti-inflammatory nutrients have recently been shown to protect bone. In the Framingham Osteoporosis Study, men with the highest tertile of vitamin C intake had significantly less loss of BMD over 4 yr relative to those with lower intakes (86). Consistently, men and women in the highest vitamin C intake tertile had a 44% lower risk of hip fracture relative to the lowest tertile (87). In the same cohort, carotenoids were also protective against 4-yr bone loss (88); and there was a 45% lower risk of hip fracture with the top tertile of total carotenoid intake compared with the lowest intake (89). In both studies, the strongest associations were seen for lycopene. A recent Australian study also found associations between lycopene and total body and lumbar spine bone status in both men and women (90), whereas a Japanese study showed associations with serum β-cryptoxanthin and radial BMD (91). Together, these data, along with the evidence for protective effects of magnesium and potassium, support protective effects of a healthy diet with abundant fruit and vegetables. Soy products contain phytoestrogens, which have also been associated with protection against bone loss but remain controversial. Evidence suggests that diets rich in phytoestrogens may protect bone, but the mechanisms of action have not been conclusively shown (92).

**CONCLUSIONS**

Vegetarian diets contain many beneficial properties. However, they can place individuals at risk of inadequate intakes for several nutrients important to bone health. Precisely how the protective factors interact with the potential shortfalls of a vegetarian diet remains unclear. However, studies that directly examine bone status and fracture outcomes suggest that the balance may leave vegetarians, and particularly vegans, at risk of bone loss and fracture. With careful selection, many of these nutrients may be obtained through food sources that include fortified products. In some cases, supplements may be advised to ensure adequacy. With attention to these considerations, good-quality vegetarian diets can provide a healthy foundation for building and maintaining healthy bones and for preventing fracture.

The author had no conflicts of interest to report.

**REFERENCES**


