Choices for achieving adequate dietary calcium with a vegetarian diet[1–3]

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ABSTRACT To achieve adequate dietary calcium intake, several choices are available that accommodate a variety of lifestyles and tastes. Liberal consumption of dairy products in the diet is the approach of most Americans. Some plants provide absorbable calcium, but the quantity of vegetables required to reach sufficient calcium intake make an exclusively plant-based diet impractical for most individuals unless fortified foods or supplements are included. Also, dietary constituents that decrease calcium retention, such as salt, protein, and caffeine, can be high in the vegetarian diet. Although it is possible to obtain calcium balance from a plant-based diet in a Western lifestyle, it may be more convenient to achieve calcium balance by increasing calcium consumption than by limiting other dietary factors. *Am J Clin Nutr* 1999;70(suppl):543S–8S.

KEY WORDS Calcium requirements, calcium bioavailability, salt, protein, vegetarian diet, sulfur-containing amino acids, caffeine

INTRODUCTION

Adequate dietary calcium is a prerequisite for maximizing peak bone mass during the first 3 decades of life and for minimizing subsequent bone loss. The strategy for reducing the risk of osteoporosis requires weight-bearing exercise and adequate sex steroid hormones in addition to good nutrition. Although many nutrients are important to bone health, calcium requires the most attention because it is the nutrient most likely to be deficient.

Recommended calcium intakes, as determined by the Institute of Medicine, are shown in **Table 1** (1). According to data collected between 1988 and 1991 on 14 801 individuals as part of the third National Health and Nutrition Examination Survey (NHANES III), Phase 1, American females > 12 y of age do not meet these recommended intakes (2). Adolescent girls consume only 68% of the 1989 recommended dietary allowance (RDA) of 1200 mg Ca/d. Men consumed more calcium than women in all phases of the life cycle and the calcium intake of African Americans was lower than that of Mexican Americans and non-Hispanic whites. Calcium intakes did not generally differ between vegetarians and nonvegetarians (3); however, dietary calcium intakes of vegans have not been well characterized.

Meeting calcium needs can be accomplished in a variety of ways. The composition of the diet can influence the amount of dietary calcium required by altering the absorption and retention of calcium. In this review, the choice of the calcium food source and the influence of salt, protein, and caffeine on calcium retention, and ultimately calcium requirements, are discussed.

CALCIUM SOURCES

Calcium can be obtained from foods that are naturally rich in calcium, from fortified foods and beverages, from supplements, or from a combination of these sources. Calcium sources should be evaluated on the basis of both content and bioavailability of calcium. A comparison of absorbable calcium per serving relative to milk is shown in **Table 2**. Previously, we reported the absorbable calcium per serving of a variety of low-oxalate plant sources and a few high-oxalate plant foods (eg, spinach and beans) (3). Since that report, we have studied additional oxalate-rich foods and vegetables commonly consumed in China (9) as well as several dairy products (12). About 75% of the calcium in the American diet is from dairy products. Calcium absorption from milk is similar to that from other dairy products (12) even though the lactose content and the chemical form of calcium in cheese or yogurt is altered during processing. Few other foods contain calcium naturally in amounts similar to milk.

Calcium bioavailability from plant foods can be affected by their contents of oxalate and phytate, which are inhibitors of calcium absorption content. This may explain why dairy calcium was more significantly correlated with bone mass than was nondairy calcium in 835 Chinese women (13). In general, calcium absorption is inversely proportional to the oxalic acid content of the food. Thus, calcium bioavailability is low from both American and Chinese varieties of spinach and rhubarb, intermediate from sweet potatoes, and high from low-oxalate vegetables such as kale, broccoli, and bok choy. A notable exception to this generalization is soybeans. Soybeans are rich in both oxalate and phytate, yet soy products have relatively high calcium bioavailability. In contrast, common dried beans, which are also

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TABLE 1
Daily reference intake values for calcium by life-stage group for the United States and Canada[1]

Life-stage group	Daily reference intake
	mg/d
Age	
0–6 mo	210
6–12 mo	270
1–3 y	500
4–8 y	800
9–13 y	1300
14–18 y	1300
19–30 y	1000
31–50 y	1000
51–70 y	1200
>70 y	1200
Pregnancy	
≤18 y	1300
19–50 y	1000
Lactation	
≤18 y	1300
19–50 y	1000

[1] From reference 1.

rich in phytate, have substantially lower calcium bioavailability (7). Chinese vegetables (except for Chinese spinach) and calcium-set tofu are unusually rich sources of bioavailable calcium. However, it is possible that the calcium contents of the Chinese vegetables listed in Table 2, which were measured in hydroponically grown plants, is higher than that of the average, field-grown counterparts because calcium from the nutrient solution in our hydroponic system is readily available for plant uptake. For other vegetables listed in Table 2, calcium content of commercial sources was used rather than the values for hydroponically grown vegetables. Unfortunately, neither commercial sources of the Chinese vegetables listed in Table 2 nor their calcium values are available to us. The availability of calcium for plant uptake from soil also varies greatly. Treatment with lime or bone meal can increase the calcium content of soils.

The high bioavailability of calcium from low-oxalate vegetables relative to milk suggests 2 things. First, the fibers in the vegetables do not inhibit calcium absorption. This has been confirmed with purified fibers (14). Second, low-oxalate vegetables may contain calcium absorption enhancers that have not yet been identified.

The low calcium content of common plant sources including most vegetables, fruit and cereal grains, makes it difficult for most Americans to meet their requirements exclusively from these foods, even when the bioavailability of calcium from these sources is high and the larger serving sizes consumed by many vegetarians are taken into account. Therefore, it is prudent for individuals who choose not to eat dairy products to include calcium-fortified foods or supplements in their diet, with the possible exception of those rare individuals who carefully plan their diet around plant foods. The calcium salts used to fortify foods or as supplements are usually selected because of functionality. Calcium salts, regardless of solubility, have fractional calcium absorption values similar that of milk, with the exception of calcium citrate malate, from which absorption is slightly higher (15). Thus, each 300 mg Ca provided by supplements or fortified beverages would provide about the same amount of absorbable calcium as 1 glass (240 mL) of milk. Approximately one-fourth of American women, 14% of American men, and only 7.5% of children aged 2–6 y take supplements containing calcium, providing median intake of 248, 160, and 88 mg/d, respectively (16). If calcium supplements are substituted for dairy products to meet calcium needs, attention to other nutrients may be needed because low calcium intakes have been associated with low intakes of magnesium and several vitamins, including riboflavin, B-6, B-12, and thiamin (17).

REDUCING DIETARY SALT VERSUS INCREASING DIETARY CALCIUM

Urinary calcium losses account for 50% of the variability in calcium retention (18). Of the nutritional factors thought to influence urinary calcium losses (protein, caffeine, and sodium intake), sodium appears to be the most important factor. Because sodium and calcium share some of the same transport systems in the proximal tubule, each 2300 mg Na excreted by the kidney pulls 40–60 mg Ca out with it (19). For example, Shortt et al (20) studied the relation between dietary sodium intake assessed by 24-h sodium excretion and urinary calcium excretion in 62 white women aged 19–60 y. Linear regression analysis showed that for each 1-g Na excreted, 26.3 mg Ca/d was lost in the urine. Thus, in adult women, 1 g of extra sodium would result in an additional rate of bone loss of 1%/y if the calcium lost in the urine came from the skeleton. Sodium intake was also found to be one of the major determinants of urinary calcium excretion in adolescent girls, whereas calcium intake itself was only poorly correlated with urinary calcium (21). Only 3% of the variance in urinary calcium excretion could be explained by calcium intake. The relation between urinary sodium and urinary calcium excretion remained significant in multivariate analyses after controlling for sex, age, body weight, and protein, calcium, and phosphorus intakes in 20–79-y-old women (22). In one case report, a 50-y-old woman with excessive salt consumption who was suffering from compression fractures of the vertebrae excreted 304 mg Ca/d in the urine while consuming 800 mg Ca/d (23). When prescribed a low-sodium diet and a 1-g/d Ca supplement, urinary calcium fell to 113 mg/d. Thus, the interplay of dietary calcium and sodium may be important to bone health.

Several intervention studies with partially controlled sodium intakes have been reported. Salt supplements of 1.17 and 2.34 g/d, consumed by 17 postmenopausal women for 4-d periods in addition to their usual diets, increased urinary calcium loss ($P < 0.05$; 24). The authors speculated that the calcium losses observed with the 2 sodium intakes, if maintained for the long term, could mobilize 7.5% and 10% of calcium stores over a period of 10 y. Clearly, this would create a major risk for osteoporosis. Supplements of 4.6 g Na/d for 4 d in men aged 21–24 y resulted in excretion increases of 68 mg Ca/d and a 27% increase in urinary hydroxyproline, suggesting increased bone resorption (25). However, urinary parathyroid hormone concentrations were unaffected. In another study, 12 young adults were asked to restrict high-salt foods for 3 d and then consume various amounts of salty foods or salt tablets for 3 d each (20). Calcium-rich foods were limited but the diets were not controlled. Twenty-four–hour urinary sodium and calcium excretions correlated positively in both female (r = 0.80, P = 0.001) and male (r = 0.44, $P < 0.05$) subjects. In a crossover, controlled diet study in men, the effect of 2 sodium supplements

TABLE 2
Comparison of sources of absorbable calcium with milk

Food	Serving size[1]	Calcium content[2]	Fractional absorption[3]	Estimated absorbable calcium[4]	Servings needed to equal 240 mL milk
	g	*mg*	*%*	*mg*	*n*
Milk	240	300	32.1	96.3	1.0
Beans					
Pinto	86	44.7	26.7	11.9	8.1
Red	172	40.5	24.4	9.9	9.7
White	110	113	21.8	24.7	3.9
Bok choy	85	79	53.8	42.5	2.3
Broccoli	71	35	61.3	21.5	4.5
Cheddar cheese	42	303	32.1	97.2	1.0
Cheese food	42	241	32.1	77.4	1.2
Chinese cabbage flower leaves	85	239	39.6	94.7	1.0
Chinese mustard greens	85	212	40.2	85.3	1.1
Chinese spinach	85	347	8.36	29	3.3
Fruit punch with calcium citrate malate	240	300	52.0	156	0.62
Kale	85	61	49.3	30.1	3.2
Spinach	85	115	5.1	5.9	16.3
Sweet potatoes	164	44	22.2	9.8	9.8
Rhubarb	120	174	8.54	10.1	9.5
Tofu with calcium	126	258	31.0	80.0	1.2
Yogurt	240	300	32.1	96.3	1.0

[1] Based on half-cup serving size (≈85 g for green leafy vegetables) except for milk and fruit punch (1 cup or 240 mL) and cheese (1.5 oz).

[2] From references 4 and 5 (averaged for beans and broccoli processed in different ways) except for the Chinese vegetables, which were analyzed in our laboratory.

[3] Adjusted for load by using the equation for milk [fractional absorption = 0.889 − 0.0964 ln load (6)] then adjusted for the ratio of calcium absorption of the test food relative to milk tested at the same load, the absorptive index. The absorptive index was taken from the literature for beans (7), bok choy (8), broccoli (8), Chinese vegetables (9), fruit punch with calcium citrate malate (10), kale (8), sweet potatoes (9), rhubarb (9), tofu (11), and dairy products (12).

[4] Calculated as calcium content × fractional absorption.

(0.506 and 4.094 g) for 2-wk periods on subjects with either low (≈1554 mg) or high (≈1876 mg) daily calcium intakes were studied (26). Although this was a small sample size ($n = 3$ per group), sodium intake significantly affected urinary calcium ($P < 0.05$).

A longitudinal study in postmenopausal women showed a negative correlation between urinary sodium excretion and bone density of the hip. Because no bone loss occurred at the total hip with an intake of 1768 mg Ca/d or with a urinary excretion of 2110 mg Na/d, it was suggested that bone loss could have been prevented by either a dietary increase of 891 mg Ca/d or by halving the daily sodium excretion (27). Because neither of these diets is common, it may be more realistic for some to reduce their sodium intake by a modest amount and increase their calcium intake by a modest amount (eg, 1198 mg Ca/d and 2.3 g Na/d) than to focus on either nutrient exclusively.

REDUCING DIETARY PROTEIN VERSUS INCREASING DIETARY CALCIUM

The effect of dietary protein on calcium balance is a well-documented phenomenon. As the intake of dietary protein increases, the urinary excretion of calcium increases as a result of decreased fractional tubular reabsorption, such that doubling protein intake results in a 50% increase in urinary calcium excretion (28). As a result, recommended intakes of dietary calcium are influenced by the protein intake of the population for which they are set. This largely explains why recommended calcium intakes for the US population are higher than those for populations in other, less-industrialized nations. By using urinary calcium values for known protein intakes from Zemel (29), dietary calcium intakes required to offset protein-induced urinary calcium losses were calculated (**Table 3**). Each additional gram of dietary protein results in an additional loss of ≥1.75 mg Ca/d. With an average absorption efficiency of 30%, this requires an additional 5.83 mg dietary Ca/d to offset the loss. When protein that is high in phosphorus is ingested, as is the case for meat, cereals, beans, and dairy products, the hypercalciuric effect of protein is offset by the hypocalciuric effect of phosphorus (28). However, increasing phosphorus increases endogenous fecal calcium to about the same extent as does decreasing urinary calcium. Thus, the effect of protein on altering calcium requirements is similar whether the loss occurs through the urine or feces.

The specific amino acid profile—especially of amino acids containing sulfur—determines the calciuretic effect of protein (29). Sulfate generated from the metabolism of these amino acids increases the acidity of the urine, causing greater amounts of calcium to be excreted in the urine. The proteins of many plants, especially legumes, have lower amounts of methionine and cysteine than do animal proteins. Young and Pallett (30) summarized the amino acid content of various protein sources based on data from the Food and Agriculture Organization and the US Department of Agriculture (**Table 4**). The concentration of sulfur-containing amino acids in cereals is similar to that in animal foods, whereas nuts and seeds have the highest concentration at 46 mg/g protein. Using US Department of Agriculture food-consumption data, Young and Pellett (30) calculated the

TABLE 3
Calcium intakes required to offset urinary losses in adults consuming various amounts of dietary protein

Protein intake	Urinary calcium loss[1]	Required dietary calcium intake[2]
g/d	*mmol/d*	*mg/d*
48	4.2	970
54	4.4	1006
60	4.7	1043
66	5	1079
72	5.3	1112
78	5.5	1149
84	5.8	1185
90	6	1219
96	6.3	1255

[1] When protein sources are rich in phosphorus, the calcium loss is shifted from urine to feces (28). Urinary calcium values per protein load were obtained from data provided in reference 29. These values, corresponding to a range in protein intakes, were determined by using an intake of 500 mg Ca/d. At the high calcium intakes suggested here, the associated absorptive hypercalcemia would result in additional calcium loss in the urine, which is not accounted for in this table.

[2] Intakes were calculated by assuming that intake of all other nutrients is constant, endogenous secretion is 120 mg Ca/d, and absorption of calcium is 30%. Because fractional absorption decreases with calcium load, absorption efficiency would actually decrease from ≈33.2% to 30.4% from the highest to lowest suggested calcium intakes, assuming loads equivalent to one-third of the calcium are ingested at each of 3 meals.

average intakes of protein and amino acids of US females of various ages. US females between the ages of 35 and 50 y consumed an average of 65 g protein/d. Intake of sulfur-containing amino acids remained constant at 34–35 mg/g protein after age 6 y.

Several studies have evaluated the protein and amino acid intake of vegetarians. Vegetarians consistently consume less protein than do their omnivorous counterparts, but in some studies this difference was not substantial. Hardinge et al (31) completed nutritional studies on 86 lactoovovegetarians, 26 vegans, and 88 nonvegetarians. Protein intakes among the lactoovovegetarian females were found to be 81.3 compared with 63.2 g/d in vegans and 93.1 g/d in nonvegetarians. Intakes of sulfur-containing amino acids by the female lactoovovegetarians, vegans, and nonvegetarians averaged 31.9, 36.4, and 34.7 mg/g protein, respectively. Register and Sonnenberg (32) calculated the nutrient composition of a 1-d vegetarian menu to show the ability of the diet to meet protein requirements. The 1-d lactoovovegetarian menu contained 78 g protein and the vegan menu contained 75 g protein, showing that both types of vegetarian diets could easily exceed recommended protein intakes. The sulfur-containing amino acid contents of the 1-d menus were similar at 32.17 mg/g protein for the lactoovovegetarian menu and 31.2 mg/g protein for the vegan menu.

Berkelhammer et al (33) and Sebastian et al (34) showed that substituting organic anions (acetate and bicarbonate, respectively) for chloride decreases urinary calcium loss markedly. Although sulfate is a significant contributor to the acid load of a meat-based diet, it is obviously not the only contributor. Therefore, the vegetarian diet tends to have an alkaline ash residue, despite the presence of sulfur-containing amino acids, that would be predicted to produce lower urinary calcium losses. However, following a vegetarian diet does not guarantee that urinary calcium will be lower than that of omnivores. Kunkel and Beauchene (35) studied the protein intake and urinary excretion of protein metabolites of 125 vegetarian and nonvegetarian women. Although the total protein intake of the vegetarians was significantly lower than that of the nonvegetarians (53.6 and 66.5 g/d, respectively) and significant differences in the intake of animal and plant protein existed between the 2 groups, the excretion of sulfate in the urine was not significantly different between the 2 groups. Therefore, some vegetarians may be living under a false sense of security with regard to their calcium balance if their protein intakes are similar to those of nonvegetarians or if their diet provides a significant sulfur-containing amino acid load. Additional research is needed to understand the quantitative relation between the sulfur-containing amino acid content in the diet, whether from plant or animal sources, and urinary calcium.

Two strategies exist for minimizing the impact of dietary protein on calcium balance while consuming a plant-based diet. The first is to consume a diet with a low protein content, a low sulfur-containing amino acid content, or both. This would effectively decrease protein-induced urinary loss of calcium and lower an individual's calcium requirement. Compliance with this approach could be difficult because cereals, nuts, seeds, and other plant foods with significant amounts of sulfur-containing amino acids would have to be restricted, which would affect the selection and variety in the vegetarian diet. The second strategy is to consume liberal amounts of dietary calcium. The reasoning is that as calcium intake increases, the calciuretic effect of protein becomes less of a concern because total calcium absorption increases at higher intakes, offsetting losses from urinary excretion. Therefore, rather than creating a lower calcium requirement by limiting protein and sulfur-containing amino acid intakes, the aim is to increase calcium consumption to offset higher intakes of protein. Consequently, the diet is less restrictive, allowing more food choices and variety, and may increase compliance. Which of these approaches to take is a matter of individual choice.

Heaney (28) recommended that the calcium-to-protein ratio of the diet be used as an evaluation of adequate calcium intake. According to data from NHANES II, most women consume diets with calcium-to-protein ratios of 9:1, which is well below the ratio of 16:1 that would be achieved by a woman consuming the current recommended dietary allowances for protein and calcium. Calcium-to-protein ratios calculated from estimated nutrient intakes of lactoovovegetarians typically exceed those of the general population (**Table 5**). Despite the lower protein intake with the vegan diet, consuming a diet free of animal products often creates protein-to-calcium ratios similar to and often lower than those of the general population. Other factors, such as the

TABLE 4
Amounts of sulfur-containing amino acids in various protein sources[1]

Food source	Amount
	mg/g
Legumes	25
Fruit	38
Cereals	28
Animal foods	39
Nuts and seeds	46

[1] From reference 30.

TABLE 5
Protein and calcium intakes of female lactoovovegetarians and omnivores[1]

Study	Lactoovovegetarians			Omnivores		
	Calcium	Protein	Ca:Pro	Calcium	Protein	Ca:Pro
	mg/d	*g/d*		*mg/d*	*g/d*	
Tylvasky and Anderson (36) (n = 20)	898	56.0	16.0	712	68.0	10.5
Tesar et al (37) (n = 366)	823 ± 44[2]	54.6 ± 2.1	15.1	902 ± 21	69.9 ± 1.1	12.9
Marsh et al (38) (n = 28)	820.7 ± 351	62.6 ± 23.7	13.1	863 ± 199	76.5 ± 20.0	11.3
Janelle and Barr (39) (n = 37)	875 ± 255	57.1 ± 10.8	15.3	950 ± 437	77.1 ± 19.7	12.3
Nieman et al (40) (n = 37)	628 ± 328	46.8 ± 3.0	13.4	633 ± 73	55.0 ± 3.1	11.5
Shultz and Leklem (41) (n = 37)	782 ± 311	60.0 ± 14	13.0	841 ± 246	62.0 ± 10	13.6

[1] Ca:Pro, calcium-to-protein ratio.
[2] $\bar{x}$ ± SD.

phytate and oxalate contents of the vegan diet, reduce the bioavailability of the limited calcium consumed. Therefore, as researchers continue to try to understand the effect of plant protein on calcium balance, the lactoovovegetarian diet, when evaluated on the basis of its calcium-to-protein ratio, appears to be the safest approach to minimizing protein-induced calcium losses and maximizing calcium balance.

REDUCING DIETARY CAFFEINE VERSUS INCREASING DIETARY CALCIUM

Although caffeine consumed in high amounts acutely increases urinary calcium (42), the effect on 24-h urinary calcium is negligible (43). The study by Berger-Lux et al (43) was a well-designed double-blind, placebo-controlled trial, in contrast with other reports that estimated caffeine consumption from food-composition tables. The amount of caffeine in a cup of coffee varies enormously with the method of preparation and strength of the brew. On average, a cup (240 mL) of coffee decreases calcium retention by only 2–3 mg. Thus, even heavy consumption of caffeine has a modest effect on calcium loss for most people.

CONCLUSIONS

Consumption of adequate dietary calcium can be accomplished within a variety of tastes and lifestyle choices. For most individuals in a Western culture, liberal consumption of dairy products is the easiest approach and is the least restrictive with regard to consumption of protein, salt, or caffeine. On the other hand, those who choose to meet their calcium needs completely from plant sources need to be aware of not only the calcium content of plants but also the bioavailability of the calcium because other plant constituents can impede calcium absorption. Also, depending on the protein and sodium content of the vegetarian diet, the calciuretic effect of a plant-based diet may not differ significantly from that of an omnivorous diet. It is important for those consuming diets free of animal products and others who avoid dairy products to adjust the protein and sodium content of their diets to maximize bone mass or to use calcium-fortified foods or supplements. Because several approaches exist for meeting calcium needs, it is the responsibility of all caregivers and institutions who feed individuals to provide dairy and dairy-free calcium-rich choices to accommodate the various lifestyles of their patients.

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