



Physical Activity, Nutrition and Bone Health

Healthy bones form the foundation for a vital, energetic life. Our skeletons confer mobility, flexibility, and mechanical support and serve as a calcium reservoir, which the body draws upon to help maintain consistent levels of calcium in the blood.

Building and maintaining healthy bones throughout life require an intricate interplay among several physiological and lifestyle factors. This review looks at the state of bone health among the U.S. population today and the latest scientific research regarding the relationships among physical activity, nutrition, and healthy bones.

BONE BASICS

Bone Architecture

Although bones often are viewed as inert, they really are dynamic, living tissue. Bones are built primarily of a collagen protein framework, which makes them flexible, and mineralized calcium phosphate (hydroxyapatite), which makes them strong and rigid. This combination allows bones to withstand considerable mechanical stress (Heaney 1999).

Bones consist of two distinct layers: an outer compact layer (cortical bone) and an inner lattice-like layer (trabecular bone). Cortical bone predominates in long bone shafts such as the forearm, whereas trabecular bone predominates in vertebral bones (lumbar) and hipbones (Heaney 1999, pp. 1328, 1329; Institute of Medicine 1997).

Throughout life, bones undergo cycles of tear-down and repair. Osteoclast cells remove old bone (resorption), and osteoblast cells lay down new bone (formation). This modeling-remodeling process is regulated by factors such as nutritional status, sex hormone status, parathyroid hormone levels, and vitamin D status (Heaney 1999).

Perhaps the most critical life stages for ensuring bone health are childhood through young adulthood. During these times, bone formation outpaces bone loss, resulting in net bone accumulation. About 50 percent of peak bone mass accrues during adolescence. About 90 percent of a person's total bone mineral content is deposited by age 18, and 99 percent is deposited by age 22. Bone density slowly builds until around age 30, when peak bone mass is reached (Matkovic 1991).

Factors Affecting Bone Health

Listed below are several modifiable and non-modifiable factors that influence bone health (adapted from the National Institutes of Health [www.osteoporosis.org]).

Modifiable factors that promote bone health:

- Regular physical activity
- Sound eating habits
- Adequate calcium consumption
- Adequate vitamin D status

Modifiable factors that increase risk for bone loss:

- ❑ Cigarette smoking and alcohol abuse
- ❑ Medications such as some types of anticonvulsants or glucocorticoids (corticosteroids, prednisone, dexamethasone)
- ❑ Low levels of estrogen in women or low levels of testosterone in men

Non-modifiable factors that increase risk for bone loss:

- ❑ Gender. Women are at greater risk than men.
- ❑ Age. Bone loss increases with age.
- ❑ Body size. Small, thin women are more susceptible than larger women.
- ❑ Ethnicity and heredity. Caucasian and Asian women are at greatest risk. African American and Hispanic women have a lower but significant risk.
- ❑ Genetics. If a parent suffers from osteoporosis or an osteoporotic bone fracture, the children tend to have reduced bone mass and increased risk.

Osteoporosis – The Weakening of America’s Bones

Osteoporosis—or “porous bones”—is an epidemic in the United States. The shocking fact is that more than 28 million Americans—or 1 in 10 people—suffer from this debilitating disease. According to the World Health Organization, the hallmarks of osteoporosis are reduced bone mass and increased bone fragility and fracture risk (Institute of Medicine 1997, p. 83). The risk for osteoporotic fractures is inversely related to current bone density, which depends on peak bone mass at maturity and the subsequent rate of bone loss (Nordin 1997).

Although osteoporosis can occur at any age, it is most common in those over age 50. During adulthood, the rate of bone loss gradually starts to outstrip the rate of bone formation, resulting in net losses (www.osteo.org). The rate of bone loss is more rapid starting at about age 55, especially following menopause (Nordin 1997).

Osteoporosis is associated with more than 1.5 million fractures in the United States each year. It has devastating impacts on quality of life, public health, and health care costs and is deadlier than many people realize. One in two people who fracture a hip never resume their former lifestyle (Kulak and Bilezikian 1998), and one in three to one in four people who fracture a hip die within a

year. Direct health care costs attributable to osteoporosis are about \$14 billion annually (National Osteoporosis Foundation 2001) and are expected to reach more than \$60 billion by 2020 (Tucci 1998).

Among those with osteoporosis, approximately 80 percent are women and 20 percent are men (National Osteoporosis Foundation 2001). Women are more susceptible because they have less total bone mass (a smaller reservoir) and the rate of bone loss accelerates during menopause. After age 50, one in two women and one in eight men will suffer one or more osteoporotic fractures.

Osteoporosis is usually “invisible” until after the sixth decade of life. Many people unknowingly lose bone mass and remain symptom-free until their bones are so porous that even nontraumatic events and everyday activities cause painful and life-threatening hip fractures or vertebral collapse and kyphosis (“dowager’s hump”) (www.osteo.org; Heaney 1993).

Even though osteoporosis may have life-shattering consequences such as hip fractures, it receives relatively little attention from the public health community, especially considering that the risk of osteoporosis for women is equal to their combined risk for breast, ovarian, and uterine cancers (Institute of Medicine 1997).

Outlook for an Aging Population

The sheer fact that the U.S. population is living longer is fueling the osteoporosis epidemic. Life expectancy soared from 47 years in 1900 to 75 years in 1998 (Kerschner and Pegues 1998). Seventy million Americans will turn 65 by 2030, an unprecedented number of senior citizens. Within this group, the “oldest old” (age 85+) are the fastest-growing segment of the U.S. population—and also the segment at the greatest risk for bone fractures (U.S. Bureau of the Census 2001).

Among an aging population, several factors compound the risk for osteoporosis, including poor-quality diets, an inability to fully adapt to low calcium intakes, and low levels or a lack of female and male sex hormones (Ensrud et al. 2000). According to the Institute of Medicine, the incidence of hip fractures may triple by 2040 (Institute of Medicine 1997, p. 83).

Given the graying of America, the outlook for bone health will worsen unless strong preventive steps are taken. The U.S. Surgeon General’s public health blueprint for the decade—*Healthy People 2010*—aims to reduce the proportion of adults with

osteoporosis by 20 percent by 2010 (Healthy People 2010).

How is Bone Health Measured?

DEXA (dual-energy X-ray absorptiometry) instruments allow rapid, painless, noninvasive, and highly reproducible measurements of bone density to be made (Institute of Medicine 1997). Bone density measurements are used to diagnose osteoporosis, low bone density, and risk of fracture and to determine rates of bone loss or the effectiveness of treatment over time (National Osteoporosis Foundation 2001; Heaney 1999). Medicare now covers bone density tests for certain individuals (National Osteoporosis Foundation 2001).

MOVING THOSE BONES: PHYSICAL ACTIVITY AND BONE HEALTH

There is no question that regular physical activity is important, as noted in *Nutrition and Your Health: Dietary Guidelines for Americans* (U.S. Department of Agriculture and U.S. Department of Health and Human Services 2000) and other authoritative reports (CDC 2000, DHHS 1996).

The health benefits of physical activity extend to bones. Weight-bearing activities such as weight training, walking, running, aerobic dancing, tennis, and gymnastics improve bone health throughout life by enhancing peak bone mass and slowing bone loss (Institute of Medicine 1997; Weaver et al. 2000; Specker 1996; National Institutes of Health 2000). Physical activity also helps prevent fall-related fractures by improving muscle strength, body balance, and reaction time. Epidemiological evidence consistently shows that the risk of hip fracture decreases by 20 to 40 percent among physically active individuals compared with the risk for their sedentary counterparts (Gregg et al. 2000).

Research is being done on exactly how physical activity enhances bone health, the consistency and duration of the effect, the best types of activity, and the optimal duration and intensity of activity.

High-intensity weight training and vigorous aerobic exercise are associated with improved bone density, especially at the site of mechanical stress (Forwood and Burr 1993; Nelson et al. 1994; National Institutes of Health 2000). In contrast, newer studies conducted with children and elderly

women suggest that activity need not be intense to have a positive effect on bone health.

For example, prepubescent children who did simple jumping exercises three times a week for 7 months showed increased bone mineral contents in the lumbar spine and femoral neck compared with those in controls who did stretching exercises (Fuchs 2001). In a large 7-year multicenter study of 10,000 elderly women, as little as 1 hour of aerobic exercise, tennis, dance, or weight training per week was associated with a reduced risk of hip and vertebral fractures. Even less than 1 hour of lower-intensity activities such as gardening, walking, and social dancing per week lowered the risk for hip fracture. Sedentary women who sat at least 9 hours/day had a greater risk of hip fracture than those who sat for less than 6 hours/day (Gregg et al. 1998).

Couch Potato Patterns Set the Stage for Poor Bone Health

On average, Americans are woefully inactive. Although most adults know that physical activity is important (ADA 2000), 60 percent are not regularly active and 25 percent are not active at all (DHHS 1996).

Children are more active than adults, but physical activity declines dramatically as they enter adolescence, according to a recent CDC report from the Centers for Disease Control and Prevention to the President (CDC 2000):

- ❑ In 1999, 35 percent of students in the 9th to 12th grades did not routinely engage in vigorous physical activity. Levels of enrollment in physical education classes dropped from 79 percent among students in the 9th grade to 37 percent among students in the 12th grade.
- ❑ Children aged 5 to 15 walked and bicycled 40 percent less in 1995 than in 1977.
- ❑ Beginning as early as age 10, rates of participation in youth sports programs decline steadily through adolescence, reaching a low at ages 14 to 15.

Physical activity also is important for individuals already diagnosed with osteoporosis, but the purpose should be to improve flexibility and excessive or sudden strain on the bones should be avoided (National Osteoporosis Foundation 2001).

Among women, extremely high amounts of physical activity that induce amenorrhea (abnormal absence or suppression of menses) are detrimental to bone health and should be avoided (ACSM 1997; ACSM, ADA, and Dietitians of Canada 2001).

The Physical Activity and Calcium Connection

The interplay between physical activity and dietary calcium in bone health is potentially important. Comprehensive reviews show that physical activity positively affects bone density when calcium intake exceeds 1,000 milligrams per day (mg/d) (Specker 1996; Weaver et al. 2000). During extreme periods of inactivity, such as prolonged bed rest, bone loss occurs even when the level of calcium consumption is high (LeBlanc 1995). Additional research is needed to explore the connection between dietary calcium and physical activity on bone health.

DIET AND BONES – THEY ARE WHAT WE EAT

The way we eat can make or break the health of our bones.

The *Dietary Guidelines for Americans* and the

Food Guide Pyramid were developed with bone health in mind, so following the recommendations made in these sources helps ensure strong bones throughout life. However, the eating habits of few Americans measure up to this advice.

According to the Healthy Eating Index, a composite measure of overall diet quality based on the *Dietary Guidelines for Americans* and the *Food Guide Pyramid*, only 12 percent of the population consumes a “good” diet, with the biggest shortfalls occurring in the calcium-rich dairy group and the fruit group (Bowman et al. 1998).

Some eating patterns negatively affect the intake of nutrients that build bones. These include skipping meals; following very low calorie diets; skimping on calcium-rich foods, fruits, vegetables, and whole grains; or eating high-calorie foods with small amounts of nutrients at the expense of more nutritious foods. Many adults and children skip breakfast, which can compromise the adequate consumption of bone-building nutrients (Nicklas et al. 1993; Haines et al. 1996; Krebs-Smith et al. 1996; Subar et al. 1998). Because aged individuals consume less food, it is especially difficult for them to maintain high nutritional quality (Blumberg 1997).

Among the nutrients playing a role in bone health are calcium; phosphorus; magnesium; fluoride; vitamins D and K; macronutrients such as protein, carbohydrate, and fat; and other dietary constituents such as oxalates, phytates, fiber, sodium, and caffeine. These are discussed in the following sections.

MINERALS AND BONE HEALTH

CALCIUM

“We walk around on our calcium reserves,” stated one expert about calcium’s integral role in bone health (Heaney 1999).

Indeed that’s true when you consider that the body typically contains 900 to 1,500 grams (g) of calcium (Heaney 1999), with about 99 percent found in bones (Institute of Medicine 1997, p. 38; Nielsen 1999).

The benefit of dietary calcium on bone health, especially among adolescents and elderly women, is well established (Institute of Medicine 1997; Heaney 2000; Welten 1995; National Institutes of Health 1994, 2000). Calcium intakes below 1,000 mg/d are associated with lower peak bone mass (Weaver et al. 2000). Up to two-thirds of osteoporotic fractures are attributable to inadequate calcium intake (Heaney 1999). Recognizing calcium’s vital role in bone health, the U.S. Food and Drug Administration allows calcium-rich foods and

Table 1 Major Sources of Bone-Building Nutrients	
NUTRIENT	MAJOR SOURCES
Calcium	Dairy products (milk, yogurt, cheese), green leafy vegetables (kale, collards, broccoli), fortified orange juice, tofu (set in calcium), other calcium-fortified foods and beverages
Phosphorus	Meat, poultry, fish, eggs, milk products, nuts, legumes
Magnesium	Seeds, nuts, legumes, dark green vegetables
Fluoride	Fluoridated drinking water, foods prepared with fluoridated water
Vitamin D	Fortified milk, fatty fish (salmon, herring), exposing skin to sunlight
Vitamin K	Leafy green vegetables (spinach, kale, broccoli, dark lettuce), margarine, plant oils

Table 2 Dietary Reference Intakes for Nutrients that Enhance Bone Health

Sample Life Stage Groups	Calcium (mg/d)	Phosphorus (mg/d)	Magnesium (mg/d)	Fluoride (mg/d)	Vitamin D (mg/d)†	Vitamin K (mg/d)
7-12 mo	270*	275*	75*	0.5*	5*	2.5*
1-3 yr	500*	460‡	80	0.7*	5*	30*
4-8 yr	800*	500	130	1*	5*	55*
Males						
9-13 yr	1,300*	1,250	240	2*	5*	60*
14-18 yr	1,300*	1,250	410	3*	5*	75*
19-30 yr	1,000*	700	400	4*	5*	120*
31-50 yr	1,000*	700	420	4*	5*	120*
51-70 yr	1,200*	700	420	4*	10*	120*
>70 yr	1,200*	700	420	4*	15*	120*
Females						
9-13 yr	1,300*	1,250	240	2*	5*	60*
14-18 yr	1,300*	1,250	360	3*	5*	75*
19-30 yr	1,000*	700	310	3*	5*	90*
31-50 yr	1,000*	700	320	3*	5*	90*
51-70 yr	1,200*	700	320	3*	10*	90*
>70 yr	1,200*	700	320	3*	15*	90*

*Adequate intakes.

†1 microgram (mg) of vitamin D = 40 international units.

‡**Entries in boldface are Recommended Dietary Allowances.**

Source: Food and Nutrition Board, Institute of Medicine, National Academy of Sciences (Institute of Medicine 1997, 2001).

dietary supplements to carry a claim that calcium helps fight osteoporosis.

The dietary reference intakes (DRIs) for calcium and other bone-building nutrients were recently revised by the Standing Committee on the Scientific Evaluation of Dietary Reference Intakes (DRI committee), Food and Nutrition Board, Institute of Medicine (see Table 2). The panel considered calcium balance and bone mineral density as the key factors for long-term bone health. Calcium balance is the net result of calcium consumption, calcium absorption, and calcium losses through feces, urine, and skin. Changing any of these factors can affect calcium balance, but calci-

um intake is the primary determinant (Matkovic and Heaney 1992).

Calcium Builds Strong Bones for All Ages

Adequate calcium intake is important throughout life, but particularly so during the early years of life to achieve peak bone mass (Recker 1993; Nieves et al. 1995). Randomized, placebo-controlled studies with prepubertal and adolescent females showed that the children had increased bone densities when they consumed calcium-enriched foods or supplements; this was particularly the case among children with habitually low cal-

cium intakes (Johnston et al. 1992; Lloyd et al. 1993; Bonjour et al. 1997).

Sufficient calcium consumption is essential for maintaining adequate bone mass from early adulthood through old age. According to a comprehensive review of 139 studies, three-quarters of 86 observational studies found a positive association between calcium intakes and parameters related to bone mass. Also, 50 of 52 controlled intervention studies showed that high calcium intakes resulted in improved accumulation of bone, greater gains in bone mass during growth, reduced amounts of bone loss among elderly individuals, or a decreased risk of fracture (Heaney 2000). Calcium supplementation prevented bone loss in elderly women during the winter, when suboptimal vitamin D status often accelerates bone turnover (Storm et al. 1998).

In contrast, a recent review of 57 studies con-

70 percent among older women (Cumming and Nevitt 1997; Reid 1998).

The interaction between calcium and estrogen is important for retarding bone loss in postmenopausal women (Bronner 1994; Haines et al. 1995; Prestwood et al. 2000). However, the relative importance of each seems to vary depending on how long menses has ceased. The rate of bone loss during the first several years of menopause is so great that high calcium intakes alone cannot arrest it (Riggs et al. 1998; Recker 1993). In controlled intervention studies, the effect of calcium supplementation alone was intermediate between the effects of placebo and the combination of calcium and hormone replacement therapy in retarding bone loss or improving the calcium balance (Aloia et al. 1994; Riggs et al. 1998). In contrast, calcium supplementation alone did retard bone loss in

Table 3 Amount of Calcium Absorbed from Various Non-Fortified Foods

Food	Serving Size	mg of Calcium per Serving	Percentage of Calcium Absorbed	Estimated Amount of Absorbable Calcium (mg)	No. of Servings Equivalent to 8 oz. of Milk
Milk, yogurt	1 cup (8 oz.)	300	32.1	96.3	1
Dried beans	1/2 cup	50	15.6	7.8	12.3
Broccoli	1/2 cup	35	61.3	21.5	4.5
Cabbage	1/2 cup	79	52.7	41.6	2.3
Kale	1/2 cup	47	58.8	27.6	3.5
Spinach	1/2 cup	122	5.1	6.2	15.5

Source: Adapted from Weaver and Heaney (1999).

cluded that dairy foods improved bone health among women younger than age 30 but not among older women (Weinsier and Krundieck 2000).

Calcium – Stemming Bone Loss During Menopause

Bone loss occurs during menopause because of a dramatic increase in levels of calcium excretion and the mobilization of skeletal reserves to help meet calcium needs. An analysis of 20 major trials of calcium loss indicates that postmenopausal women in control groups lose bone mass at the rate of 1 percent per year, whereas the rate for subjects taking calcium supplements is 0.014 percent (Nordin 1997). Calcium supplementation reduced the relative risk of osteoporotic fractures by 25 to

women who were 10 years beyond menopause (Devine et al. 1997). Among postmenopausal women with established osteoporosis and previous spinal fractures, calcium supplementation alone reduced bone loss and the incidence of new fractures (Chevalley et al. 1994; Recker et al. 1996).

Calcium Food Sources and Absorption

Dairy foods are the primary sources of calcium in the United States, providing more than 73 percent of the calcium in the food supply, followed by fruits and vegetables (9 percent) and grain products (5 percent) (Institute of Medicine 1997). For individuals who do not meet their calcium needs with dairy foods, nutrient-dense calcium-fortified foods and beverages such as orange juice, juice drinks,

Table 4 Dietary Reference Intakes for Calcium Versus Median Intakes, by Age and Sex

Sample Life-Stage Groups	Calcium DRI (mg/d)*	Median Daily Calcium Intake†
7-12 mo	270	703
1-3 yr	500	766
4-8 yr	800	808
1-3 yr	500	766
Males		
9-13 yr	1,300	980
14-18 yr	1,300	1,094
19-30 yr	1,000	954
31-50 yr	1,000	857
51-70 yr	1,200	708
>70 yr	1,200	702
Females		
9-13 yr	1,300	889
14-18 yr	1,300	713
19-30 yr	1,000	612
31-50 yr	1,000	606
51-70 yr	1,200	571
>70 yr	1,200	517

*Adequate intakes.

† (CSFII) data (as cited by the Institute of Medicine [1997]). The CSFII survey was done conducted before the introduction of numerous calcium-fortified foods and beverages, including breakfast bars, beverages, and cereals.

Source: Food and Nutrition Board, Institute of Medicine, National Academy of Sciences (Institute of Medicine 1997).

and ready-to-eat cereals are other sources of calcium (Table 3 lists several common calcium-containing foods).

The efficiency of calcium absorption is influenced by several factors such as vitamin D status and various dietary components. Calcium is absorbed at similar efficiencies from many foods with calcium, calcium-fortified foods, and dietary supplements (Institute of Medicine 1997, pp. 73-74). However, calcium is poorly absorbed from foods such as spinach, rhubarb, sweet potatoes, and dried beans that are rich in oxalate, which is a potent inhibitor of calcium absorption (Weaver and Heaney 1999). Phytate, which is abundant in raw beans, soy isolates, nuts, and grains, inhibits calcium absorption to a lesser degree (Institute of Medicine 1997, p. 73; Weaver and Heaney 1999, p. 147). The amount of calcium absorbed from calcium-fortified soy milk is lower than that absorbed from cow's milk (Heaney et al. 2000). Table 3 shows the amount of calcium absorbed from various foods.

Calcium Supplements: How Well Absorbed Are They?

Although calcium-rich foods are the preferred calcium sources, supplements are recommended for individuals who cannot achieve adequate intakes solely through diet.

In the past, attention focused on the relative bioavailabilities of different forms of supplemental calcium. Most forms (calcium carbonate, calcium citrate, calcium lactate, calcium gluconate, and tricalcium phosphate) are comparably well absorbed if they disintegrate (National Institutes of Health 1994). The level of disintegration of a supplement is voluntarily disclosed via a United States Pharmacopoeia designation on the label.

One particularly well-absorbed form of supplemental calcium is calcium citrate-malate (CCM), which also is used to fortify beverages and juices with calcium. Calcium carbonate also is well absorbed by individuals with normal gastric acid secretion or when consumed with a meal, which stimulates acid secretion. In other direct comparison studies, CCM and calcium carbonate were also equally well absorbed when taken with a meal (Heaney et al. 1999; Recker 1993).

Because the percentage of total calcium absorbed decreases as the amount of calcium entering the intestine increases, the total amount of supplemental calcium consumed daily should be taken across two or three doses rather than as a single dose (Heaney 1991).

Efficiency of Calcium Absorption Throughout Life

The efficiency of calcium absorption varies with age. Absorption is greatest in infants and adolescents to aid in growth and development (Matkovic 1991). The bodies of young individuals (ages 9 to 17 years) can adapt to short-term low-calcium intakes by increasing intestinal absorption and decreasing urinary losses to conserve calcium for skeletal deposits (O'Brien et al. 1996.) Among healthy adults, the percentage of calcium absorbed in the intestines varies widely. According to a recent study of pre- and postmenopausal women, the mean amount of calcium absorbed was 35 percent of the amount consumed and ranged from 17 to 58 percent (Wolf et al. 2000).

The efficiency of calcium absorption declines with age, contributing to an increased risk for hip fracture. According to the multicenter, prospective cohort Study of Osteoporotic Fractures, postmenopausal women who consumed low-calcium diets and experienced low levels of intestinal calcium absorption were at great risk for hip fractures (Ensrud et al. 2000).

Calcium Intakes Compared with Recommendations

Table 4 compares DRIs for calcium with the median daily calcium intakes by age and sex. The greatest gaps occur precisely when calcium requirements rise, that is, during adolescence, when calcium is needed to build bone mass, and during old age, when calcium is required to retard bone loss.

Between 75 and 90 percent of females age 8 and older and boys ages 9 to 13 do not meet the requirements for adequate calcium intakes (Institute of Medicine 1997). This translates into inadequate calcium intakes for millions of young girls, adolescents, and adults.

PHOSPHORUS

Eighty-five percent of the body's phosphorus is found in bone, where it binds with calcium to form the mineral hydroxyapatite, which confers strength and rigidity to bones (Institute of Medicine 1997, p. 38; Nordin 1997). Low amounts of dietary phosphorus are accompanied by acute bone demineralization and the loss of calcium in the urine (Knochel 1999, p. 160).

Phosphorus Food Sources and Absorption

Phosphorus is abundant in the food supply and is well absorbed (55 to 70 percent) from most sources except foods high in phytates, such as raw beans, soy isolates, nuts, and grains (discussed below) (Institute of Medicine 1997, p. 147).

In the United States, about half of dietary phosphorus comes from protein-rich foods such as milk, meat, poultry, and fish. About 12 percent comes from cereals (Knochel 1999). Some soft drinks contain phosphorus in the form of phosphoric acid. Cola and pepper-type soft drinks contain approximately 40 mg of phosphorus per 12-ounce serving; non-cola soft drinks typically do not contain phosphorus (U.S. Department of Agriculture, Nutrient Data Laboratory 2001).

Vitamin D regulates the efficiency of intestinal phosphorus absorption (Institute of Medicine 1997). Unlike calcium, the efficiency of phosphorus absorption does not vary with the amount consumed. The consumption of high levels of magnesium along with phosphorus decreases the amount of phosphorus absorption (Shils 1999, p. 174). Intakes of calcium within a reasonable range do not significantly interfere with phosphorus absorption (Institute of Medicine 1997, p. 149).

Does Phosphorus Negatively Affect Calcium Absorption?

According to scientific data (Institute of Medicine 1997, pp. 154, 185, 186), phosphorus does not appear to negatively affect calcium absorption. The ratio of calcium to phosphorus consumed matters during infancy and periods of rapid growth, but not during adulthood (Institute of Medicine, pp. 152, 153). In human balance studies, a 30-fold range in the calcium:phosphorus ratio did not affect calcium absorption or calcium balance. The DRI committee concluded that for most age groups there is no rational basis for relating the amounts of calcium and phosphorus consumed to each other (Institute of Medicine 1997, p. 153).

In one observational study, Mexican children who consumed large amounts of phosphoric acid-containing beverages exhibited slightly reduced serum calcium levels (Mazariegos-Ramos 1995). Given the available data, the DRI committee could not conclude whether the effect was due to the phosphoric acid in the soft drinks (Institute of Medicine 1997). A recent study of carbonated beverages and urinary calcium excretion in women showed that phosphoric acid did not increase the level of urinary calcium excretion in the subjects (Heaney 2001).

Phosphorus Intakes Compared with Recommendations

The Recommended Dietary Allowance for phosphorus is 700 mg for adults age 19 and older. Adult diets in the United States have an average of approximately 1,320 mg of phosphorus per 2,000 calories and an average of 1,550 mg of phosphorus per 2,500 calories (Institute of Medicine 1997, p. 156). Because phosphorus is abundantly distributed in the food supply and good intestinal absorption is coupled with low levels of urinary excretion, dietary phosphorus deficiency is extremely rare (Institute of Medicine 1997, p. 157).

MAGNESIUM

Magnesium is a cofactor in more than 300 enzymatic reactions and plays a major role in bone cell function and hydroxyapatite crystallization and growth. About half of the body's magnesium is found in bone (Shils 1999, p. 169). Bone magnesium also serves as a reservoir for maintaining normal serum magnesium levels (Institute of Medicine 1997, p. 191).

Magnesium deficiency may play a role in osteoporosis. According to a 4-year observational study, higher intakes of dietary magnesium correlated with higher hipbone densities in men and women (Tucker 1999). The results of controlled trials in which pre- and postmenopausal women were given magnesium supplements are conflicting. Additional research is required to more fully understand the role of magnesium in long-term bone health (Institute of Medicine 1997).

Magnesium Food Sources and Absorption

Magnesium is found in a wide variety of foods. Fruits, vegetables, grains, and animal products each contribute about 16 percent of dietary magnesium. Dairy foods contribute about 20 percent of dietary magnesium among adolescents and about 10 percent among adults (Shils 1999, pp. 172-173).

About half of the magnesium in a typical U.S. diet is absorbed. Absorption is affected by several food components, most notably dietary fiber and phytates (discussed below). Like calcium, the efficiency of magnesium absorption is inversely proportional to the amount consumed. Dietary phosphate (PO_4) decreases the amount of magnesium absorbed (Institute of Medicine 1997), but the body maintains its magnesium balance by decreasing the amount lost through urinary excretion (Shils 1999, p. 174).

Magnesium Intakes Compared with Recommendations

Given the wide distribution of magnesium among plant and animal foods, magnesium deficiency among healthy people consuming a typical U.S. diet is unlikely (Shils 1999 pp. 169, 172). Among hospitalized and very ill patients, rates of magnesium deficiency are reported to range from 7 percent to greater than 40 percent (Shils 1999, p. 182).

FLUORIDE

More than 99 percent of the body's fluoride is found in bones and teeth. Fluoride is famed for its beneficial role in dental health, which is the basis for the newly revised adequate intake level (see Table 2) (Institute of Medicine 1997 p. 50).

Among adults, about half of the fluoride absorbed each day is deposited into bones and teeth. The rate of deposit into bone tissue varies with age and is more efficient in young children to support skeletal development (Institute of Medicine 1997). Pharmacological levels of fluoride can stimulate new bone formation (Institute of Medicine 1997).

Fluoride Sources and Absorption

In the United States, fluoridated water is the primary dietary source of fluoride. On average, the level of fortification is approximately 1 mg of fluoride/quart of water (Institute of Medicine 1997, pp. 292, 293). Although fluoride is ubiquitous in foods, the levels are typically low and vary considerably (Nielsen 1999; Institute of Medicine 1997).

The intestinal absorption of fluoride is quite efficient, ranging from 75 to 90 percent (Nielsen 1999). Because fluoride has a high affinity for calcium, poorly absorbed compounds can form when calcium foods are coingested, which decreases the amount of fluoride absorbed intestinally up to 10 to 25 percent (Institute of Medicine 1997, pp. 289, 291).

Fluoride Intakes

Adequate fluoride intakes range from 2 to 4 mg/d for prepubescents, adolescents, and adults. Total dietary fluoride intakes (fluids plus food) range from 1.4 to 3.4 mg/d for adults living in areas with fluoridated water (Institute of Medicine 1997, pp. 292, 293). Fluoridated toothpaste and other dental products can contribute significant amounts

of fluoride, even exceeding the amounts from dietary sources, if they are routinely swallowed (Institute of Medicine 1997, p. 295).

EFFECT OF FIBER AND PHYTATES ON BONE MINERAL ABSORPTION

Current dietary guidance promotes increased fiber intake through the consumption of larger amounts of fruits, vegetables, and whole grains. Theoretically, plant-based diets with very high levels of fiber and phytates can alter a person's mineral balance, but this is not a problem if fiber is consumed at the recommended levels (20 to 35 g/d) (Institute of Medicine 1997, p. 81). Diets very high in fiber (39 to 59 g/d) result in decreased levels of magnesium absorption and retention compared with those for diets with lower levels of fiber (9 to 23 g/d).

Many high-fiber foods such as cereals, peas, beans, and nuts are rich in phytate, the storage form of phosphorus. Phytate, rather than fiber per se, inhibits intestinal calcium and magnesium absorption by binding these nutrients to phosphate groups (Weaver and Heaney 1999, p. 147; Institute of Medicine 1997, p. 194). In addition, the amount of phosphorus absorbed from high-phytate foods varies because human intestines lack the enzyme phytase and must depend on colonic bacteria and phytases intrinsic to foods (Institute of Medicine 1997, pp. 151-152). Because corn and oats are low in phytase, the amount of phosphorus absorbed from these foods is low (Knochel 1999, p. 158). Yeast contains phytase, so leavened breads should not interfere with mineral absorption (Weaver 1997, p. 147).

VITAMINS AND BONE HEALTH

VITAMIN D

Vitamin D is necessary for the absorption and deposition of calcium and phosphorus in bones and teeth. It is manufactured in the skin and is also obtained through dietary sources.

Vitamin D is especially important for bone health in later years of life. Trials involving supplementation with reasonable amounts of vitamin D show enhanced bone health among elderly individuals (Reid 1998). However, some studies show that supplemental calcium is more effective than supplemental vitamin D in reducing hipbone loss (Peacock et al. 2000).

A combination of vitamin D and calcium seems to be particularly effective for enhancing bone health (Reid 1998). In controlled studies of healthy

elderly women and men, supplementation with reasonable amounts of vitamin D and calcium led to improved bone density and fewer osteoporotic fractures compared with the numbers among the control subjects (Chapuy et al. 1992; Dawson-Hughes et al. 1997; Baeksgaard et al. 1998; O'Brien 1998). In addition, supplementation with the combination of vitamin D and calcium decreased the amount of body sway among elderly women after 8 weeks, an improvement that can help prevent falls and subsequent osteoporotic fractures (Pfeifer et al. 2000).

Rickets: Resurgence of a Forgotten Disease?

Vitamin D deficiency causes rickets, a painful, deforming bone disease characterized by undermineralization of the skeleton (Holick 1999). In the past, rickets was fairly common in the United States but was virtually eradicated after routine vitamin D fortification of most milk products in the 1930s (Holick 1999). According to several recent reports, however, rickets is again on the rise and vitamin D supplementation may be prudent for dark-skinned infants who are exclusively breast-fed and not exposed to sufficient sunlight (Kreiter et al. 2000).

Vitamin D Sources and Absorption

Very few foods naturally contain vitamin D. Milk and other vitamin D-fortified foods and fatty fish are excellent dietary sources.

For most individuals, vitamin D requirements are met primarily from vitamin D synthesis in the skin resulting from exposure to sunlight (Institute of Medicine 1997). Factors that can limit synthesis include residence in far northern or far southern latitudes, highly pigmented skin, and the routine use of sunscreens (Holick, 1999).

Several factors put elderly individuals—especially frail elderly individuals living in far northern latitudes—at risk for poor vitamin D status. These factors include low levels of consumption of calcium- and vitamin D-rich foods, reduced efficiency of intestinal vitamin D absorption, and less exposure to sunlight (thus the subsequent lack of synthesis of vitamin D in the skin and production of the hormonally active form in the kidney) (Blumberg 1997). Health professionals should encourage elderly individuals to consume adequate amounts of vitamin D-fortified foods or supplements.

Vitamin D Intakes Compared with Recommendations

An accurate assessment of dietary vitamin D intake is not available because food composition

data for foods fortified with vitamin D vary widely (Institute of Medicine 1997). However, median intakes fall well below the recommended levels for some age groups. For example, the median vitamin D intake among young women is estimated to be 2.9 micrograms per day (mg/d) (Institute of Medicine 1997), and among seniors it is estimated to be 2.3 mg/d (Blumberg 1997). For women ages 19 to 50, the recommended vitamin D intake is 5 mg/d; for women ages 51 to 70 the recommended vitamin D intake is 10 mg/d, and for women ages 71 and older the recommended vitamin D intake is 15 mg/d.

VITAMIN K

Vitamin K plays a role in the proper functioning of osteocalcin, a bone matrix protein. Limited clinical research suggests that adequate vitamin K intake is associated with decreased bone turnover and decreased urinary calcium excretion (Institute of Medicine 2001, p. 9).

Although vitamin K is not widely distributed in the U.S. food supply, intakes appear to be sufficient (Institute of Medicine 2001, Appendix C-10). The major sources of vitamin K in the U.S. diet are spinach, collards, broccoli, dark lettuce, margarine, and plant oils. In addition, turnip greens, kale, and Brussels sprouts are excellent sources of vitamin K (Institute of Medicine 2001).

OTHER MICRONUTRIENTS

Micronutrients such as vitamin C, zinc, manganese, copper, and boron also play a role in bone health. These micronutrients, with the exception of boron, are cofactors for enzymatic reactions in the synthesis or modification of bone matrix compounds. The report by the DRI committee provides a detailed discussion of these nutrients and bone health (Institute of Medicine 1997).

MACRONUTRIENTS

Protein

Dietary protein increases the levels of excretion of calcium and magnesium in the urine (Institute of Medicine 1997). Every 1-g increase in dietary protein intake is accompanied by a 1- to 1.5-mg increase in urinary calcium excretion (Institute of Medicine 1997, p. 75; Kerstetter et al. 1998). However, most protein-rich foods also are high in phosphorus, which decreases urinary calcium excretion (Weaver and Heaney 1999, p. 147). Although high levels of dietary protein increase the level of urinary magnesium, this is not a concern if

magnesium intake is adequate (Institute of Medicine 1997, p. 194).

Conflicting data on the effect of protein on urinary calcium from two recent studies are noteworthy. In the Framingham osteoporosis study of 600 elderly women and men, no adverse effects on bone health were observed from higher intakes of animal protein (Hannan et al. 2000). In contrast, a study of 1,000 elderly women showed that those who consumed a high ratio of animal to plant protein experienced a higher rate of femoral bone loss and had a higher risk of hip fracture (Sellmeyer 2001). However, the latter findings have been questioned because of internal inconsistencies in the data (Heaney 2001). Although protein's short-term effects on urinary calcium loss are clear, its negative effects on long-term bone health are less clear.

In practical terms, the potential negative effect of dietary protein on urinary calcium excretion is a concern only when calcium intake is low and when calcium absorption fails to offset the losses in urine. A calcium:protein ratio of 20 mg:1 g likely provides adequate skeletal protection (Heaney 1998). The DRI committee concluded that adjusting the recommended intakes for calcium according to the amount of protein consumed was unwarranted (Institute of Medicine 1997, p. 76).

At the other end of the spectrum, inadequate dietary protein is harmful to bone health, especially among elderly individuals. A low protein intake (34 g/d) is associated with poor overall nutritional status, compromised recovery from osteoporotic fractures, and increased bone loss in elderly individuals (Institute of Medicine 1997, p. 76; Delmi et al. 1990; Hannan et al. 2000). In clinical intervention trials, the normalization of protein consumption among undernourished elderly individuals independently improved clinical outcomes after hip fracture (Bonjour et al. 1997a).

Carbohydrates

There is no evidence that carbohydrate intake has a direct physiological effect on bone health. It has been hypothesized, however, that a high-carbohydrate diet may compromise bone status indirectly by displacing calcium-rich foods and beverages in the diet. For example, several studies show that the levels of consumption of calcium-rich milk have decreased and that the levels of consumption of soft drinks, juices, and juice drinks have increased, especially among adolescent boys and young girls (Guthrie and Morton 2000; Fisher et al. 2001; Harnack et al. 1999). However, the U.S. Department of Agriculture (2001) noted recently that the relationship between the consumption of sugars and nutrient displacement has not been

observed consistently. Further studies are needed to determine if there is actually a cause-and-effect association between these two phenomena.

Fat

Dietary fat is typically well absorbed (97 to 99 percent). Only during steatorrhea does fat intake negatively affect calcium balance, due to the formation of insoluble calcium soaps in the intestine (Weaver and Heaney 1999, p. 148). In a recent study, dietary fat intake correlated positively with intestinal calcium absorption (Wolf et al. 2000).

OTHER DIETARY CONSTITUENTS

Sodium

Because urinary sodium excretion and urinary calcium excretion occur together in the kidneys, increasing the level of dietary sodium triggers urinary calcium losses (Massey and Whiting 1996). According to data from salt-loading trials and with free-living individuals, when calcium consumption is moderate or high, 500 mg of sodium ingested as sodium chloride will draw out about 10 mg of calcium (Institute of Medicine 1997, p. 75; Massey and Whiting 1996).

Data regarding the long-term effects of sodium on bone health are sparse (Burger et al. 2000; Institute of Medicine 1997). Several studies report correlations between sodium intake and biomarkers of bone turnover (Dawson-Hughes et al. 1996) and hipbone loss (Devine et al. 1996), whereas others find no correlations with bone density in elderly men and women or in well-nourished prepubertal children (Dawson-Hughes et al. 1996; Jones et al. 2001). Possible shortcomings of the latter studies include the use of cross-sectional versus longitudinal designs and single versus repeated 24-hour measures of urinary sodium excretion.

The DRI committee concluded that these data are insufficient to warrant the establishment of different calcium intake recommendations on the basis of levels of sodium consumption (Institute of Medicine 1997, p. 75).

Caffeine

Caffeine causes a temporary rise in urinary calcium levels for 1 to 3 hours after the ingestion of caffeine; however, the amount of calcium excreted over 24 hours is unchanged (Weaver and Heaney 1999, p. 148). In addition, the net effects on the skeleton are modest when the calcium intake exceeds 800 mg/d (Institute of Medicine 1997).

Also, recent data show that the caffeine in carbonated soft drinks has a negligible effect on calcium excretion (Heaney 2001).

Heavy caffeine consumption (equivalent to more than two to three cups of brewed caffeinated coffee per day) is associated with some bone loss in postmenopausal women with low calcium intakes (Harris and Dawson-Hughes 1994; Krall and Dawson-Hughes 1999; Institute of Medicine 1997). The consumption of modest amounts of milk can offset this bone loss (Barrett-Connor et al. 1994).

Older individuals with low calcium intakes should increase their calcium consumption and moderate their caffeine consumption as appropriate. The DRI committee concluded that data are insufficient to warrant the establishment of different calcium intake recommendations on the basis of levels of caffeine consumption (Institute of Medicine 1997).

EMERGING RESEARCH ON SOY

Preliminary and sometimes conflicting research suggests that soy foods have a positive effect on bone health. Two small 6-month studies showed that soy protein and isolated isoflavones (a component of soy), respectively, had beneficial effects on spinal bone density (Potter et al. 1998; Alekel et al. 2000). However, not all studies show that soy protein has a favorable effect (Gallagher 2000). A much larger 3-year study with older women found that a synthetic isoflavone (ipraflavone) did not slow bone loss and induced lymphocytopenia in 13 percent of the subjects (Alexandersen et al. 2001). As yet, it is not possible to draw clear conclusions about the effects and safety of soy compounds on long-term bone health.

WHERE ARE THE RESEARCH GAPS ON BONE HEALTH?

By nature, nutrition research is constantly evolving and often generates more questions than it answers. In terms of bone health, well-designed studies are needed to better understand:

- ❑ The types, intensity, and duration of physical activity required to optimize bone health throughout life and the interplay of physical activity with dietary calcium
- ❑ The relative importance and interplay between dietary calcium and hormone replacement therapy in postmenopausal women
- ❑ The influence of dietary magnesium on long-term bone health and the risk of osteoporotic fractures

- ❑ The effects of sunscreens on vitamin D status
- ❑ The influence of micronutrients such as boron, manganese, and vitamin K
- ❑ The long-term effects of sodium and protein
- ❑ The effects and safety of soy compounds and other phytochemicals
- ❑ The effects of diet and lifestyle in men and minority populations
- ❑ Attitudinal and behavioral barriers and motivators for improving bone health

SUMMARY AND CONCLUSIONS

Achieving and maintaining optimum bone health require a mix of many modifiable and non-modifiable factors and are important throughout the life cycle.

In the United States, osteoporosis is a silent epidemic with enormous scope and public health effects for millions of women and men. It generates a huge burden on the health care system, compromises quality of life, and each year kills more people than breast cancer or prostate cancer. Regular physical activity, particularly weight-bearing activity, plays a key role in bone health and should be encouraged.

Millions of Americans, particularly young girls and women, are not consuming enough calcium.

Health professionals must be alert for conditions that compromise vitamin D status, such as living in far northern or far southern latitudes for housebound elderly individuals. Bone density screening tests are rapid and painless methods for determining the risk of osteoporosis and appropriate therapies.

Although dietary protein, sodium, and caffeine can increase urinary calcium losses, it appears to be unlikely that moderate intakes compromise long-term bone health when dietary calcium intake is adequate. Additional research is needed.

In line with the *Dietary Guidelines for Americans* and the *Food Guide Pyramid*, dietary advice should emphasize the consumption of a variety and adequate amounts of bone-building foods and beverages, particularly calcium-rich foods, and moderate amounts of protein and sodium.

Because many individuals fall short on their calcium intakes, encouraging the consumption of adequate amounts of calcium-rich and calcium fortified foods and beverages should be a priority.

Emerging research is exploring the potential benefits of soy compounds on bone health. Available evidence is somewhat conflicting; thus, health care professionals are advised to stay informed about new studies in this area.

Nutrition science constantly evolves, and future

research will better elucidate the independent and combined roles of modifiable factors such as physical activity and nutrition on bone health.

Health professionals can play a pivotal role in optimizing bone health across the life cycle, particularly during growth and old age.

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