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10th Edition

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Food and Nutrition Board
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FOOD AND NUTRITION BOARD SUBCOMMITTEE ON THE TENTH EDITION OF THE RDAS

RICHARD J. HAVEL *(Chairman)*, Cardiovascular Research Institute, University of California, San Francisco, California
DORIS H. CALLOWAY, Department of Nutritional Sciences, University of California, Berkeley, California
JOAN D. GUSSOW, Department of Nutrition Education, Teachers College, Columbia University, New York, New York
WALTER MERTZ, Human Nutrition Research Center, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, Maryland
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ALDON GRIFFIS, *Research Assistant*
MARIAN F. MILLSTONE, *Research Assistant*

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9
Minerals

CALCIUM

The adult body contains approximately 1,200 g of calcium, approximately 99% of which is present in the skeleton. Bone mineral consists of two chemically and physically distinct calcium phosphate pools—an amorphous phase and a loosely crystallized phase. The skeleton contains two major forms of bone: trabecular (spongy) bone, exemplified by the vertebral bodies, and denser cortical bone, such as the femur. Bone is constantly turning over, a continuous process of resorption and formation. In children and adolescents, the rate of formation of bone mineral predominates over the rate of resorption. In later life, resorption predominates over formation. Therefore, in normal aging, there is a gradual loss of bone (Arnaud, 1988).

The remaining 1% of body calcium is found in extracellular fluids, intracellular structures, and cell membranes. This extraskeletal calcium plays an essential role in such vital functions as nerve conduction, muscle contraction, blood clotting, and membrane permeability. Blood calcium concentration is maintained within very narrow limits by the interplay of several hormones (1,25-dihydroxycholecalciferol, parathyroid hormone, calcitonin, estrogen, testosterone, and possibly others), which control calcium absorption and excretion, as well as bone metabolism.

Levels of soft tissue calcium are maintained at the expense of bone in the face of inadequate calcium intake or absorption. Under such circumstances, there is either inadequate mineralization of bone in the young or mineral is withdrawn from bone with a consequent reduction of bone strength.

Calcium is lost from the body in feces, urine, and sweat. The fecal calcium consists of unabsorbed dietary calcium, the amount of which depends on dietary intake and other factors, and a small portion of the endogenously secreted calcium (about 100 to 150 mg/day), which escapes reabsorption. Urinary calcium excretion of adults is about 100 to 250 mg/day, but varies widely among persons consuming self-selected diets (Nordin et al., 1967). Urinary excretion is influenced by hormonal and dietary factors. Among the latter are protein, sodium, and some carbohydrates, which increase calcium excretion, and phosphorus, which decreases it. Except under conditions of extreme sweating, loss of calcium from the skin is small (about 15 mg/day).

Calcium Absorption

Intestinal absorption of calcium is variably influenced by several nutritional and physiological factors (Avioli, 1988). Studies of calcium absorption have frequently been flawed by failure to include the extended period (4 weeks or more) required for adaptation to changes in dietary intake and to control for intervening dietary variables. Nonetheless, the literature is consistent on several points. The efficiency of absorption is increased during periods of high physiologic requirement. Thus, children may absorb up to 75% of ingested calcium as compared to the 20 to 40% typically observed in young adults in the United States. Absorption is impaired in the aged (Heaney et al., 1982). A higher percentage of ingested calcium is absorbed at low intakes than at high intakes. Above an intake of about 800 mg/day in normal adults, absorption is approximately 15% of the amount ingested (Heaney et al., 1975). Vitamin D is a recognized promoter of calcium absorption. The role of protein and phosphorus is less clear. Dietary protein enhances calcium absorption (McCance et al., 1942) in the protein intake range between inadequate and adequate levels, but has little additional effect beyond RDA levels of protein (Chu et al., 1975). The effect of phosphorus differs with the source, but, excluding phytate phosphorus (see below), this element appears to have little if any depressing effect on calcium absorption (Spencer et al., 1978, 1986).

It is uncertain if there are biologically important differences in the absorption of calcium from different foods or diets. In animal models, the presence of lactose tends to enhance paracellular calcium absorption, but this effect has not been consistently demonstrated (Scrimshaw and Murray, 1988). Phytate and oxalate bind calcium, rendering it insoluble, and certain fiber fractions may interfere with

calcium absorption. These substances are believed to be of little practical importance at intakes typical for the U.S. diet (Judd et al., 1983; LSRO, 1987; Schwartz et al., 1986).

Dietary Sources and Usual Intakes

Calcium intake varies widely among individuals in the United States but is generally higher in males than in females. The 1977–1978 Nationwide Food Consumption Survey (USDA, 1981) reported an average daily intake of 743 mg for all people, ranging from 530 mg for women 35 to 50 years old to 1,179 mg for 12- to 18-year-old boys. No group of adult females had a calcium intake equal to or greater than the RDA of 800 mg. Black women ingested less dietary calcium than whites (452 compared to 610 mg/day) (USDA, 1987).

Dairy products contribute more than 55% of the calcium intake of the U.S. population (Block et al., 1985). Other contributors to the daily intake of calcium are some leafy green vegetables (such as broccoli, kale, and collards), lime-processed tortillas, calcium-precipitated tofu, and calcium-fortified foods. Bones, especially the soft bones of fish (e.g., sardines, salmon) and tips of poultry leg bones, are rich and often unrecognized sources of calcium. Water is a variable source. Several proprietary antacid preparations are calcium salts that may constitute an underreported calcium source.

Bone Formation and Retention

Although calcium is a major constituent of bone, it is only one of many factors affecting bone health. Genetic influences determine bone mass; sex hormones and physical activity influence bone metabolism. Many dietary constituents are either essential for, or complementary to, the proper utilization of calcium, including vitamin D (Parfitt et al., 1982), copper (Davis and Mertz, 1987), zinc (Hambidge et al., 1986), manganese (Hurley and Keen, 1987), fluorine (Krishnamachari, 1987), silicon (Carlisle, 1986), and boron (Nielsen, 1987).

The growth of the skeleton requires a positive calcium balance until peak bone mass is reached. Mineralization of bone continues for some years after longitudinal bone growth has ceased. Most of the accumulation of bone mineral occurs in humans by about 20 years of age, but some bone mineral is added during the third decade. Bone mass then begins to decline slowly during the fifth decade in both sexes, as evidenced by progressive reduction of bone density. The rate of loss accelerates greatly about the time of menopause in

women and remains high for several years. Bone loss accelerates much later in men (by a decade or more). This results in gradually diminishing bone strength and increased risk of fractures. The risk of fracture is less at a given age in people who have achieved larger bone mass during the period of bone mass accretion than in those with lower peak bone mass (Arnaud, 1988; Heaney, 1986).

Peak bone mass appears to be related to intake of calcium during the years of bone mineralization. Investigations have usually involved estimation of past calcium intake from a history of food consumption patterns, in which differing habitual milk consumption is the chief contributor to differences in calcium intake. Thus, intakes of other nutrients (e.g., protein, phosphorus, and, importantly, the vitamin D added to most milk in the United States) are likely to covary with calcium. In a study of two population groups in Yugoslavia with different, long-standing intake patterns (500 and 1,100 mg of calcium per day), greater bone mass was found at all ages and in both sexes in the high calcium community (Matkovic et al., 1979). Since the rate of bone loss was the same in adults of the two communities, the finding of more bone mass in the older age groups of the high-calcium district must reflect higher peak bone mass attainment. In studies conducted in the United States, investigators have reported significant correlations between current bone density and past milk or calcium intake in adult women (Halious and Anderson, 1989; Hurxthal and Vose, 1969; Sandler et al., 1985). In another U.S. study, present calcium intake was compared with bone density of postmenopausal women in two Iowa communities where the water supply contained different levels of calcium over at least a 50-year period (60 compared to 375 mg/liter), resulting in average calcium intakes of 964 compared to 1,326 mg/day, respectively (Sowers et al., 1985). There were no detectable differences in measured bone density between communities. After adjustment for confounding factors, there was a small but significantly higher bone density in the Iowa women who currently consumed *both* 800 mg or more of calcium and 400 IU or more of vitamin D per day. There is, however, no clear evidence that bone density of postmenopausal women is related to concurrent dietary calcium intake within a wide range (Garn, 1970; Garn et al., 1969) except, perhaps, where this reflects a high-calcium food consumption pattern established in childhood.

The postmenopausal rate of decline in bone mineral is strongly dependent on estrogen status. Estrogen replacement slows the rate of bone loss. Evidence that supplementary calcium (1.5 to 2.5 g/day) can retard the rate of postmenopausal bone loss is mixed (NRC, 1989), but the balance of evidence suggests that calcium alone has

only a small effect on cortical bone loss and none on trabecular bone (Freudenheim, 1986; Riis et al., 1987). Combined daily treatment with 0.3 mg of conjugated estrogens plus 1 g of calcium supplement has, however, been reported to be as effective as 0.6 mg of conjugated estrogen (widely accepted to be the minimum effective dose for prevention of bone loss) without added calcium (Ettinger et al., 1987). The observed inverse relationship between body weight and risk of hip fracture in older women (heavier women having less risk of fracture) may be due in part to the maintenance of higher levels of estrogen by peripheral conversion of precursor steroids to estrogen in adipose tissue (Kiel et al., 1987).

In the subcommittee's judgment, the most promising nutritional approach to reduce the risk of osteoporosis in later life is to ensure a calcium intake that allows the development of each individual's genetically programmed peak bone mass during the formative years. The importance of meeting recommended allowances at all ages is stressed, but with special attention to intakes throughout childhood to age 25 years.

Relationship to Phosphorus and Protein Intakes

The level of dietary protein and phosphorus can affect the metabolism of, and requirement for, calcium, primarily as a result of their opposing effects on urinary calcium brought about by changes in fractional tubular reabsorption of calcium. The effect on urinary excretion outweighs the small effects on absorption described above. An increase in protein intake reduces fractional tubular reabsorption (Allen et al., 1979; Kim and Linkswiler, 1979) and results in an increase in urinary calcium excretion (Johnson et al., 1970; Margen et al., 1974). In contrast, an increase in phosphorus intake increases fractional reabsorption and causes urinary calcium to decrease (Hegsted et al., 1981; Spencer et al., 1978). Because of the opposing effects of protein and phosphorus on urinary calcium and calcium retention, a simultaneous increase in the intake of both, a pattern characterized by milk, eggs, and meat ingestion, has but little effect on calcium balance at recommended levels of calcium intake (Spencer et al., 1988).

The low ratio of calcium to phosphorus in the U.S. diet was of concern in the past. Animal studies indicated that excessive phosphorus intake led to secondary hyperparathyroidism, resulting in loss of calcium from the skeleton (LSRO, 1981). This effect was not seen in monkeys (Anderson et al., 1977), and studies in humans have failed to demonstrate effects of dietary phosphorus intake on calcium balance at adequate levels of calcium intake (Spencer et al., 1988).

Other Potential Functions

A high intake of calcium has been associated with lower blood pressure in some studies (McCarron et al., 1984), but not in others (Ackley et al., 1983). Animal studies show that high levels of dietary calcium protect against cell proliferation in the colon induced by fat and bile acids (Bird, 1986; Wargovich et al., 1983). The evidence from human studies is, however, insufficient to support an inference that high calcium diets protect against the development of colon tumors. These subjects are reviewed in the Food and Nutrition Board report *Diet and Health* (NRC, 1989).

Recommended Allowances

Adults and Adolescents An optimal calcium intake is difficult to define, given the substantial adaptive capacity and the long lag period before changes in status can be detected. It is not surprising that recommendations in different countries vary widely, from a low of 400 mg/day for women in Thailand to a high of 1,000 mg for both sexes over 75 years of age in the Netherlands. Concern for the high proportion of postmenopausal women at risk for osteoporosis has led some to suggest that the RDA for calcium should be increased markedly (NIH, 1984). This subcommittee is not persuaded by the evidence in hand that the long-standing RDAs should be revised upward in response to this medical concern. Nor is the subcommittee convinced that levels should be lowered to those recommended by international groups (e.g., FAO, 1962) despite the evidence that many population groups seemingly maintain satisfactory status with much lower intakes of calcium than the RDA.

The age at which peak bone mass is attained is uncertain, but probably is not less than 25 years. The subcommittee thus recommends an extra calcium allowance to permit full mineral deposition through age 24 rather than through age 18 years, as in previous editions of the RDA.

The recommended calcium allowance for adults is based on an estimate of 200 to 250 mg/day of obligatory loss and an estimated absorption rate of 30 to 40%. Calcium accretion during the growing years averages 140 to 165 mg/day and may be as high as 400 to 500 mg/day during the pubertal growth period (Garn, 1970). Intestinal calcium absorption is efficient in youth and adapts in relation to

needs. In setting the RDA, however, the absorption rate is conservatively estimated to be 40%.

An intake of 1,200 mg is recommended for both sex groups from ages 11 to 24 years. For older age groups, the previous allowance of 800 mg is retained. These amounts of calcium can easily be obtained if dairy products are included in the diet. A balanced diet furnishes, in addition to calcium, other nutrients necessary for bone health. The subcommittee emphasizes that its recommendations do not address the possible needs of persons who may have osteoporosis and should receive medical attention.

Pregnancy and Lactation The newborn contains approximately 30 g of calcium, most of which is deposited during the third trimester of intrauterine development (Pitkin, 1985). Calcium retention is 200 to 250 mg/day during that period. Human milk contains approximately 320 mg calcium/liter. This concentration corresponds to 240 mg in the average daily milk secretion of 750 ml; 300 mg encompasses the probable upper boundary of production (+2 SDs).

The calcium absorption rate has been reported to increase during pregnancy and lactation in rats (Halloran and DeLuca, 1980) and adolescent girls (Heaney and Skillman, 1971). There is no clear relation between women's bone health and either their number of pregnancies or lactation history in populations that consume currently recommended amounts of calcium (Koetting and Wardlaw, 1988; Lambke et al., 1977). This evidence suggests it is prudent to recommend a calcium intake of 1,200 mg throughout pregnancy and lactation, irrespective of age.

Infants and Children Infants thrive on an average intake of 240 mg of calcium from 750 ml of human milk, of which they retain approximately two-thirds. Allowing 25% for variance, intake would be 300 mg, of which 200 mg is absorbed. The retention of calcium from formulas based on cow's milk is less than one-half. Therefore, the recommendation for formula-fed infants is 400 mg/day for the first 6 months of life. This amount is provided by typical infant formulas now in use in the United States. An allowance of 600 mg/day would suffice for the next 6 months and 800 mg/day at ages 1 to 10 years. These latter allowances are arbitrary, since specific data on requirements of this age group are lacking.

Excessive Intakes and Toxicity

Although no adverse effects have been observed in many healthy adults consuming up to 2,500 mg of calcium per day, high intakes

may induce constipation and place up to half of otherwise healthy hypercalciuric males at increased risk of urinary stone formation. A high calcium intake may inhibit the intestinal absorption of iron, zinc, and other essential minerals (Greger, 1988). Ingestion of very large amounts may result in hypercalciuria, hypercalcemia, and deterioration in renal function in both sexes (Avioli, 1988). Supplementation to a total calcium intake much above the RDA is not recommended.

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PHOSPHORUS

Phosphorus is an essential component of bone mineral, where it occurs in the mass ratio of 1 phosphorus to 2 calcium. Approximately 85% (700 g) of the phosphorus in the adult body is found in bone. Phosphorus also plays an important role in many and varied chemical reactions in the body. It is present in soft tissues as soluble phosphate ion; in lipids, proteins, carbohydrates, and nucleic acid in an ester or anhydride linkage; and in enzymes as a modulator of their activities. Energy for metabolic processes derives largely from the phosphate bonds of adenosine triphosphate (ATP), creatine phosphate, and similar compounds.

Phosphorus is efficiently absorbed by the small intestine as free phosphate (Avioli, 1988). Phosphorus absorption probably takes place by three different mechanisms: (1) calcium-coupled, vitamin D-dependent; (2) noncalcium-coupled, vitamin D-dependent; and (3) noncalcium coupled, vitamin D-independent (Parfitt and Kleereko-per, 1980).

Infants absorb from 65 to 70% of the phosphorus in cow's milk and 85 to 90% of that in human milk. Children and adults absorb 50 to 70% of the phosphorus in normal diets and as much as 90% when the intake is low (LSRO, 1981).

Polyphosphate (sodium hexametaphosphate), which is used in the processing of food, is efficiently hydrolyzed to orthophosphate in the intestine, where it is well absorbed (Zemel and Linkswiler, 1981). Approximately 50% of phytate phosphorus is absorbed (Parfitt et al., 1964).

Dietary Sources and Usual Intakes

Phosphorus is present in nearly all foods. The amount available in the food supply from unprocessed primary commodities, about 1,430 to 1,520 mg per capita per day, has been relatively constant during the past 75 years, despite marked changes in food consumption patterns (Bunch, 1987). The mean daily phosphorus intake is approximately 1,500 mg/day for adult males (USDA, 1986) and 1,000 mg/day for adult females (USDA, 1987). True intakes may be 15 to 20%

higher, however, since the phosphorus supplied by numerous food additives in processed foods is typically not accounted for in tables of food composition (Oenning et al., 1988).

Major contributors of phosphorus are protein-rich foods and cereal grains. About half the food phosphorus in the U.S. diet comes from milk, meat, poultry, and fish. Cereal products contribute about 12%. Diets based heavily on convenience foods may derive 20 to 30% of phosphorus from food additives (Greger and Krystofiak, 1982).

Meats, poultry, and fish, exclusive of bone, contain 15 to 20 times more phosphorus than calcium. There is twice as much phosphorus as calcium in eggs, grains, nuts, dry beans, peas, and lentils. Only milk, natural cheeses, green leafy vegetables, and bone contain more calcium than phosphorus. Cow's milk contains both more calcium and phophorus than does human milk, and the ratios of the elements differ widely. The ratio of calcium to phosphorus in cow's milk is 1.3 to 1 and that in human milk is 2.3 to 1.

The calcium-to-phosphorus ratio in the U.S. diet varies, depending on food consumption patterns. The calcium-to-phosphorus ratio is higher in diets of infants and children than in diets of adults. The average ratio is 1 to 1.8 for adults between 35 to 50 years of age (USDA, 1984), but may be as low as 1 to 4 for those whose diets are low in dairy products and green vegetables.

General Signs of Deficiency

Because almost all foods contain phosphorus, dietary phosphorus deficiency does not usually occur. An exception is small premature infants fed human milk exclusively. Such infants need more phosphorus than is contained in human milk for the rate of bone mineralization required (Von Sydow, 1946). Without additional phosphorus, hypophosphatemic rickets may develop (Rowe et al., 1979).

Serious phosphorus deficiency has been induced in patients receiving aluminum hydroxide as an antacid for prolonged periods (Bloom and Flinchum, 1960; Lotz et al., 1968). Aluminum hydroxide binds phosphorus, making it unavailable for absorption. Phosphorus deficiency results in bone loss and is characterized by weakness, anorexia, malaise, and pain.

Recommended Allowances

Adults, Children, and Pregnant and Lactating Women The precise requirement for phosphorus is unknown. Previous editions have set the allowance for phosphorus equal to calcium for all ages except