Review

Achievement of peak bone mass in women is critically dependent on adolescent calcium intake

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Abstract

Introduction

Prevalence of osteoporosis is dramatically increasing. While adequate calcium and vitamin D intake combined with weight-bearing exercise is recommended throughout life to prevent osteoporosis, the adolescent growth period is increasingly recognised as a critical time period when future osteoporosis risk is established. The review focuses on adolescent patterns of calcium consumption in relationship to future osteoporosis risk.

Conclusion

Dietary changes in adolescents promoting soda consumption at the expense of dairy products may underlie the increase in osteoporosis prevalence. Prevention efforts among female adolescents need to focus on reducing soda and increasing dairy consumption, promoting wider usage of calcium and vitamin D supplementation, and expanding calcium fortification of foods that are frequently consumed by adolescents.

Introduction

Peak bone mass is achieved at approximately age 30 for men and women. Many factors predict peak bone mass including nutrition and weight-bearing exercise. Recent dietary changes have promoted a shift away from calcium consumption during adolescence. Milk drinking is being replaced by soda consumption, which can lead to reduced calcium intake and absorption. Failure to achieve a healthy peak bone mass will increase the risk of osteoporosis later in life. The following review will summarise the literature in relationship to describing calcium intake, different sources of calcium, the timing of intake and resulting impact on bone development.

Discussion

Calcium

Calcium intake influences skeletal calcium retention and growth during childhood and adolescence[1]. Maintenance of healthy calcium levels is critically important not only for bone formation, but also for neuronal excitability and muscle contraction[2]. Plasma calcium is maintained in a dynamic steady state alternating between dietary intake, absorption across intestinal epithelium, bone formation and kidney excretion.

Calcium is principally stored in bone and is continually sculpted, reshaped and repaired by remodelling[3]. Remodelling is tightly regulated and accomplished by osteoclast and osteoblast cells. Bone undergoes re-sorption, or breakdown of the bone, by osteoclasts, while osteoblasts form new bone through synthesis of the bone matrix. Bone acts as a storage reservoir of calcium, and, if the concentration in blood falls below normal values, calcium in bones is released to the plasma. If a chronic deficiency is sustained for long periods, circulating calcium is maintained at the expense of skeletal mass[4]. Calcium requirements are greater during adolescence due to growth and intensive bone and muscular development. Recommended daily calcium intake in adolescents ranges from 1,000 to 1,300 mg[5–8]. Providing adequate calcium during the adolescent period is critical to achieving peak bone mass in young adulthood, and, if intake is insufficient, individuals could develop an increased risk of osteoporotic fractures later in life[1].

Micronutrients That Affect Calcium Absorption

Calcium is also affected by other micronutrients such as sodium and phosphate. Sodium promotes urinary calcium excretion as a mechanism of compensation resulting in increased bone remodelling and loss[9,10]. High phosphate has been linked to low serum vitamin D, which can adversely affect bone metabolism leading to hypocalcaemia[11]. While sodium and phosphate reduce calcium, potassium has a protective effect. An inverse association between potassium and urinary calcium excretion exists in healthy White women where ingestion of potassium leads to conservation of calcium[12].

Vitamin D increases calcium absorption. In a small controlled trial of US 12-year-old girls conducted over 1 year with higher calcium and vitamin D supplementation in one group compared to controls of a lower dosage, results showed percent increases in trabecular bone mineral content (BMC) and volumetric bone mineral density (BMD) in the supplementation group compared to controls (p < 0.001)[13]. Results from a longitudinal study of girls aged 5–15 years, showed that high intake of soda resulted in reduced intake of both calcium and vitamin D[14].

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Children & Adolescents

Importance Of Vitamin D

Adolescents receive vitamin D from sun exposure, milk, fortified food, cod liver oil, yokes of eggs and fatty fish[15,16]. Children require a minimum vitamin D serum level of 11 ng/ml, according to the Institute of Medicine[5], with lower levels increasing the risk of stress fractures[16], rickets, osteoporosis[16,17], myasthenia and ostealgia[17].

Most children and adolescents do not absorb enough vitamin D from sunlight. Vitamin D absorption depends on ultraviolet B exposure intensity, skin colour and amount of melanin, and, is diminished during the fall and winter seasons, reflecting decreased day length and an increased tendency to stay indoors during colder temperatures. High-risk groups for low vitamin D include children who spend extended time indoors, and obese children with poor metabolism who do not exercise outdoors[17].

Most children and adolescents are deficient in vitamin D. Data from the US population show females from age 14 to 50 had the lowest intake and were 50% less likely than males to have adequate vitamin D intake[18]. Females 9–13 years old obtained 70% of recommended levels from diet plus supplements, while female teenagers (ages 14–18) had 45%[18]. Another adolescent study showed vitamin D deficiency prevalence of 24.1% (<15 ng/ml) and insufficient intake at 42% (<20 ng/ml)[19].

Nutrition and calcium absorption

Recent dietary changes have promoted a shift away from calcium consumption during adolescence. Over a 10-year period among black and white girls, milk intake decreased by 25% and soda consumption increased by almost 300%[20]. Adolescent girls are at high risk for hypocalcaemia and osteoporosis due to increased carbonated beverage intake and low milk product consumption in the United States[21,22].

Americans receive most calcium from dairy products. About 62% of dietary calcium consumed by adolescents originates from dairy products[23]. Recently, calcium consumption has declined because carbonated beverages are increasingly consumed. Carbonated beverages have an inverse effect on bone mineralisation. Soda consumption substitutes for milk and additionally, soda contains high levels of phosphoric acid known to limit calcium absorption[24].

Calcium supplementation and influence on BMD

Calcium supplements, an important contributor to calcium intake, exist in several chemical formulations including elemental calcium, calcium citrate malate, calcium carbonate, calcium carbonate with gluconolactate and calcium phosphate from milk extract, all of which have been shown to increase BMD[25–30].

Calcium supplementation increases BMD in post-menarchal girls. Two double-blind, placebo-controlled trials using 1,000 mg calcium carbonate among Israeli post-menarchal girls[26] and British[27] adolescent girls aged 16–18 years, showed increases in bone measures resulting from calcium carbonate. The Israeli study had mean calcium supplementation of 1,110 mg/day (including dietary calcium) for treatment compared to 480 mg/day in controls[26]. After 1 year of supplementation, BMD for total body and lumbar spine ($p < 0.05$) significantly increased for treatment compared to placebo control[26].

While short-term effects were observed following 1 year of calcium carbonate supplementation in the Israeli study[26], another study determined whether these effects were long term. Follow-up was completed 3.5 years after withdrawal of the supplement[28]. The lumbar spine and femoral neck BMD were higher in the calcium-supplemented group compared to the placebo in the follow-up, but differences were not statistically

significant[28]. The original calcium supplementation group did not have more bone mass accrual, but the positive effect in the original study ($p = 0.03$) was still evident in total BMD for girls with greater than 75% compliance during follow-up ($p = 0.05$)[28].

Calcium supplementation coupled with exercise might have a greater impact on BMD rather than calcium alone. However, calcium carbonate was found to have a greater impact by itself in increasing BMD. A random double-blind study of British adolescent girls was conducted over 15.5 months with 1,000 mg of calcium carbonate per day and three 45-minute exercises, implemented in a factorial design[27]. The combined calcium and exercise interventions had no effect on BMC, bone area (BA) or size-adjusted BMC. However, calcium intervention alone had greater BMC at the spine ($p < 0.05$), the ultra-distal radius ($p = 0.002$) and hip ($p < 0.05$)[27]. Calcium supplementation may therefore effectively build bone mass, apart from exercise, in adolescent girls.

The clearest associations between BMD and calcium supplementation was observed in twin studies. Two placebo-controlled trials were conducted in twins with similar data methods, baseline characteristics and calcium intake[29,30]. The first trial implemented supplementation of 1,000 mg/d of calcium carbonate in pre-pubertal and post-menarchal American identical twins over 3 years. One twin was randomly assigned calcium malate, while the other received a placebo[29]. Among the twin pairs who were pre-pubertal throughout the study, twins given supplements had significantly greater increases in BMD. Among the post-menarchal twins who went through puberty or were already post-pubertal, no differences in BMD were observed according to supplementation status[29]. The second trial consisted of Australian monozygotic and dizygotic pre-menarchal twins who were studied over a 2-year period with 1,200 mg calcium carbonate supplement given to one member of the

twin pair[30]. Calcium supplementation was associated with increased BMD (p < 0.05), compared with placebo[30]. Calcium supplementation effectively increased BMD at regional sites over 6–18 months, but the gains were not maintained to 24 months[30]. Both twin studies demonstrated that calcium supplementation was associated with BMD increases for twins before menarche, suggesting that calcium supplementation may have more impact prior to the onset of menarche. After menarche, the promoting effects of ovarian oestrogen on BMD may confound the influence of calcium supplementation.

Calcium supplementation, through consumption of calcium-rich foods, may increase BMD. A 18-month randomised controlled trial of British White adolescent girls had baseline intake of 746 mg/day for both the milk group and controls[31]. The intervention group increased milk intake to 1,125 mg/day, with results showing that BMD and BMC increased with regional gains specifically in the legs (p = 0.005) and pelvis (p = 0.003)[31].

Supplemental milk intake promotes bone mineral improvement in other study designs as well. In a cross sectional study of White female pre- and post-menarchal adolescents, mean calcium consumption was 200 mg/day, with an average of 166 ml/day from milk, the most frequent dairy product consumed.[32] Adolescents with less than 55 ml/day of milk had 8% lower BMC and 7% lower BMD. Girls with osteopenia had the greatest representation among the low milk consumers (27%), compared to medium and high milk consumers (15 and 11%). Milk intake was associated with lumbar vertebral BMC (p = 0.009) and BMD (p = 0.009)[32].

Milk consumption may be more effective than calcium supplements in promoting BMD increases. A randomised controlled clinical trial of Caucasian female adolescents was followed over 7 years and received either calcium malate of 1,000 mg, placebo, or dairy products[33]. Overall,

the greatest increases were observed in the dairy group who had higher BMD and became taller compared to the other groups, with the greatest growth areas seen in the proximal radius (p = 0.008) and cortical area of proximal radius (p = 0.0003)[33].

Calcium fortification of frequently consumed food may be another source of calcium. One cohort study conducted over a 1-year period, comprised of adolescent Chinese girls, included an intervention group that was given 600 mg/day of calcium-fortified soymilk compared to controls with no soy milk[34]. Positive significant increases of BMD (p = 0.001) and BMC (p = 006) were observed for the hip region among the soy group compared to controls[34]. Calcium fortified foods may therefore be an effective way to ensure adequate calcium intake, particularly among sub-groups with low consumption of dairy products such as Chinese adolescents.

Many calcium trials show immediate improvement in bone density measures, however whether improvements can be maintained over longer time periods is unclear. A randomised controlled trial was conducted originally on Swiss mid-puberty girls with 850 mg of calcium phosphate extract administered for 48 weeks compared to placebo control[25]. Three and a half years later, the intervention and placebo groups were reassessed. There were notable differences on mean areal BMD in five of six skeletal sites (p = 0.010–0.049); for BMC (p = 0.031), and BA (p = 0.04), with the intervention exceeding the placebo group[25]. Milk extracted calcium phosphate salt was positively associated with bone and longitudinal growth over 3 years after supplementation ended. Another study of 159 Chinese children given supplemental calcium over 18 months did not however confirm maintenance of longer-term improvement.[35] The study originally demonstrated a significant increase in radial bone mass with calcium intake of 300 mg/day, however 1-year later the significant

differences compared to the control group had disappeared. Results suggested that the effect of calcium supplementation on bone mineral gain was transient and not sustained over a longer term, although the Chinese children may not have had sufficient dietary intake of calcium to sustain the improvement.

Dietary calcium intake in childhood and adolescence appears to be predictive of BMD and BMC in adulthood. Using the National Health and Nutritional Examination Survey (NHANES) data of 3251 White women over 20–49, milk intake in childhood was associated with higher total hip BMC and BA (p = 0.003)[36]. Milk intake in adolescence was associated with higher hip BMC (p = 0.02) and BMD (p < 0.006), but not BA (p = 0.13). Total hip BMC and BA were lower in women with the lowest milk intake compared to high childhood intake (p < 0.01). In women over age 50, BMC and BMD were reduced with low calcium intake in childhood, and similarly for low calcium intake in adolescence. There was no association with lifetime fracture between 20 and 49 and milk intake in childhood and adolescence, but after 50, lifetime fracture was associated (p = 0.04)[36].

Achievement of peak bone mass and future risk of osteoporosis

Prevalence of osteoporosis, a chronic disease traditionally associated with aging, has dramatically risen.[37] Osteoporosis is associated with significant morbidity and mortality affecting more than 10 million Americans over age 50, roughly 80% of which are women in the United States. Osteoporosis is expected to increase to 14 million in 2020[37]. Postmenopausal women in temperate and affluent societies are at risk for disease, and nutrition may be pivotal in prevention of fractures and resulting risk for premature deaths[38].

The highest at-risk group for future osteoporosis is adolescent females with low calcium intake. Inadequate

calcium intake in girls may increase risk of osteoporosis later in life since 95% maximum bone mass is acquired before 18 years old[39]. Evidence from retrospective studies show regular consumption of dairy products in adolescence was linked to lower levels of post-menopausal bone loss[40,41]. Most evidence supports positive associations between calcium intake during adolescence and achievement of peak bone mass. About 25% of bone mass is acquired between the ages of 12 to 14 in females[42]. Bone that has been already synthesised is modelled and remodelled with the rate of formation exceeding resorption[4]. Before puberty, growth hormone and oestrogen increase in preparation for menarche which also affects peak bone mass, with slightly more evidence suggesting that late menarche may negatively affect peak bone mass[40].

Bone mass achieved in adolescence determines bone strength in adulthood. For example, if an adolescent is at a high percentile of bone mass distribution, they will most likely be at a high percentile during adulthood[39]. During growth, most calcium is accumulated and retained by age 20 and continues to be consolidated until 30–35 years old[11,21].

Conclusion

Current dietary practices among US adolescent females are shifting toward increased soda consumption at the expense of milk and dairy products. Bone growth during adolescence requires higher levels of calcium intake, and by age 18, most bone mass is achieved. It is becoming more likely that reduced calcium intake in adolescence plays a major role in the rising prevalence of osteoporosis. Studies conducted in adolescent women show several ways that the future risk of osteoporosis can be prevented. Dairy product consumption, and calcium and vitamin D supplementation are the most successful methods to prevent future risk of osteoporosis. Among populations with low

consumption of dairy products, calcium fortification of commonly consumed foods is also effective.

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