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Review

Update on the possible nutritional importance of silicon

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ABSTRACT

Convincing evidence that silicon is a bioactive beneficial trace element continues to accumulate. The evidence, which has come from human, animal, and in vitro studies performed by several laboratories, indicate that silicon in nutritional and supra nutritional amounts promotes bone and connective tissue health, may have a modulating effect on the immune or inflammatory response, and has been associated with mental health. A plausible mechanism of action for the beneficial effects of silicon is the binding of hydroxyl groups of polyols such that it influences the formation and/or utilization of glycosaminoglycans, mucopolysaccharides, and collagen in connective tissue and bone. In addition, silicon may affect the absorption, retention or action of other mineral elements (e.g., aluminum, copper, magnesium). Based on findings from both animal and human experiments, an intake of silicon of near 25 mg/d would be a reasonable suggestion for an adequate intake that would assure its nutritional benefits. Increased intakes of silicon through consuming unrefined grains, certain vegetables, and beverages and cereals made from grains should be recognized as a reasonable dietary recommendation.

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Contents

Introduction

Silicon is nutritionally essential for some lower forms of life [1]. Silicon has a structural role in diatoms, radiolarians, and some sponges. Diatoms, which are unicellular microscopic plants, have an absolute requirement for silicon as monomeric silicic acid for normal cell growth. Silicon also may be essential for some higher plants (e.g., rice). Because silicon deprivation has not been shown to interrupt the life cycle in mammals, or to have a defined biochemical function, silicon is not generally accepted as an essential nutrient for higher animals and humans. However, for over 40 years, reports about silicon having beneficial, especially on connective tissue and bone formation, in higher animals and humans have appeared. Initial experiments performed in the 1970s used supra nutritional supplemental amounts of silicon (100 and 500 mg/kg diet) to prevent abnormalities in animal models fed low-silicon diets of questionable nutritional quality based on growth data. The silicon supplementation alleviated abnormal bone structure and strength in chicks and rats; abnormal bone cartilage characterized by decreased hexosamine in chicks; and decreased

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collagen and prolyhydroxylase activity in skull bone from cultured chick embryos [1,2]. Concern about dietary quality resulted in the question of whether the supra nutritional supplements were alleviating abnormalities caused by a silicon deprivation or induced by some other sub-optimal dietary factor.

Silicon, bone and connective tissue

Experiments performed since 2000 have indicated that only nutritional amounts of silicon are needed to prevent bone, hexosamine, and collagen metabolism abnormalities, similar to, but of less magnitude than those reported in the 1970s, in animal models fed apparently nutritionally adequate diets low in silicon. In three studies, silicon supplementation of 10 or 35 mg/kg diet containing <2.0 mg/kg silicon, was used to show that the silicon deprivation in rats decreased collagen formation [3] and femur hydroxyproline concentration [4] and increased urinary helical peptide excretion [5]. Another study provided drinking water containing 53.2 μg/g silicon to rats fed diets containing 3.2 μg/g silicon for 26 weeks [6]. The silicon deprivation reduced bone growth plate thickness and increased chondrocyte density. In mice, a silicon supplement of 50 μg/g to a diet containing a soluble silicon content of 0.2 μg/g increased femur dry and ash weights, calcium and hydroxyproline contents, and alkaline phosphatase activity, and decreased femur tartrate-resistant acid phosphatase and urinary excretion of hydroxyproline [7]. Silicon supplementation also increased femur strength and stiffness, and bone marrow mRNA expression related to osteoblastogenesis.

Recent in vitro studies also indicate that silicon promotes bone formation. Orthosilicic acid at physiological concentrations was found to stimulate collagen type 1 synthesis in human osteoblast-like cells and enhance osteoblastic differentiation in culture [8]. Silicon in silica-based bioactive glass and ceramics has been implicated in the in vivo efficiency of bone engineering implants through involvement in osteoblast proliferation and differentiation, type 1 collagen synthesis, and apatite formation [9,10].

Supra nutritional amounts of silicon also have beneficial effects on bone in ovariectomized rats. A silicon supplement of 500 mg/kg diet for 30 d increased longitudinal growth and mineral content of the femur [11]. In another study, ovariectomized rats were fed a calcium-deficient AIN-93M diet and compared to rats fed the same diet supplemented with 500 mg/kg silicon as sodium metasilicate for 10 weeks [12]. The silicon supplementation significantly increased bone mineral density of the femur and tibia and C-telopeptide type 1 collagen levels in serum. Choline-stabilized orthosilicic acid orally supplemented at a dose of 1 mg/kg body weight daily for 30 weeks was found to partially prevent femoral bone loss in aged ovariectomized rats [13]. Another study with aged (17 weeks) ovariectomized rats found that daily oral administration of 20 mg silicon/kg body weight significantly increased femur and tibia bone mineral density [14].

Recent epidemiological studies have indicated that nutritional intakes of silicon are beneficial for bone health in humans. Dietary silicon was positively associated with bone mineral density in four hip sites of men and premenopausal women in the Framingham Offspring cohort of 1251 men and 1596 women [15]. Large differences of up to 10% were found between the highest (>40 mg/d) and lowest (<14 mg/d) quintiles of silicon intake. Also in the Framingham Offspring Cohort, the beneficial effect of a moderate consumption of beer on hip and spine bone mineral density was associated with silicon in the beer [16]. In addition, silicon intake was positively associated with bone mineral density at the femur neck in late premenopausal women and postmenopausal women on hormone replacement therapy in the Aberdeen Prospective Osteoporosis Screening Study [17]. The lowest quartile of silicon intake was 16 mg/d and highest quartile was 31.5 mg/d. Quartile of energy-adjusted silicon intakes were negatively associated with urinary markers of bone resorption (pyridinoline and deoxypyridinoline crosslinks) and positively associated with the serum N-terminal propeptide of type 1 collagen, a marker of bone formation.

Although animal, in vitro, and epidemiological findings indicate increased dietary silicon is associated with improved bone mass or density and bone turnover markers, human silicon supplementation or intervention studies have found bone mass improvements only in a small number subjects, only a limited number of positive bone turnover marker changes, and just subjective changes in skin and hair. In a review, it was reported that a 28 mg/d silicon supplement for 12 weeks increased spine bone mineral density by 2.5% in six women with low bone mass [18]. In support of this report was a double-blind, placebo-controlled study completed by 136 women supplemented daily with 1 g calcium and 20 μg vitamin D_3, daily supplements of 3, 6, or 12 mg silicon as choline-stabilized orthosilicic acid, or a placebo for 12 months [19]. The 6 and 12 mg doses of silicon significantly increased the bone formation marker of type 1 collagen at 12 months. Another study that used choline-stabilized orthosilicic acid as a supplement involved 50 women with photo-damaged skin [20]. A supplement of 10 mg/d silicon for 20 weeks improved the photo-damaged skin surface and mechanical properties, and decreased hair and nail brittleness.

In contrast to the limited positive reports, is a study involving 17 postmenopausal women with low bone mass that were randomized to drinking either purified water or artesian water containing 86 mg/L silicon for 12 weeks [21]. The silicon-rich artesian water significantly increased urinary silicon excretion but the purified water did not. Bone turnover markers procollagen type 1, N-terminal propeptide, bone specific alkaline phosphatase, and osteocalcin in serum were not significantly affected within or between groups.

The limited supplementation findings assert the need for randomized controlled trials of silicon supplementation to establish whether achieving a specific dietary intake of this element results in benefits for bone and connective tissue health. These trials should involve a significant number of participants that could be stratified by serum silicon and with supplementation long enough to have measurable effects on changes in bone or connective tissue health.

Silicon and immune and inflammatory response

In 1988, it was suggested that silicon had a regulatory role in the cell cycle of lymphocytes because monomethylsilanetriol at an optimal concentration of 10 mg/L silicon in culture media stimulated peripheral lymphocyte proliferation and decreased lymphoblast proliferation [22]. This possible effect of silicon in nutritional amounts received little attention until 2002 when it was reported that mitogen-induced DNA synthesis of splenic T-lymphocytes from silicon deprived (2.3 mg/kg diet) compared to silicon supplemented (35 mg/kg diet) rats was increased when the rats were fed normal adequate dietary arginine but decreased when fed a supplemental 5 g/kg diet [23]. Since then, findings from two other studies with rats have suggested that silicon supplementation (35 mg/kg diet) vs. silicon-deprivation (2.8 and 1.9 mg/kg diet) might affect the immune or inflammatory response. When injected with type II collagen to induce a long-term (four weeks) inflammatory response, circulating lymphocyte counts were higher and neutrophil counts were lower in silicon-deprived than-supplemented rats [24]. On the other hand, silicon deprivation did not affect acute-phase (2 h) inflammatory markers changes induced by the injection of the endotoxin lipopolysaccharide [25]. However, the endotoxin increased the liver and femur concentrations of silicon in silicon-deprived rats but not in silicon-supplemented rats, which suggests a relation between silicon and the inflammatory or immune response. Further research is required

to establish whether silicon has a beneficial modulating effect on this response.

Silicon and mental health

In 1996, it was reported that an association between cognitive impairment and aluminum in drinking water depended upon the silica concentration in water [26]. High levels of aluminum appeared to have a deleterious effect on cognitive function when the silica concentration was low, and high silica concentrations had a protective effect on the association between high aluminum and impaired cognitive function. In 2000, it was reported that the 8-year follow-up of subjects in the Paquid cohort showed that the exposure to drinking water with silica concentrations ≥11.25 mg/L was associated with a lower risk for developing Alzheimer's disease [27]. Higher silica in drinking water was also found to be associated with a reduced risk of developing Alzheimer's disease in seven-year follow-up of 1462 women (aged ≥75 years) participating in the Epidemiology of Osteoporosis Study [28]. The apparent beneficial effect of silicon on cognitive function has been postulated to occur because a reaction between silicon as silicic acid and aluminum compounds such as aluminum hydroxide forms aluminosilicate [29]. Formation of aluminosilicate prevents aluminum absorption and retention, and thus prevents chronic aluminum accumulation that may cause or enhance neurodegeneration in the brain [30]. This hypothesis does not support the suggestion that silicon has a beneficial effect through a biochemical mechanism.

Plausible silicon mechanism of action

A plausible biochemical mechanism of action for silicon is some type of structural or binding role that affects the formation of connective tissue where it is strongly bound in significant concentrations [1,2]. This binding role is supported by the finding that silicon easily forms stable complexes with polyols that have at least four hydroxyl groups [31]. Such polyols include hexosamine and ascorbate used to form glycosaminoglycans, mucopolysaccharides, and collagen involved in connective tissue formation and stabilization and bone formation. In plants, silicon apparently binds hydroxyl groups of proteins involved in signal transduction [32]. A similar action in higher animals might be the basis for associating silicon with influencing the immune or inflammatory response, mental function, and gene expression of factors involved in osteoblastogenesis and osteoclastogenesis.

The hypothesis that silicon may be beneficial by altering the absorption and utilization of other mineral elements involved in bone metabolism, immune or inflammatory response, or cognitive function cannot be discounted. In addition to aluminum discussed above, silicon, especially in supra nutritional amounts, has been reported to facilitate the absorption, retention, and/or utilization of copper [33] and magnesium [34].

Silicon metabolism

Several recent studies of silicon have involved its dietary intake, absorption, transport, retention, and excretion. These studies suggest that silicon may have a significant role in higher animals and humans because silicon is well regulated by the body. Silicon is relatively well absorbed when consumed from various foods and drinks. One study found an average of 41% of silicon in food was excreted in urine, which is an indicator of absorption [35]. A study determining the absorption of silicon from different foods and supplements found it was highest from monomethyl silanetriol and beer (64% of dose), followed by green beans (44%), orthosilicic acid solution (43%), choline-stabilized orthosilicic acid (17%), and bananas (4%) [36]. An in vitro method found the per cent availability of silicon from various foods and drinks ranged from 0.6% from beans to 100% from beer [37].

Evidence that silicon is efficiently transferred to tissues and urine is that the silicon concentration in blood remains relatively constant over a range of dietary intakes [37]. Reported mean or median fasting human serum concentrations of silicon range from 10 to 31 μg/dL [37,38]. Some absorbed silicon is transferred to tissues because it is present in all tissues including brain [1,18]. Much of the silicon retained by the body is found in connective tissues, including aorta, bone, skin, tendon, and trachea [1]. After ingestion, most absorbed silicon is excreted within 4–8 h in the urine [18], most likely as orthosilicic acid and/or magnesium orthosilicate. Thus, the kidney apparently is a major regulator of silicon in the body.

Silicon status indicators

Because reported fasting serum concentrations range from 10 to 31 μg/dL, concentrations in the lower part or below this range might be an indication of a suboptimal silicon status. In addition, a consistent urinary silicon excretion below 14 mg/d may be indicating that an individual has a suboptimal intake of silicon because this excretion compared with 40 mg/d was associated with decreased bone mineral density in humans [15]. This finding also suggests that there is a dose-response to silicon for its beneficial effects.

Beneficial intakes of silicon

On the basis of extrapolations from animal data, weak balance data from humans, and the usual amount of silicon excreted daily by humans, it has been suggested that an adequate intake to achieve the beneficial effects of silicon might be between 10 and 25 mg/d [39]. Based on the findings from 1251 men and 1596 pre- and postmenopausal women in the Framingham Offspring Cohort, the beneficial intake most likely is near the 25 mg/d intake or slightly higher. The majority of the intakes in this cohort were within a relatively narrow range of 23.6 ± 8.9 mg/d for women and 27.5 ± 10.7 for men. The highest bone mineral density found was in the highest silicon intake quintile with intakes ranging from 30.2 to 63.2 mg/d and 34.4 to 118.0 mg/d compared to the lowest quintile ranges of 7.1–16.7 and 7.6–18.8 mg/d for premenopausal women and men, respectively [15]. The higher silicon intakes by men may be the result of higher beer consumption. The silicon in barley and hops is solubilized during the beer-making process, which makes this beverage a rich source of silicon. Other foods rich in silicon include cereals and cereal products (especially less refined cereals and oat-based products), dried fruit, beans, spinach, and lentils [40].

Conclusion

Recent findings provide additional evidence that silicon in nutritional amounts is beneficial for bone growth and maintenance. In addition, silicon in nutritional amounts might have a beneficial effect in the immune or inflammatory response and in mental health. Supra nutritional amounts of silicon also may promote bone health. Plausible mechanisms of actions have been suggested for the beneficial effects of silicon. Recent epidemiological findings suggest that intakes near 25 mg/d might promote bone health. Although randomized controlled trials evaluating the effectiveness of silicon supplementation are needed, consideration should be given for providing dietary guidance for silicon. If the science base is not considered strong enough to set an adequate intake level, an appropriate action would be to recommend the consumption of

foods and beverages that provide an intake of silicon that studies to date suggest are beneficial for health and well-being.

Conflict of Interest

The author has no conflict of interests to declare.

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