Silicon: A Nutritional Beneficence for Bones, Brains and Blood Vessels?

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Ample evidence exists to indicate that silicon is essential for forming or maintaining normal healthy bones, brains and blood vessels, and thus may be a factor in the occurrence of some human diseases involving these tissues.

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Silicon has been long suspected to be important in maintaining health in humans.[3] Before much was known about silicon in biology, one of the luminaries of medical science, Louis Pasteur, predicted that silicon would be found to be an important therapeutic substance for many diseases. At the beginning of this century, numerous French and German reports suggested that the prediction of Pasteur would become fact. These reports described therapeutic successes in treating numerous diseases, including atherosclerosis, hypertension and dermatitis with sodium silicate, with simple organic silicon compounds and with tea made from the silicon-rich horsetail plant. However, by 1930, silicon in medicine faded into obscurity as a consequence of therapeutic failures and inadequate evidence for silicon being biologically active. For the next 40 years, silicon, as consumed in the diet, was generally considered a biologically inert, harmless, nonessential element for living organisms except for some lower forms of life (diatoms, radiolarians and sponges) in which silica serves a structural role.

In 1972, it was reported that silicon was essential for bone formation.[5] About the same time, other

reports appeared suggesting, like earlier reports, that inadequate dietary silicon may contribute to some cases of atherosclerosis and hypertension, in addition to some bone disorders and the aging process.[6] Since then, reports have periodically appeared that give further support for silicon being nutritionally important in preventing some chronic diseases associated with aging. Surprisingly, these reports seem to have been generally ignored or considered inconsequential by clinical and nutritional professionals, media personnel or the general public. For 20 years, the battle of bringing attention to the nutritional importance of silicon has been essentially fought by Dr. Edith Carlisle.[5-10] Recently, we decided to join the fray. Based upon our findings during the past 2 years, we believe the possibility that silicon is needed for healthy bones, blood vessels and brain deserves more attention by the research and clinical communities.

SILICON BIOCHEMISTRY

Organosilicon compounds are analogues of organocarbon compounds[19]; thus, the possibility of a silicon-based life analogous to a carbon-based life has been a seductive idea for science fiction writers. Support for this possibility could be the finding that silicon can partially replace carbon in the biosynthetic processes of nocardioform chemoautotrophic bacteria from leprosy tissues.[11] However, the biochemistry of silicon makes it unlikely that silicon-based life exists anywhere in the universe. Silicon is larger and less electronegative than carbon. Silicon forms very rigid bonds; they do not bend, nor does silicon undergo stereochemical conversions as easily as carbon.[19] Nonetheless, silicon has some properties that make it a possible structural or bonding agent in living organisms. Silicon forms Si—O—C bonds with a strong ionic component that can be transferred from an oxygen atom to another with only small changes in energy, and thus the Si—O bridge could act as a "switch" mechanism.[19] Also, hydrogen bonding via silanol groups could occur *in vivo*. For example, hydrogen-bonded complexes between silicic acid and compounds containing hydroxy groups can be sufficiently stable to be important in the secondary structure of biopolymers such as collagen.

In animals and humans, silicon is found both in the free and bound forms. Silicic acid probably is the free form. The bound form of silicon never has been rigorously identified.

SILICON AND BONE

Silicon deprivation results in abnormal skeletal development in animals.[5-8, 19] In silicon-deficient chicks, the leg bones have a reduced circumference, thinner cortex and reduced flexibility. In both silicon-deficient chicks and rats, skulls are abnormally shaped with the cranial bones appearing flatter, or more "serpent-like," than normal. Bone matrix of skulls from silicon-deficient chicks lacks the normal striated trabecular pattern of normal chick skulls. The deficient chick skull shows a nodular pattern of bone arrangement indicative of an immature or primitive type of bone.

Silicon deprivation results in abnormal skeletal development.

The distribution of silicon and the biochemical changes caused by silicon deprivation in bone indicate that silicon influences bone formation by affecting cartilage composition and ultimately cartilage calcification. Carlisle found that silicon is localized in the active growth areas, or the osteoid layer and within the osteoblasts, in young bone of mice and rats.[6-8] Carlisle also found that the more mature the bone mineral, the smaller the amount of measurable silicon.[6-8] In the process of bone mineralization, initially silicon and calcium contents rise congruently in osteoid tissue. In the more advanced stages of mineralization, the silicon concentration falls markedly while the calcium concentration approaches proportions in bone apatite. These findings suggest that silicon is involved in the initiation of calcification through some effect on the preosseous matrix.

Further support of the concept that the primary role of silicon in bone formation involves the organic matrix is that hexosamine (glycosaminoglycans) and collagen concentrations are depressed while macromineral composition of bone mineral is not markedly affected in bone of silicon-deficient animals. Extraction and purification procedures have shown silicon to be chemically combined with the glycosaminoglycan fraction of several types of connective tissue.[6-8] In addition, findings have been obtained which suggest that silicon is involved with phosphorus in the organic phase in the series of events leading to calcification.[7] Although these findings do not define the specific role of silicon in calcification, they strongly suggest that silicon is involved in allowing an association between phosphoprotein-mucopolysaccharide macromolecules and collagen, which play a role in the initiation of calcification and the regulation of crystal growth.

In the last few years, a large number of extracellular matrix macromolecules containing glycosaminoglycans and saccharide, and for which functions are beginning to be defined, have been described.[14] Some of these macromolecules provide an association between cells and their surrounding matrix; this association allows cells to monitor the composition and properties of the matrix and to respond to matrix alterations by changing their synthetic activity. Silicon may be necessary for the association between one or more of these macromolecules and cells, and in this way affects cartilage composition and ultimately cartilage calcification.

We recently found further evidence that silicon status affects a circulating or local macromolecular mediator of bone metabolism. Mediators extracted from bones can stimulate bone cell proliferation, collagen synthesis and bone formation of embryonic chick tibia in culture and ectopic bone formation in rats. We implanted subcutaneously in the thoracic region of rats

gelatin capsules containing powdered bone from silicon-deprived or silicon-adequate rats. Compared to those implanted with the silicon-deficient bone, animals implanted with silicon-adequate bone exhibited decreased calcium and increased copper concentrations in their tibias (Table 1) and had a higher uptake of a ^{45}Ca tracer in femur. This suggests that silicon-adequate bone powder contained a substance that affected bone composition elsewhere and that was present in lower quantity in silicon-low bone powder. In addition, the ^{45}Ca uptake by ectopic bone (implanted bone powder) was higher in silicon-adequate than silicon-deprived rats (Figure 1).

Based upon the substantial evidence accumulated to date, there is little doubt that silicon deprivation affects bone health. Because silicon apparently affects the initiation and rate of calcification of bone, silicon may be an important factor in disorders characterized by an imbalance between bone formation and resorption. Furthermore, because silicon affects cartilage composition, including articular cartilage, inadequate silicon nutriture may be of consequence in some joint disorders such as osteoarthritis.

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Table 1
Effect of Dietary Silicon and Implant Source on Calcium and Copper Concentrations of Tibia in Rats*

Treatment		Tibia Ca	Tibia Cu
Implant	Silicon	(mg/g dry wt)†	(μg/g dry wt)†
+	+	194 ± 2	4.98 ± 0.07
+	−	198 ± 2	4.89 ± 0.08
−	+	207 ± 2	4.25 ± 0.07
−	−	207 ± 2	4.01 ± 0.07

* Implant (+) indicates that implant bone was taken from rats fed a silicon-supplemented (50 μg/g) diet. Implant (−) indicates that implant bone was taken from rats fed a silicon-low (1.2 μg/g) diet. Silicon (+) identifies animals fed a silicon-adequate (35 μg/g) diet; silicon (−) identifies animals fed a silicon-deficient (0.6 μg/g) diet. Source of bone for implant affected tibia calcium concentrations $p \leq 0.0002$ and copper concentrations $p \leq 0.0001$.
† Mean ± SEM.

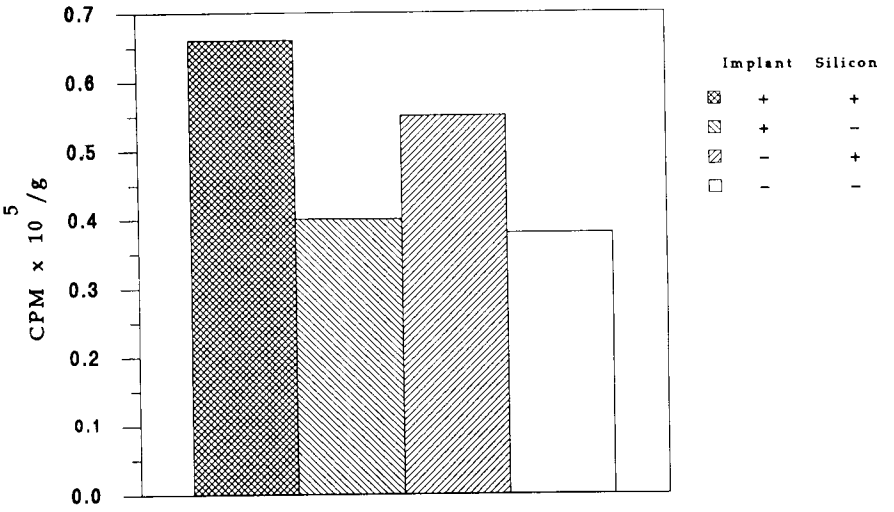

Figure 1. Means of ^{45}Ca expressed as counts per minute × 10^5/g of ectopic bone. The dietary silicon effect on retention of ^{45}Ca in the implant (demineralized bone powder) is significant at $P \leq 0.0004$. The implant source did not affect ^{45}Ca retained in the ectopic bone. Implant (+) indicates source of implant bone was rats fed a Si-supplemented (50 μg/g) diet. Implant (−) indicates source of implant bone was rats fed a Si-low (1.2 μg/g) diet. Silicon (+) identifies animals fed a Si-adequate (35 μg/g) diet; silicon (−) identifies animals fed a Si-deficient (0.6 μg/g) diet.

SILICON AND THE BRAIN

Recently, signs of silicon deprivation in rats have been described that seem unrelated to connective tissue and bone. Rats fed a low-calcium diet accumulated high amounts of aluminum in all brain regions examined when dietary aluminum was high and silicon was low; aluminum content was increased 14-, 5- and 4-fold in the caudate, thalamus and hippocampus, respectively, over that found in those areas of similarly treated, but calcium-adequate, rats.[9] No increase in brain aluminum occurred with a low-calcium, high-aluminum diet supplemented with silicon. Also, brain aluminum increased in calcium-adequate mature rats (aged 10 months upon initiation of deprivation) fed a silicon-deficient diet for 18 months. The aluminum contents in the hippocampus, posterior cortex and cerebellum were 26, 24 and 126% higher, respectively, in silicon-deprived than in silicon-supplemented rats. In thyroidectomized rats, aluminum supplementation markedly decreased brain zinc content if the diet was low in silicon; no decrease occurred when silicon was supplemented to the diet.[10]

Further evidence that silicon performs a vital function in the brain is the pattern of distribution of silicon in the brain. The concentration of silicon is higher in brain than in plasma. Furthermore, silicon concentrations vary widely among the different brain regions, with much higher concentrations in the hippocampus, caudate and lentiform nucleus than in the spinal cord and brain stem.[9]

Electron probe analysis has associated silicon with calcium and phosphorus in the brain.[15] The relationship between calcium and silicon is discussed above. A possible biochemical relationship between phosphorus and silicon may involve protein phosphorylation. This suggestion is supported by the finding that the addition of silicate to silicon-starved diatoms resulted in three proteins showing a significant

and rapid change in phosphorylation.[18] In other words, silicon apparently affected the phosphorylation and dephosphorylation of specific proteins.

Alzheimer's disease has been associated with an increased concentration of aluminum in the brain. In this disease, calcium homeostasis, protein phosphorylation and membrane iron metabolism of certain target neurons are disturbed. Perhaps because silicon is associated with calcium and phosphorus in the brain, silicon deprivation, especially when dietary calcium is low, has an effect similar to the Alzheimer's disease process. That is, it changes the blood-brain barrier, which allows aluminum to enter and accumulate in nerve cells when dietary aluminum is high.

Although the mechanism through which silicon affects brain biochemistry is unknown, accumulating evidence clearly indicates that silicon is needed to prevent detrimental changes in the brain, especially under stress conditions of low dietary calcium, high dietary aluminum and/or inadequate thyroid function. Thus, silicon nutriture may be of consequence in some aging and disease processes that affect the brain.

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SILICON AND BLOOD VESSELS

Because blood vessels contain glycosaminoglycans and collagen, which are affected by silicon deprivation, it is not surprising that silicon has been implicated in maintaining normal blood vessels and in preventing atherosclerosis.[2, 16, 20] The first suggestion that silicon may be beneficial in preventing atheromas and arteriosclerosis appeared in 1911. Since 1965, numerous findings have been obtained to support this suggestion.

French investigators have reported that the silicon content of normal human aorta decreases markedly with age and that the concentration of silicon in the arterial wall decreases with the development of atherosclerosis.[16] The changes in the aortic silicon content were found to occur mainly in the elastin and mucopolysaccharide fractions. Also, in rabbits, the induction of atheroma by an excess of cholesterol resulted in a rapid fall in the silicon concentration of aorta; silicon supplementation ameliorated this fall and decreased or delayed the appearance of atheromas. Other observations supporting the concept that silicon nutriture is important for healthy blood vessels is that of an inverse relationship between the concentration of silicic acid in drinking water and the prevalence of cardiovascular disease in Finland[20] and that blood vessels of old rats with chronic hypertension contain relatively low amounts of silicon and have a shortage of collagen fibers, which require silicon-rich hyaluronic acid for their development.[2]

The beneficial role of silicon in preventing atheroma formation has been suggested to involve assuring the integrity of elastic fibers and thus impermeability of the arterial wall to fatty infiltration and calcium deposition.[16] This suggestion is supported by the finding that silicon inhibits the diffusion of dye into rabbit derma.[16]

A major piece of evidence is lacking to make a strong case for silicon being nutritionally important for blood vessel integrity; that is, abnormalities in blood vessels have not been described as a sign of silicon deprivation in experimental animals. This lack, plus the fact that relatively high amounts of silicon were used to induce the beneficial effects described, allows for the possibility that silicon may have been acting pharmacologically instead of physiologically in the animal experiments done to date involving blood vessel integrity. Here, pharmacologically is defined as "the ability of a relatively high dietary intake of a substance to either alleviate an abnormality caused by something other than a nutritional deficiency of that substance or alter some biochemical function or biologic structure in a manner that can be construed as beneficial." The possibility that silicon can act pharmacologically is indicated by the finding that, while a silicon supplement of 5 mg/kg of diet had no effect, 135, 270 and 540 mg/kg supplements increased aortic elastin in copper-adequate rats.[13] Moreover, the 540 mg/kg supplement, but not the other supplements, increased aortic elastin in copper-deficient rats; these rats have defective elastin formation.

Much remains to be learned about the nature of the beneficial effects of silicon on blood vessel health and whether a decline in aortic silicon content enhances the atherosclerotic process. Nonetheless, the findings to date indicate that further studies are warranted in determining whether inadequate dietary silicon may contribute to cardiovascular diseases such as ischemic heart disease and hypertension.

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SILICON METABOLISM

Little is known about the metabolism of silicon. Apparently, the form of dietary silicon determines whether it is well absorbed. In one study, humans absorbed only about 1% of a large single dose of an aluminosilicate compound but absorbed over 70% of a single dose of methylsilanetriol salicylate, a drug developed for the treatment of circulatory ischemias and osteoporosis.[1] Further evidence that some forms of silicon are well absorbed is that daily urinary silicon excretion apparently is over 50% of daily silicon intake.

Average daily intakes of silicon have been suggested to range from about 20 to 50 mg/day.[17] This suggestion was based on limited, perhaps somewhat questionable food analyses, and the composition of the Food and Drug Administration's (FDA) Total Diet, which contains substantial amounts of grains

and cereals. The calculated silicon content of the FDA Total Diet was 19 mg/day for women and 40 mg/day for men. These values seem reasonable because one report of a study involving 23 individuals indicated that normal urine contains about 21 mg/L, and that about 33 mg of silicon is excreted daily in urine.[4] However, this report stated that others had found much lower, in addition to similar, amounts in urine. These values indicate that the elimination of absorbed silicon is mainly through the urine where it probably exists as magnesium orthosilicate.[4]

DIETARY CONSIDERATIONS OF SILICON

Although a biochemical function for silicon is unknown, the preceding strongly suggests that silicon is required by humans. However, postulating a silicon requirement for humans is difficult; no appropriate human data are available and only limited usable animal data exist. We have found that rats fed about 4.5 mg of silicon/kg of diet, mostly as the very available sodium metasilicate, do not differ from rats fed about 35 mg of silicon as sodium metasilicate/kg of diet; both prevent, equally well, silicon deficiency signs exhibited by rats fed about 1.0 mg of silicon/kg of diet (Table 2). Animals diets contain about 4000 kcal/kg. The food an average person consumes daily often contains between 2000 and 2500 kcal. Thus, if dietary silicon is highly available, based on animal data, the human requirement for silicon is quite small, perhaps in the range of 2 to 5 mg/day. However, silicon as found in most diets probably is not as absorbable or available as sodium metasilicate; significant amounts probably occur as aluminosilicates and silica from which silicon is not readily available. Furthermore, factors such as aging and low estrogen status apparently decrease the ability to absorb silicon.[12] Thus, the recommended intake of silicon may be found to be between 5 and 10 mg/day.

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Total dietary silicon intake of humans varies greatly with the amounts and proportions of foods of animal (silicon-low) and plant (silicon-high) origin consumed and the amounts of refined and processed foods in the diet. Normally, refining reduces the silicon content of foods. However, in recent years, silicate additives have been increasingly used in prepared foods and confections as anticaking or antifoaming agents. Although this increases total dietary silicon, most of it is not bioavailable. The silicon content of drinking water, and beverages made thereof, shows geographical variation; silicon is high in hard water and low in soft water areas. The richest sources of silicon are unrefined grains of high fiber content, cereal products and root vegetables.

CONCLUDING STATEMENTS

Ample evidence exists to indicate that silicon can be accepted as an essential nutrient for higher animals, including humans. Findings from animals indicate that silicon nutriture apparently affects macromolecules, such as glycosaminoglycan, collagen and elastin, and thus is needed for healthy bones, brains and blood vessels. Although more should be known about the physiologic function and requirement for silicon before doing so, it is seductive to speculate about specific disorders that can be augmented or caused by inadequate silicon nutriture; those that have been proposed are atherosclerosis, osteoarthritis and hypertension. Even if these speculations are not found to be true, because the silicon content in human diets can easily be lower than that inducing changes in animals (especially those containing refined and animal product foods), and because the response of animals to silicon deprivation can be enhanced by stressors commonly found with humans, such as low dietary calcium, high dietary aluminum and low estrogen status (postmenopausal), finding pathologic conditions caused by silicon deprivation would not be surprising. Thus, silicon probably should be considered a nutrient of concern for humans.

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Table 2
Comparison of Some Bone Variables of Rats Fed Three Concentrations of Silicon for 9 Weeks

Si (μg/g diet)	Skull P (mg/g dry wt)	Hydroxyproline of Humerus (mg/g dry wt)	Hexose of Humerus (mg/g dry wt)
1.0	91.1 ± 2.3	26.5 ± 0.46	33.08 ± 6.55
3.5	97.8 ± 3.0	30.4 ± 2.14	10.94 ± 0.58
35	99.8 ± 2.7	32.9 ± 1.19	11.15 ± 0.71
p value of Si effect	0.07	0.02	0.005

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Media Corner

Eating for Two is a comprehensive 39-minute video program with support materials that provides information on prenatal diet, weight gain, exercise, harmful substances and practical meal planning. The program interweaves interviews with nutritionists and physicians and interviews with mothers and expectant women. Purchase price: $79.95. Production date: 1992. Contact: Cambridge Educational, PO Box 2153, Charleston, VW 25328-2153. Phone: 1-800-468-4227; fax: 304-744-9351.

Nutrition for the Over-50 Gang is a 15-minute videotape that addresses several nutritional issues relating to older adults, such as osteoporosis and constipation. Purchase price: $79.95. Production date: 1992. Contact: National Health Video, 12021 Wilshire Blvd., Suite 550, Los Angeles, CA 90025. Phone: 310-472-2275.

Cartoon Slides, by Linda McDonald, MS, RD, is a set of 20 humorous slides that can be incorporated into other slide presentations. Production date: 1992. Price: $79.95. Contact: Nutritional Counseling Education Services, 1904 E. 123rd St., Olathe, KS 66061-5886. Phone: 800-445-5653.

Weight Watchers' **Journey to the Health Zone** is a comprehensive in-school curriculum that helps children in kindergarten and first-grade understand the relationship of food and daily activity to their bodies and to begin taking responsibility for healthy habits. The kit consists of an audio cassette with sing-along songs, a read-aloud story book, a poster and a teacher's guide. Production date: 1992. To obtain kits, contact your local Weight Watchers organization.

The TerminEater is a 16-minute video program directed at upper level elementary school children. Produced by the Arizona project LEAN Coalition, the video, a parody of the Arnold Schwartenaeger films, entertains children while motivating them to reduce fat consumption. Accompanying materials: guidebook containing student activities and worksheets. Production date: 1993. Price: $39.95 plus S&H. Contact: Arizona Project LEAN Coalition, 3605 North 7th Avenue, Phoenix, AZ 85013.

The Food Guide Pyramid, a 16-minute videotape, guides consumers on what foods to eat, what nutrients are in these foods and how to make the best nutritional choices. Production date: 1993. Price: $69.95. Contact: National Health Video, 12021 Wil shire Blvd., Suite 550B, Los Angeles, CA 90025. Phone: 800-543-6803.

How to Read the New Food Label, an 18-minute videotape geared toward the consumer, features an explanation of standardized serving sizes, health claim regulation, descriptor word definitions, added nutrient listings such as total fat, fiber, complex carbohydrates, and new reference values (RDI and DRV). Production date: 1993. Price: $79.95. Contact: National Health Video, 12021 Wilshire Blvd., Suite 550B, Los Angeles, CA 90025. Phone: 800-543-6803.

Interdisciplinary Nutrition Curriculum, developed by the Penn State Nutrition Center for grades 6 through 8, uses nutrition as the vehicle to interrelate core and allied subjects. The curriculum consists of three thematic units: Prehistoric vs. Modern Diet, Growing to the Max and Food-Environment Connection. Contents include lesson plans, student worksheets, background information, transparencies and a videotape. Production date: 1992. Price: $98.00 plus $6.00 S&H. Contact Penn State Nutrition Center, 417 E. Calder Way, The Pennsylvania State University, University Park, PA 16801-5663. Phone: 814-865-6323.

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