# Dietary silicon intake and absorption[1–3]

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**ABSTRACT**

**Background:** Increasing evidence suggests that silicon is important in bone formation. The main source of silicon for humans is the diet, but the bioavailability of silicon from solid foods is not well understood.

**Objective:** We estimated the dietary intake of silicon by adults, separately for men and women and for different age groups. Foods that were major contributors to silicon intake were identified. We then estimated the gastrointestinal uptake of silicon from major food sources and studied how uptake correlated with the silicon contents of the foods.

**Design:** Silicon intakes were determined in cohorts from the original Framingham Study and the Framingham Offspring Study by using a 126-item food-frequency questionnaire. Gastrointestinal uptake of silicon from foods was estimated in 3–8 healthy subjects by using urinary silicon excretion as a surrogate measure of silicon uptake.

**Results:** Mean silicon intakes in men (30 and 33 mg/d in the original Framingham and Framingham Offspring cohorts, respectively) were significantly higher than those in women (24 and 25 mg/d in the 2 cohorts, respectively; $P = 0.0001$). Silicon intake decreased with age ($P < 0.001$, adjusted for sex). The major food sources were beer and bananas in men and bananas and string beans in women. Silicon was readily available from foods; a mean of 41% of the ingested silicon was excreted in urine. The silicon content of the foods consumed was significantly correlated with urinary silicon excretion ($P = 0.019$).

**Conclusions:** Solid foods are a major source of available silicon. The association between dietary silicon intake and bone health should now be investigated. *Am J Clin Nutr* 2002;75:887–93.

**KEY WORDS** Silicon, orthosilicic acid, phytolithic silica, silicon intake, gastrointestinal absorption, bioavailability, cohort study, diet, nutrition, bone formation

## INTRODUCTION

Evidence that silicon plays a major role in bone formation has been accumulating recently, yet the bioavailability of silicon from the diet is unclear. Indeed, it is assumed that silicon, as orthosilicic acid [$Si(OH)_4$], is available only from fluids (such as drinking water and beer) but not from foods, in which it exists as polymeric or phytolithic silica (1–5). However, because fluids account for only 20–30% of total silicon intake (6–8), and because silica in solid foods could be hydrolyzed to orthosilicic acid in the gastrointestinal tract (9,10), studies should be done to determine whether silicon may be available from foods. This issue has special importance for epidemiologic studies that aim to correlate silicon intake with bone health.

Studies of silicon deprivation in growing animals conducted in the early 1970s showed reduced growth and marked defects of bone and connective tissue (11, 12). In addition, silicon supplementation of postmenopausal women with osteoporosis not only inhibits bone resorption but also increases trabecular bone volume (13) and bone mineral density (14). These results are supported by the ovariectomized rat model of postmenopausal osteoporosis (15, 16), in which oral silicon completely abrogates the loss of bone mass. We showed in osteoblast cell lines and human bone marrow stromal cells in vitro that physiologic concentrations of orthosilicic acid increase the synthesis of bone markers including type I collagen, the major organic component of bone matrix (DM Reffitt, N Ogston, R Jugdaohsingh, et al, unpublished observations, 2001). Orthosilicic acid may also be involved in the mineralization of bone matrix (17, 18).

Several reports about the silicon content of foods have been published (6–8). However, no data are available on the bioavailability of silicon from solid foods. Bioavailability data are available only for dietary fluids (5, 9, 19, 20). The bioavailability of silicon from phytolithic silica in plant-based foods is thought to be low. It is believed that much, if not all, of this silicon is excreted in the feces (1, 3–5, 21). This assumption has not, however, been confirmed.

The kidney is the major route of excretion of absorbed silicon, which is highly filtered and only slightly reabsorbed by the tubules (9). Thus, urinary silicon is a good proxy for absorption (9)

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[2] Supported by the US Department of Agriculture (contract no. 53-3K06-5-10), the National Institutes of Health (RO1 AR/AG 41398), the NIH/NHLBI (contract 1-HC-38038), The Wellcome Trust (for support of the inductively coupled plasma optical emission spectrometer), and The Special Trustees of St Thomas' Hospital (to RJ). SHCA was supported by an Entry Level Training Fellowship from The Wellcome Trust.

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Received April 2, 2001.

Accepted for publication June 4, 2001.

**TABLE 1**
Characteristics of the study population

| | Framingham Offspring cohort[1]: age groups (y) | | | | | Original Framingham cohort[2]: age groups (y) | | |
|---|---|---|---|---|---|---|---|---|
| | 26–39 | 40–49 | 50–59 | 60–69 | 70–83 | 67–69 | 70–79 | 80–95 |
| Sample size | | | | | | | | |
| Men | 94 | 403 | 529 | 458 | 121 | 25 | 273 | 76 |
| Women | 96 | 508 | 602 | 493 | 114 | 50 | 429 | 123 |
| Weight (kg) | | | | | | | | |
| Men | 86.7 ± 14.7[3] | 86.9 ± 13.7 | 88.9 ± 15.1 | 84.7 ± 12.2 | 81.9 ± 14.8 | 86.5 ± 14.2 | 79.0 ± 12.5 | 74.2 ± 10.7 |
| Women | 68.3 ± 14.9 | 69.6 ± 16.0 | 70.1 ± 13.8 | 68.8 ± 14.5 | 68.4 ± 12.9 | 67.5 ± 11.5 | 64.6 ± 13.0 | 61.0 ± 10.7 |
| Height (cm) | | | | | | | | |
| Men | 177.3 ± 6.9 | 176.6 ± 6.0 | 176.0 ± 6.4 | 173.7 ± 6.3 | 172.2 ± 6.3 | 173.9 ± 6.2 | 170.7 ± 6.9 | 168.6 ± 6.8 |
| Women | 164.7 ± 6.1 | 163.5 ± 5.9 | 161.8 ± 5.5 | 159.7 ± 5.6 | 157.1 ± 5.7 | 159.0 ± 6.8 | 156.8 ± 6.2 | 154.1 ± 6.9 |
| BMI (kg/m$^2$) | | | | | | | | |
| Men | 27.6 ± 4.4 | 27.8 ± 4.1 | 28.7 ± 4.5 | 28.0 ± 3.6 | 27.5 ± 3.8 | 28.5 ± 4.7 | 27.1 ± 4.0 | 26.1 ± 3.5 |
| Women | 25.2 ± 5.5 | 26.0 ± 5.8 | 26.8 ± 5.2 | 27.0 ± 5.5 | 27.7 ± 5.3 | 26.7 ± 4.3 | 26.3 ± 5.2 | 25.7 ± 4.3 |

[1] Minimum and maximum ages were 30 and 83 y for men and 26 and 81 y for women, respectively.
[2] Minimum and maximum ages were 68 and 95 y for men and 67 and 93 y for women, respectively.
[3] $\bar{x}$ ± SD.

and was used in the present study as a surrogate measure of silicon uptake from the gastrointestinal tract. The aims of this study were to determine *1*) the intake and gastrointestinal uptake of dietary silicon in adults and *2*) whether the silicon content of foods can be used as a marker for its uptake.

## SUBJECTS AND METHODS

### Framingham Study cohorts

The subjects in the study of silicon intake were members of the Framingham Study cohorts. The population-based original Framingham Heart Study cohort was established in 1948 to examine risk factors for heart disease. This cohort included 5209 men and women, most of whom were white (22–24). The subjects, who were aged 28–62 y at study entry, are seen biennially for a physical examination and a battery of questionnaires and tests. Since the study began 50 y ago, nearly two-thirds of the subjects have died. The surviving, now elderly, cohort subjects are still representative of the general Framingham population in terms of age and sex distribution. At biennial examination 20 (1988–1989), 976 cohort members (602 women and 374 men) completed a semi-quantitative food-frequency questionnaire.

The Framingham Offspring Study cohort members are the children (and their spouses) of the original Framingham Heart Study cohort. The Framingham Offspring Study began with 5135 participants in 1971, and subjects are examined every 4 y. There were 3799 participants in the fifth examination cycle, from 1991–1995. Food-frequency questionnaires were available for 3418 subjects (1813 women and 1605 men) and the results were included in this analysis.

To determine silicon intakes separately for men and women and for different ages, subjects in both cohorts were separated by sex into 10-y age groups (**Table 1**). The protocol for this study was approved by the Institutional Review Board for Human Research at Boston University.

### Experimental subjects

Healthy subjects with normal renal function (defined as normal plasma creatinine concentrations) were recruited from the Gastrointestinal Laboratory at St Thomas' Hospital and the Department of Nutrition and Dietetics at King's College London. Study 1 was conducted with 8 subjects (4 men and 4 women). Their mean (±SD) values for age and body mass index (BMI, in kg/m$^2$) were 29.5 ± 7.4 y and 23.1 ± 2.2, respectively. In study 2, the subjects were 2 men and 1 woman (mean age: 27.7 ± 5.5 y; mean BMI: 22.2 ± 2.2).

Ethical approval for these studies was obtained from King's College London Local Research Ethics Committee. The details of both studies and their potential risks were explained to the subjects, each of whom signed a consent form before the study began.

### Study design and methods

*Silicon intake in the Framingham Study cohorts*

Usual dietary intakes of subjects in the Framingham cohorts were assessed with a semi-quantitative, 126-item food-frequency questionnaire (25, 26). This questionnaire has been validated for many nutrients and in several populations (25–27). Before the examination, these questionnaires were mailed to the subjects, who were asked to complete them and bring them to their appointments. Completed questionnaires were excluded, as previously reported (28), if calculated energy intakes were <2.51 or >16.74–17.57 MJ/d or if >12 food items were left blank. A total of 976 questionnaires from the original Framingham cohort and 3418 questionnaires from the Framingham Offspring cohort were analyzed for silicon intake. Processing of the questionnaires to calculate food intake amounts and energy intakes was carried out at Harvard University in Boston.

Silicon values per 100 g (as consumed) of each food item in the food-frequency questionnaire were first obtained from the collated data of Pennington (6). Silicon contents of composite foods were then calculated from the individual components of these foods. If values for reported silicon contents of foods varied between laboratories, additional analyses were performed independently by the authors at King's College London. With the exceptions of liquor and orange juice, our data correlated highly ($r = 0.82$; $n = 28$) with values reported by Pennington (6). Therefore, in almost all instances we used the Pennington values in the database, but we used our own values for orange juice (0.01 ± 0.01 mg Si/100 g;

range: 0.0004–0.25 mg/100 g) and liquor (0.13 ± 0.04 mg Si/100 g; range: 0.06–0.21 mg/100 g).

The data were entered into a data management program (SAS, version 8.1; SAS Institute Inc, Cary, NC) at the Dietary Assessment Research Program at Tufts University in Boston. Data were corrected for the weight of each food item as reported by each individual subject. Because the data were presented as dry weight, silicon contents of brown rice, white rice, and pasta were corrected by 0.30, 0.39, and 0.30, respectively, on the basis of US Department of Agriculture published factors for converting between cooked and raw forms of these foods (29). The silicon values for all the food items were then summed to obtain total silicon intake per subject. We then divided the silicon intake for each food item by the total silicon intake per subject to obtain the proportional ranking of food sources.

### *Silicon uptake in the experimental subjects*

Two studies were undertaken in the experimental subjects. First, we investigated whether silicon was available from a meal of silicon-rich foods that did not include silicon-containing fluids (study 1). Second, we investigated the gastrointestinal uptake of silicon from the major food sources of silicon in the Framingham cohorts (study 2).

In both studies, subjects fasted overnight from 2200 onward. They continued to fast until 6 h after ingestion of the test meal (≈1500). Throughout this study period, subjects ingested ultra-high purity (UHP) water (0.166 L/h) with negligible silicon content (26 μg/L). No other foods or drinks were permitted during the study period.

The UHP water (18 MΩ/cm) was from an Elga (High Wycombe, United Kingdom) water purifier. Blood samples were collected into 10-mL polypropylene transport tubes (Medfor Products, Farnborough, United Kingdom). Urine was collected in preweighed, 2.5-L polypropylene Mauser bottles (Aldrich Chemical Co, Gillingham, United Kingdom). These bottles had been rinsed thoroughly with UHP water and air-dried in a clean-air room. Clean-air facilities (class J clean-air room and class C laminar air-flow workstation) were used throughout to avoid contamination of the samples with silicon.

Foods were purchased from supermarkets and local shops in London. The corn flakes and museli used were Kellogg's Corn Flakes and Kellogg's All-Bran Plus, respectively (Kellogg Marketing and Sales Co Ltd, Manchester, United Kingdom). The wheat biscuits were Weetabix (Weetabix Ltd, Kettering, United Kingdom). The white rice was Uncle Ben's Long Grain Rice (packed in Belgium for Pedigree Master Foods, Master Foods Ltd, Dublin). The raisins were Safeway Homebaker California Seedless Raisins (produced in California for Safeway, Hayes, United Kingdom). The mineral waters were Evian and Volvic (Danone Group, London). All the other foods used were the shops' own brands.

*Study 1.* Study 1 was conducted over 2 d. Subjects fasted overnight and then at 0900 on day 1 emptied their bladders and thereafter collected urine for 3 h in a single container (predose urine sample). During this time period, they ingested only 0.5 L UHP water. At the end of this period, the subjects returned to their normal eating habits. Subjects fasted again overnight from day 1 to day 2. At 0900 on day 2, each subject had an all-plastic intravenous cannula (Venflon, 1.2 mm × 45 mm; Infusion Therapy AB, Helsingborg, Sweden) inserted into a forearm vein. Subjects then emptied their bladders, and two 5-mL blood samples were collected 10 min apart for baseline silicon measurements. The blood was collected into polypropylene transport tubes without anticoagulant. Each subject then ingested a meal of 100 g white rice (microwave cooked), 150 g green beans (microwave cooked), and 100 g raisins. The total silicon content of this meal was 13.15 mg. A 5-mL blood sample was collected immediately after consumption of the meal ($t$ = 1 min) and additional 5-mL samples were obtained at 20-min intervals for 2 h and then at 60-min intervals for another 4 h (total of 6 h).

Two urine collections were completed after consumption of the meal, from 0 to 3 h and from 3 to 6 h. Thus, each collection lasted for a total of 3 h. Each subject ingested 0.5 L UHP water during each 3-h urine collection. At the end of the 6-h period, each subject ate a low-silicon lunch consisting of 100 g potato waffle (grilled) and 200 g peeled orange. The meal supplied a total of 1.09 mg Si. A final 3-h urine collection (from 6 to 9 h) was then completed, and again each subject ingested 0.5 L UHP water during this period. Samples of the ingested meals were retained for total silicon analyses (*see* Sample analyses, below).

*Study 2.* Study 2 was conducted over 25 d. Throughout this time period, subjects fasted overnight. On days 1 and 2 at 0900, subjects emptied their bladders and then ingested 0.5 L UHP water. An additional 0.5 L UHP water was consumed from 3 to 6 h by each subject. Subjects collected their urine for 6 h in a single container on both days, which were considered baseline days 1 and 2. Thereafter, on days 3–25, the single-item meals listed in **Table 2** (B1–H2) were ingested at 0900 and 6-h urine collections were then completed. Again, 1 L UHP water was ingested during each 6-h period. Samples of the meals were retained for total silicon analyses.

### *Sample analyses*

Blood and urine samples were processed and analyzed for total silicon by inductively coupled plasma optical emission spectroscopy (Jobin-Yvon JY24; Instrument SA, Longjumeau, France) at a wavelength of 251.611 nm as described previously (9). Samples of the meals were also analyzed for total silicon content by inductively coupled plasma optical emission spectroscopy at 251.611 nm. Food and beverage samples were analyzed in 3 different ways, depending on the specific food: *1*) without pretreatment (used for UHP water and mineral waters), *2*) after dilution (used for milk, orange juice, and liquor), and *3*) after microwave-assisted acid digestion (used for solid foods). The silicon contents of foods were determined for their edible portions.

## Statistical analysis

The results are expressed as means ± SDs unless otherwise stated. We compared the silicon intakes of men and women by using a two-sample $t$ test and we analyzed for a correlation between silicon intake and age by using linear regression analysis. Both of these analyses were done with SAS for WINDOWS, version 8.1 (SAS Institute Inc), and for both, $P < 0.05$ was considered statistically significant.

In the silicon uptake studies, comparisons to baseline were made by using paired, one-tailed Student's $t$ tests in MICROSOFT EXCEL 97 SR-1 (Microsoft, Redmond, WA). Because 3 postdose urine collections were compared with baseline silicon excretion in study 1, and 22 foods were compared with UHP water (the control) in study 2, a Bonferroni correction for multiplicity of testing was applied to the $P$ values. Thus, significance was set at $P < 0.017$ (0.05/3) in study 1 and $P < 0.0023$ (0.05/22) in study 2. We used Pearson's product-moment correlation coefficients to analyze

**TABLE 2**
Meals, portion sizes, and silicon intakes in study 2[1]

| Meal and food source | Portion ingested | Silicon intake |
|---|---|---|
| | | *mg* |
| Baseline | | |
| A1: UHP water[2] | 1 L | 0.03 |
| Cereals[3] | | |
| B1: corn flakes[4] | 100 g | 2.42 |
| B2: wheat biscuits[5] | 100 g | 2.78 |
| B3: high-bran cereal[6] | 100 g | 10.17 |
| Breads | | |
| C1: white | 200 g | 3.38 |
| C2: whole-meal | 200 g | 4.50 |
| C3: granary | 200 g | 8.94 |
| C4: croissants | 100 g | 1.67 |
| Rice and pasta[7] | | |
| D1: white rice[8] | 200 g | 2.48 |
| D2: brown rice (with husks) | 200 g | 4.14 |
| D3: pasta (frusili) | 250 g | 1.50 |
| Vegetables | | |
| E1: potato waffles (grilled) | 200 g | 0.90 |
| E2: new potato (with skin)[9] | 200 g | 0.58 |
| E3: carrot (raw, peeled) | 200 g | 4.58 |
| E4: lettuce, iceberg (raw) | 250 g | 1.03 |
| E5: green beans (cooked)[9] | 250 g | 6.10 |
| Fruit | | |
| F1: banana (yellow, peeled) | 250 g | 13.60 |
| F2: orange (peeled) | 210 g | 0.67 |
| F3: strawberries | 200 g | 0.24 |
| F4: raisins (California seedless) | 100 g | 8.25 |
| Milk | | |
| G1: Cold semi-skimmed | 0.4 L | 0.21 |
| Mineral waters | | |
| H1: mineral water[10] | 0.5 L | 3.44 |
| H2: mineral water (high-silicon)[11] | 0.5 L | 7.23 |

[1] Each meal included only the food source listed, without any additional components, although 1 L ultra-high purity (UHP) water was also consumed by each subject over the 6-h urine collection period for meals B1–H2.
[2] 1 L UHP water was consumed as 0.5 L at $t = 0$ h with an additional 0.5 L from 3 to 6 h.
[3] Ingested with 0.4 L cold semi-skimmed milk.
[4] Kellogg's Corn Flakes; Kellogg Marketing and Sales Co Ltd, Manchester, United Kingdom.
[5] Weetabix; Weetabix Ltd, Kettering, United Kingdom.
[6] Kellogg's All-Bran Plus; Kellogg Marketing and Sales Co Ltd.
[7] Cooked by boiling in tap water.
[8] Uncle Ben's Long Grain Rice; Pedigree Master Foods, Master Foods Ltd, Dublin.
[9] Cooked in a microwave.
[10] Evian; Danone Group, London.
[11] Volvic; Danone Group.

for a correlation between silicon intake and urinary silicon excretion; $P < 0.05$ was considered significant.

## RESULTS

### Silicon intake in the Framingham Study cohorts

Total daily dietary intakes of silicon in the 2 Framingham Study cohorts are shown in **Figure 1**. At all ages, intakes were significantly greater in men than in women. The mean intakes for men and women, respectively, were 33.1 ± 19.4 and 25.0 ± 11.4 mg/d in the Framingham Offspring cohort and 29.6 ± 14.8 and 24.2 ± 9.5 mg/d in the original Framingham cohort. Silicon intakes decreased significantly with age in the Framingham Offspring cohort ($P < 0.001$, adjusted for sex); on average, intakes were 0.1 mg lower for every additional year of age. The major dietary contributors to total silicon intakes are shown in **Table 3**.

### Silicon uptake in the experimental subjects

In study 1, the mean baseline serum silicon concentration was 7.5 ± 3.1 μmol/L (range: 2.5–12.2 μmol/L; $n = 8$). A full set of blood samples was obtained from 7 of the 8 subjects. For these subjects, the peak increase over baseline was measured in the serum 100–120 min after ingestion of the silicon-rich meal (**Figure 2**A). The mean increase above baseline in the area under the curve from 0–6 h after the meal was 32.9 ± 7.9 μmol·h. This accounted for 7.0 ± 1.7% of the total silicon ingested; we used mean estimated plasma volumes of 2.13 L for women and 2.46 L for men (30).

Urinary excretion of silicon also increased significantly above baseline after ingestion of the meal (Figure 2B). The silicon excreted during the first 6 h (corrected for baseline silicon excretion) accounted for a mean of 38.2 ± 10.9% of intake. Only a small percentage of the ingested silicon (4.7 ± 3.7% of intake, baseline corrected) was present in the 6–9-h urine collection. It is likely that much of this amount came from ingesting the low-silicon lunch, which supplied 1.09 mg Si. Therefore, in study 2, urine was only collected from 0 to 6 h after the meals.

Urinary silicon excretion during the 6 h after subjects consumed different foods (study 2) is shown in **Figure 3**. Marked increases above baseline in the excretion of silicon were measured for cereals, whole-meal bread, granary bread, rice, pasta, green beans, raisins, and mineral waters. The results showed that little silicon was available from bananas, despite their high silicon content (5.44 mg/100 g edible portion). Overall, a positive

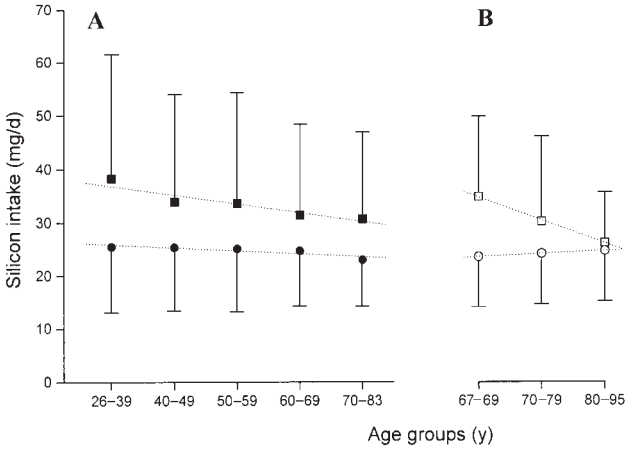


**FIGURE 1.** Mean (±SD) total dietary silicon intakes in men (■, □) and women (●, ○) in the Framingham Offspring cohort (A) and the original Framingham cohort (B). Silicon intakes were significantly higher in men than in women in both cohorts ($P = 0.0001$; two-sample $t$ test). Sample sizes were as follows for men and women, respectively: in the Framingham Offspring cohort, 94 and 96 for 26–39 y, 403 and 508 for 40–49 y, 529 and 602 for 50–59 y, 458 and 493 for 60–69 y, and 121 and 114 for 70–83 y; in the original Framingham cohort, 25 and 50 for 67–69 y, 273 and 429 for 70–79 y, and 76 and 123 for 80–95 y.

**TABLE 3**
Major (top 10) food sources that contributed to total silicon intakes in the study population[1]

| | Men | | Women | |
|---|---|---|---|---|
| Ranking | Food source | Contribution | Food source | Contribution |
| | | % | | % |
| Framingham Offspring cohort[2] | | | | |
| 1 | Beer | 17.6 ± 23.7 | Bananas | 10.5 ± 10.1 |
| 2 | Bananas | 9.1 ±10.2 | String beans | 4.6 ± 4.5 |
| 3 | White bread | 4.6 ± 6.0 | White bread | 4.6 ± 6.2 |
| 4 | Cold cereal | 4.5 ± 6.3 | Cold cereal | 4.4 ± 5.8 |
| 5 | Coffee | 3.5 ± 3.7 | Dark bread | 3.7 ± 5.0 |
| 6 | Beans and lentils | 3.3 ± 4.0 | Beans and lentils | 3.7 ± 4.6 |
| 7 | Pizza | 3.2 ± 3.5 | Coffee | 3.5 ± 3.9 |
| 8 | Dark bread | 3.1 ± 4.7 | Muffins and bagels | 3.5 ± 4.1 |
| 9 | String beans | 3.0 ± 3.1 | Beer | 3.3 ± 10.0 |
| 10 | Muffins and bagels | 2.7 ± 3.5 | Cooked oatmeal | 3.3 ± 6.6 |
| Original Framingham cohort[3] | | | | |
| 1 | Bananas | 13.4 ± 13.1 | Bananas | 13.9 ± 12.2 |
| 2 | Beer | 10.6 ± 19.6 | String beans | 5.4 ± 4.9 |
| 3 | White bread | 5.4 ± 7.3 | Cooked oatmeal | 5.3 ± 9.2 |
| 4 | Cold cereal | 5.0 ± 5.9 | Cold cereal | 5.3 ± 6.5 |
| 5 | Cooked oatmeal | 4.3 ± 7.5 | Dark bread | 5.3 ± 6.7 |
| 6 | String beans | 4.1 ± 4.4 | White bread | 4.7 ± 6.8 |
| 7 | Beans and lentils | 3.6 ± 4.4 | Potatoes | 3.8 ± 3.3 |
| 8 | Potatoes | 3.2 ± 2.9 | Beans and lentils | 3.0 ± 4.1 |
| 9 | Dark bread | 3.2 ± 4.4 | Muffins and bagels | 2.3 ± 3.5 |
| 10 | Muffins and bagels | 2.5 ± 4.5 | Coffee | 2.2 ± 3.0 |

[1] $\bar{x}$ ± SD.
[2] Total percentage contribution of the foods listed: 54.6% and 45.1% for men and women, respectively.
[3] Total percentage contribution of the foods listed: 55.3% and 51.2% for men and women, respectively.

correlation between silicon intake and excretion in urine (a surrogate measure for uptake) was observed (**Figure 4**).

## DISCUSSION

Total dietary intakes of silicon in the 2 Framingham cohorts were between 13 and 62 mg/d, similar to the previously reported values of 20–50 mg/d from Western diets (6–8, 21, 31). Silicon intakes in the present study were also ≥2-fold higher than typical Western intakes of iron and zinc, 2 other elements of physiologic importance. Thus, the diet is a major source of silicon for humans, with higher intakes obtained from diets rich in grains, cereal products, and plant-based foods than from dairy and animal products (6–8). Asians and Indians have much higher silicon intakes than do Western populations (32, 33) as a result of their higher intakes of plant-based foods (32, 34), and it is interesting that in these communities there is a lower incidence of hip fracture than in the West (35).

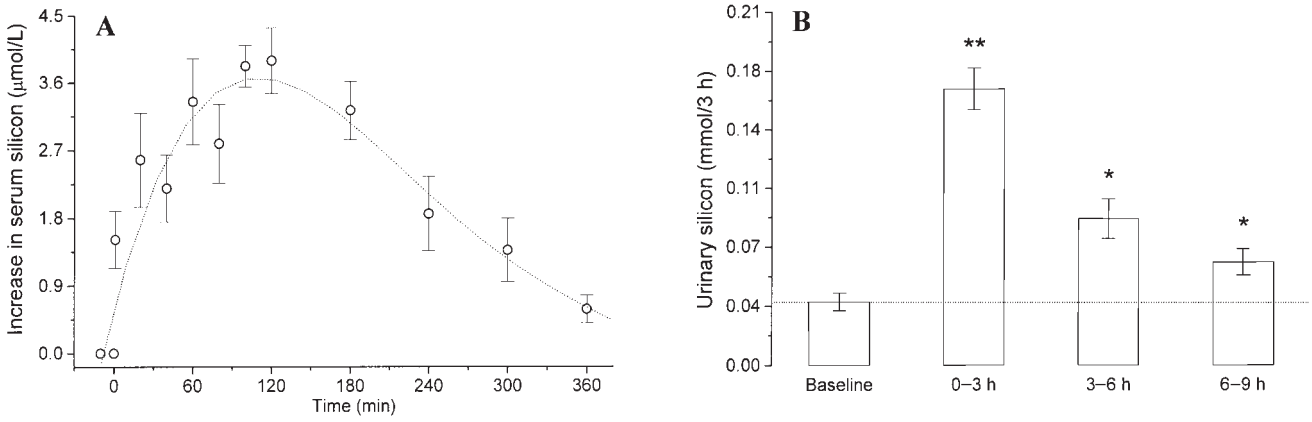


**FIGURE 2.** Mean (±SE) increase in serum silicon concentration (A; $n = 7$) and mean (±SE) excretion of silicon in urine (B; $n = 8$) for the experimental subjects in study 1 after ingestion of the test meal (total silicon intake: 13.15 mg). The first 2 values in A are the baseline serum concentrations in 2 predose blood collections; the mean of these values was used to calculate the subsequent increase in serum silicon. The dotted line in B represents the mean baseline excretion of silicon in urine. At 6 h postdose, subjects ingested a low-silicon lunch (total silicon intake: 1.09 mg). *,**Significantly higher than baseline urinary silicon excretion (paired, one-tailed $t$ test with Bonferroni correction for multiple comparisons): *$P < 0.01$, **$P < 0.001$.

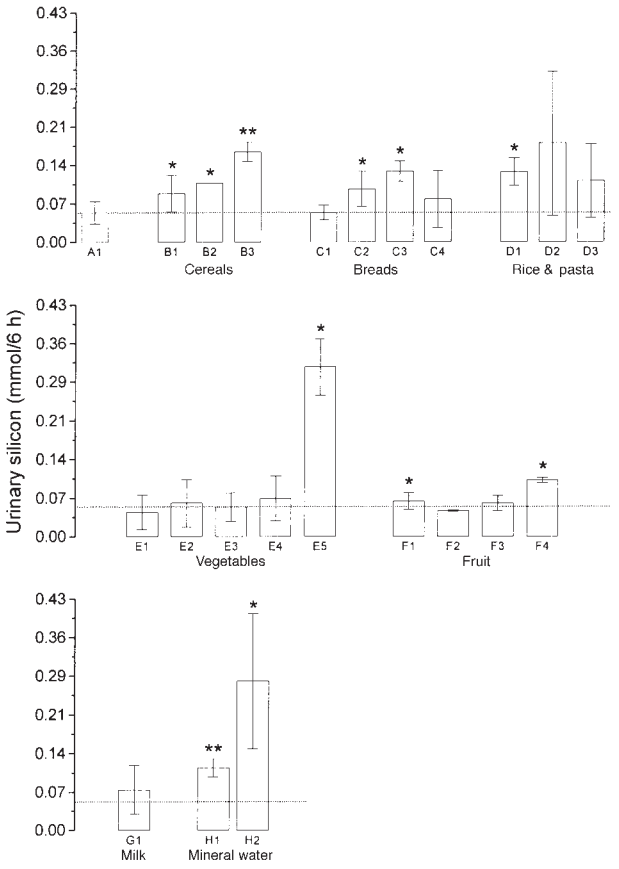


**FIGURE 3.** Mean (±SD) excretion of silicon in 6-h urine collections after ingestion of single-item meals by experimental subjects in study 2 ($n$ = 3 for all bars except $n$ = 2 for B2). The dotted lines represent the mean baseline urinary silicon excretion (also shown by the bar labeled A1) after ingestion of ultra-high purity water. Baseline excretion for each subject was calculated from 2 separate 6-h urine collections. $^{*,**}$Significantly higher than baseline urinary silicon excretion: $^{*}P \leq 0.05$ (paired, one-tailed $t$ test), $^{**}P \leq 0.0023$ (paired, one-tailed $t$ test with Bonferroni correction for multiple comparisons).

In the present study, silicon intakes were 20–33% higher in men than in women, and silicon intakes decreased in both sexes with increasing age. In a younger population (25–30 y), Pennington (6) calculated that women's intakes (18.9 mg/d) were one-half those of men (40.1 mg/d). The primary reason for this difference was higher beer consumption by the young men, which accounted for 45% of their total silicon intake. In the present study, beer was also the highest contributor to total silicon intake in men (Table 3). A previous study showed that silicon in beer is readily bioavailable because it is solubilized during the mashing process of beer making (5). However, no previous study investigated silicon bioavailability from other major food sources such as bananas, grains and grain products (eg, bread, cold cereal, and oatmeal), and string beans (Table 3). Coffee was a source of dietary silicon because of its drinking water content, and pizza was also a source because of its bread base. Surprisingly, rice and pasta, which contain large amounts of silicon (6), were not among the major contributors to silicon intake in the 2 cohorts (mean contributions: 2.6–3.2% from brown rice and 2.4–3.1% from pasta in the Framingham Offspring cohort). This indicates that intakes of rice and pasta were low in our population.

Once we had confirmed that silicon is readily available from meals, as shown by its rapid absorption and rapid excretion in the urine (Figure 2), we then investigated absorption from some individual foods. Overall, a mean of 40.9 ± 36.3% of ingested silicon was excreted over a 6-h period in the urine, again confirming that food-based, phytolithic silica is digested and absorbed from the gastrointestinal tract. Silicon in grains and grain products (rice, breakfast cereals, breads, and pasta) was readily absorbed, as indicated by the mean urinary excretion of 49 ± 34% of intake (range: 10–100%). However, except for green beans and raisins, the silicon in vegetables and fruit was less readily absorbed, as indicated by the mean urinary excretion of 21 ± 29% of intake (range: 0–40%). Surprisingly, silicon uptake was low (2.1 ± 1.2% of intake) from bananas, which are high in silicon (5.4 mg Si/100 g edible portion) and were one of the highest contributors to silicon intake in the Framingham cohorts. This suggests either that silicon is mainly present in an unavailable form in bananas or that this silicon is absorbed late from the gastrointestinal tract (after 6 h). In general, however, silicon was readily available from foods and in many cases, it showed absorption similar to that of silicon from fluids. For instance, urinary silicon excretion (as an indicator of absorption) was 41–86% from corn flakes, white rice, and brown rice and was 50–86% from mineral waters.

Finally, we found a significant correlation between silicon intake and urinary silicon excretion (a surrogate measure of silicon uptake), suggesting that the silicon contents of foods can be used to estimate exposure in future epidemiologic studies. This should allow researchers to estimate the effect of dietary silicon on bone health. A daily minimum requirement (recommended daily intake) for silicon has not been established, but was estimated at 10–25 mg/d on the basis of the 24-h urinary excretion of silicon (17, 20). This value is consistent with our data because we found a mean silicon uptake of 40.9% from foods, and from this value we estimated the mean daily absorption of silicon to be 12.1 and 13.5 mg/d in men and 9.9 and 10.2 mg/d in women in the original Framingham and Framingham Offspring cohorts,

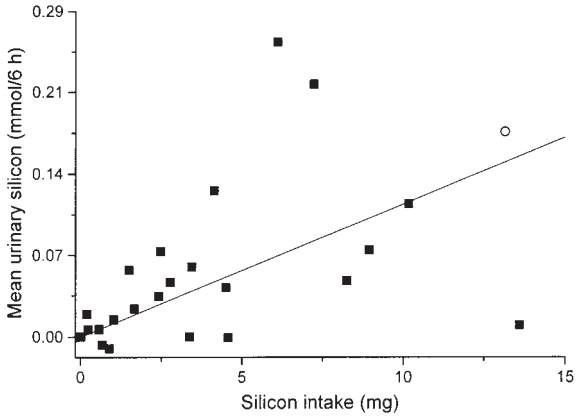


**FIGURE 4.** Correlation between silicon intake from meals and mean urinary silicon excretion (6-h collections, corrected for baseline silicon excretion) in experimental subjects (studies 1 and 2). The data point from study 1 (○) is the mean of values for 8 subjects after they ingested the test meal containing 13.15 mg Si. The data points from study 2 (■) represent the means of values from 3 subjects after they ingested the different single-item meals. The correlation, $r$ = 0.5, was significant at $P$ = 0.019. The equation for the line is $y = 0.326x$.

respectively. These values would increase slightly if silicon intakes from drinking water were included.

In conclusion, foods are major sources of available silicon for humans. We confirmed that in the Framingham cohorts, daily silicon intakes were markedly higher in men than in women, mainly because of higher beer consumption by men. We showed for the first time that silicon intakes of both sexes decrease with increasing age. Neither silicon deficiency nor a silicon-responsive condition have yet been identified in humans (36), and dietary silicon excess has not been linked to any diseases (32). Future studies can now investigate whether silicon intake influences bone mass.

We thank Janice Maras and Ning Qiao of Tufts University in Boston for database development and analysis of silicon intake in the Framingham Study.

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