

SILICON IN FOODS: CONTENT AND BIOAVAILABILITY

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The silicon content of various foodstuffs marketed in Belgium was measured by a validated graphite furnace absorption spectrometric method. Dietary intake has been identified as the major source of silicon. However, data on its bioavailability remain scarce and insufficient. In vitro methods can provide an indication of bioavailability in case of lacking in vivo data. Bioavailability of silicon from different foodstuffs was estimated using an in vitro continuous flow gastroduodenal simulation method. The major food sources of silicon were unrefined grains, cereal products and root vegetables. The availabilities of silicon from, meat, milk and beers were high, whereas low availability was observed for seafood and cereal products. Plotting the availability data versus the total elemental silicon content of the foods revealed an exponential inverse relationship. The inverse relationship between silicon content and silicon availability was found in all foods, with the exception of various silicon containing drinks. Nevertheless, food categories classified as major silicon sources in the diet still appear to provide the highest absolute amounts of available silicon per 100 g of food including breakfast cereals, bread and baking products, and beers.

Keywords: Silicon, Concentration level, Foodstuffs, Availability.

INTRODUCTION

It is evident that silicon plays an important role in human physiology. Besides its important role in bone mineralization and soft tissue development, silicon is nowadays claimed to have beneficial effects on several human disorders. Examples are its role in prevention of osteoporosis, ageing of skin, hair and nails and atherosclerosis.^[1–6] Several reports about the silicon content of foods have been published.^[7–11] Data on the daily intake of silicon from 24-h duplicated meals, measured by validated graphite furnace atomic absorption have been published previously by our group.^[12] However, besides intake level, the bioavailability of the element is of paramount importance in normal physiology. As recently pointed out, data on the bioavailability of silicon are scarce and need to be established.^[13,14] Exploring the bioavailability of silicon from foods in humans is impaired by several factors such as natural abundant and the lack of detailed information on Si-metabolism in human.

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A dynamic continuous flow dialysis can be used as an alternative in vitro technique to study bioavailability of minerals and trace elements in meals,^[15,16] infant formulae and milks.^[17–20] It is an in vitro simulation of the digestion of food. The strength of this model, since it does not provide absolute bioavailability data, is its ability to demonstrate relative differences in availability comparing different foodstuffs. Besides, it proved to be very useful in predicting changes in availability after addition of various food ingredients.^[15] The aim of this paper is to contribute to the knowledge on the bioavailability of silicon from various food items in a standardized and well-defined in vitro experiment.

MATERIAL AND METHODS

Foods Used

Various foodstuffs were collected at different places in the Antwerp and Brussels region (Belgium) at the beginning of September 1997.

Silicon Determination

A Perkin Elmer model 4100 ZL Zeeman atomic absorption spectrometer (AAS), equipped with a PE AS-70 autosampler, was used for all experiments. The manufacturer's recommendations for wavelength, spectral width and lamp current parameters were followed. The adapted programme, matrix modification and the analytical features for silicon determination were published earlier.^[12] All procedures (lyophilisation, destruction, and elemental analysis) were carried out in duplicate. Sample preparation and microwave oven destruction with optimized heating programme was carried out as described elsewhere.^[12]

To check accuracy of the AAS-technique, an interlaboratory trial on spectrometric determination of silicon in certain food items and biological samples was performed, because of the lack of certified reference material.^[21,22] Mean Si-value (\pm SD) from water was 16.4 ± 1.0 mg/L ($p_j = 13$, number of participating laboratories), from spinach after destruction 3.32 ± 0.15 mg/L ($p_j = 10$) and from beer after destruction 8.65 ± 0.47 mg/L ($P_j = 10$). Precision of the procedure was checked by analyzing ten replicates of diluted destruction liquids and mean Si-values (\pm SD), were 28.2 ± 1.0 mg/kg flour, 4.51 ± 0.23 mg/kg spinach and 1.64 ± 0.05 mg/kg yoghurt (fresh weight). Characteristic mass yielded Si-values of 47 pg /0.0044 A-s and detection limit in the destruction liquid was $31.8 \mu\text{g/l}$.

Bioavailability Studies

Detailed description of the optimized procedure of the continuous flow dialysis model can be found elsewhere.^[23] The continuous flow in vitro dialysis model consisted of two phases: a gastric and a duodenal stage. Prior to the gastric stage, 10–50 g of the food was brought to pH 2.0 with 6N HCl. Pepsin was added and the sample was placed two hours at 37°C in a shaking water bath (120 strokes/min). The intestinal phase was mimicked in a stirred cell under a pressure of 3.5 bars at 37°C.

Continuous removal of dialyzed compounds was obtained through a dialysis membrane with molecular weight cut off of 1000 Da. During the first 30 min of dialysis the pH of the digest was gradually increased from acid to neutral by use of a dialysis bag (MWCO 10–12 kDa) filled with 1M NaHCO₃. After 30 min of dialysis, pancreatin-bile extract was

added to the neutralized sample and dialysis was continued for another two hours. The availability of the element was directly calculated from the amount of element that passed the dialysis membrane in proportion to the total elemental content of the food sample, following the equation:

$$\% \text{ availability} = D/W \times A \times 100\%, \quad (1)$$

where D is the total amount (μg) of dialysed silicon; W is the dry weight (g) of food sample; and A the concentration of silicon in the food sample ($\mu\text{g}/\text{g}$).

According to their silicon concentration and water content, 10 to 50 g of foodstuff were taken through the procedure. Four replicate samples were used for each item and 10 replicates for calculation of the precision. Recovery and precision of the procedure on 0.5, 2.5, and 75.0 mg Si/100 ml standard solutions yielded mean values of 107, 101, and 102%, respectively, and 0.336 ± 0.04 , 1.76 ± 0.12 , and 58.8 ± 1.4 mg Si/100 ml, respectively.

RESULTS

Silicon content. Table 1 summarizes the silicon content and the bioavailability for various food items. High silicon values were observed in breakfast cereals and vegetables, while low values were found in meat and dairy products. Fish also showed low values,

Table 1 Availability data for silicon in various foodstuffs (mean \pm SD).

Food item	Total Si content ($\mu\text{g}/100$ g food; wet weight)	Availability (%)
Meat		
Beef (minced)	121	72 ± 15
Chicken (breast)	109	40 ± 4
Seafood		
Mussels	9588	5.5 ± 0.6
Scampi	1000	11.1 ± 0.8
Cereals		
Breakfast	8250	7.7 ± 2.5
Oat flakes	18,800	2.1 ± 0.4
Rice (whole)	16,200	7.6 ± 1.3
Whole wheat flour	2770	20.0 ± 0.5
Milk and formulae		
Cow's milk	76	49 ± 8
Soy milk	580	72
Milk for toddlers	124	62 ± 1
Infant formulae (brand 1)	2080	64 ± 5
(brand 2)	1275	55 ± 7
Vegetables and fruit		
Beans	5577	0.6 ± 0.1
Leek	63	75 ± 11
Spinach	1782	4.9 ± 0.3
Bananas (mixed)	6195	5.8 ± 0.7
Drinks		
Beer (tin can)	1980	109 ± 0.8
Tea (infusion of leaves)	18,100	20 ± 2

with the exception of mussels, which appeared to be silicon rich (8.4 ± 0.8 mg/100 g). Within the fruit group, the silicon content of dried fruit and bananas was remarkably high. Particularly high levels were obtained for instant coffee, tea and soup. Unrefined grains tend to be higher in silicon concentration than refined products, like rice, bread and cereals.

Silicon level in mineral waters reveal a wide range from 0.076 to nearly 2 mg/100 ml. Daily water consumption in Belgium is about 1.5 L/person, consequently water can contribute in a large extent to the daily silicon intake. 80% of the tested beers show silicon levels of about 2 mg/100 ml and higher, therefore beer can be considered as a medium source of the element.

Availability. Plotting the availability data versus the total silicon content reveals an exponential inverse relationship ($y = 68.85 \times^{-0.4923}$, $R^2 = 0.442$) (Figure 1). Food items previously found to contain high silicon levels showed very low availability: beans (0.6%), oat flakes (2.1%) and mussels (5.5%).^[10,16,18] Nearly all food items from both categories milk and meat revealed availabilities between 40 and 70%. Tea leaves and wheat flour displayed intermediate silicon availabilities. Beers, waters, and milks proved to contain highly available silicon.

Because of this relationship—i.e., low silicon availability and concomitant high silicon content—the variation (range) in the amount of available silicon (absolute; μg) between food items is relatively small. With respect to the differences in the concentration levels between the different food items, a range of almost 1000 is observed, whereas this range is reduced to almost 100 at the availability levels (absolute; μg). Food categories, previously classified as silicon rich, still appear to provide the highest amounts of available silicon per 100 g of food. These include, from high to low, breakfast cereals, bread and baking products, and beer ordered from high to low. Infant formula proved to be an important source of silicon for infants because of their high silicon content and a considerable availability.

DISCUSSION

Analysis of the various individual foodstuffs in Belgium reveals that cereals and grains contain more silicon than meat products. Especially breakfast cereals, rice and bread and baking products appear to have high silicon content. Meat and dairy products

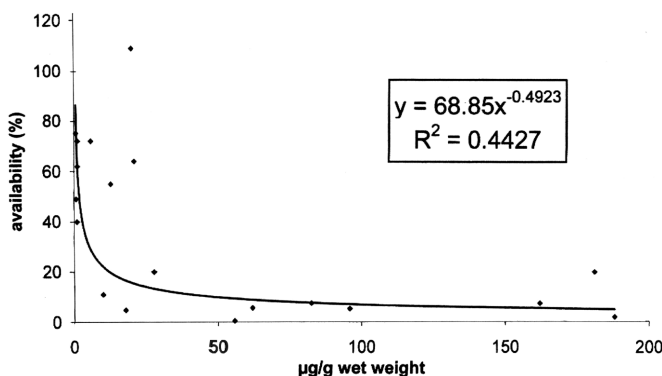


Figure 1 Silicon availability from various foodstuffs as a function of silicon content.

proved to be particularly poor in silicon, while vegetables, fruit and fish displayed a rather heterogeneous pattern. These observations correlate well with published data.^[13]

In our study silicon content was determined in a variety of foodstuffs commercially marketed in Belgium to identify foods that are silicon sources in the Western diet. Vegetarian foodstuffs contained varying amounts of silicon.^[10] High levels were found in rice products, a fungus-based meat substitute (Quorn®) and in roasted barley containing mostly more than 2 mg Si/100 g wet weight. People adhering to a vegetarian diet, therefore, consume more silicon than people consuming normal non-vegetarian meals.^[10] The high silicon content of fish, especially shellfish, may be explained by the enormous water filtration capacity of these organisms. The addition of amorphous silicon dioxide as anticaking agent to instant food may be responsible for the high silicon levels found in instant tea.

In this study, availability of silicon from various foodstuffs was determined by an *in vitro* continuous flow dialysis method as an estimate of the bioavailability of the element. Bioavailability can be described as that portion of a nutrient that can be used. This means that any potentially available part of a nutrient after gastrointestinal digestion should be attributed to its availability. However, measuring the release and solubilization of micronutrients *in vitro* does not necessarily represent the efficiency with which they will be translocated by the intestinal mucosa and used for metabolic functions. Both measurements are also partly dependent on physiologic factors. Therefore, *in vitro* methods are particularly useful to predict the release of micronutrients from meals and to identify underlying food portions that affect bioavailability without considering host-related influences.

The availability data on silicon from various foodstuffs demonstrated high values for those food items, which appeared to have low total silicon content, along with low availability for those with high elemental content (Table 1). Taking into account the mean silicon concentration of food categories and food consumption patterns in Belgium, it appears that as few as seven food groups supply more than 80% of the daily dietary intake of the element.^[12]

The high availability of silicon from beers was in agreement with observations of Bellia et al.^[24] They calculated that 42–75% (mean 56%) of silicon in beer was excreted in urine within 8 h after ingestion. During fabrication of beers with hot mashing techniques orthosilicic acid may be extracted from the phytolytic silica, a hydrated polymer $\text{SiO}_2 \cdot n\text{H}_2\text{O}$, present in barley. Reffitt et al.^[25] also suggested that orthosilicic acid is readily absorbed from the gastrointestinal tract of man and subsequently excreted in urine. Mean uptake of silicon from an ingested orthosilicic acid (27–55 mg Si/l) in water was 50.3% (range 22–75%) based on urinary analysis following dosing.

Availability of silicon from daily meals taken on subsequent days is about 30% with rather small day-to-day variation. Meals were collected by 24-h duplicate portions and availability determined by the *in vitro* methodology. This value is somewhat lower than the overall mean of $40.9 \pm 36.3\%$ in the Framingham study.^[13] In the latter study, availability data were calculated from urinary silicon excretion over a 6-h period after ingestion of various food groups. The observations in the Framingham cohorts on bananas were confirmed in our study. Not only the silicon content was very similar, but also little silicon was available from the edible portion.^[13]

Much of the silicon present in cereals is phytolytic silica with poor bioavailability.^[24] This was also proven by Kelsay et al.^[26] Silicon intake on a high fiber diet is almost twice the amount compared with intakes on a low fiber diet. Urinary excretions of silicon were 58% and 35% of the intake on the low and high fiber diets. Mean silicon balance was negative in both diets but significantly more negative for the high fiber diet ($p < 0.01$).

Although most food categories with high silicon content show relative low availability, when calculated as absolute available amounts (μg) these food categories still provide major amounts of silicon from the daily diet.

The relatively high availability of Si from milk and infant formulae is an interesting feature in view of the probable essential character of this element for bone growth.^[27–29] As a result of high consumption of vegetables-based food,^[30–32] Asians^[33] and Indians^[34] have a much higher silicon intake than a Western population: 19 mg/day for Belgium (12), 31 mg/day for the UK (12) and 30 mg and 33 mg/d in the original Framingham and Framingham offspring cohorts, respectively.^[13] In the latter study higher intake was proven for men compared to women and silicon intake increased as a function of age.^[13] Blood silicon levels in China did not significantly differ from values found in Belgium as proven in a small study, on a limited number of persons.^[3] This may support the hypothesis that most of the silicon from rich food items may be not available, since daily silicon intakes are much higher in China (139 mg/day) compared to Belgium (19 mg/day). The higher silicon intake was not reflected in serum concentration levels in humans.

CONCLUSION

Due the inverse relationship—i.e., low silicon availability and concomitant high silicon content—conditions of silicon deficiency and excess have not been demonstrated in humans. Correspondingly, clinical signs of silicon deficiency responsive to supplemental dietary intake, obligatory for proving essentiality, could not be identified for this element.^[33–35] On the other hand, homeostatic regulation of serum silicon levels,^[3] with respect to pregnant women, may prove supporting evidence for the essential character of this element. More extensive longitudinal studies have to be carried out to enforce these promising observations.

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