Silicon Content of Italian Mineral Waters and Its Contribution to Daily Intake

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ABSTRACT: Dietary intake is the main source of silicon for humans. The essentiality of silicon for man has not been clearly established, and no suitable data are available for the establishment of a tolerable upper intake level. Recently, a few cases of silica stones in subjects not ingesting trisilicate antacid have been reported, as well as 1 case of renal silica calculi in a 10-mo-old boy, ascribed to the silicate-rich mineral water used to dilute milk. The purpose of this study was to collect extensive data on the silicon content of mineral water that could be combined with data on different foods to study the overall intake of silicon in the diet and to evaluate the potential risk associated with a high intake of this element. Results relating to 207 brands of mineral water show a low silicon concentration (<10 mg/L) in 77% of samples, with the highest levels (>25 mg/L) occurring primarily in water from volcanic areas. The contribution of mineral water to the total consumption of silicon was calculated, considering both the average intake of water by the Italian population and the recommended intake. When the estimated daily intake with solid foods and other beverages was added, the intake was in the range of 45 to 69 mg/d for a consumption of 700 mL of water and 48 to 99 mg/d for a consumption of 1500 mL of water. These values are near or above the upper limit of the typical dietary intake of 20 to 50 mg silicon/d, which is regarded as unlikely to cause adverse effects. The assumption of silicon by newborns deserves particular attention, in view of their special sensitivity and of a reported case of urinary silica calculi in an infant. The levels of silicon we found never reached the value found in the case described.

Keywords: silicon, mineral water, daily intake

Introduction

Silicon is a nonmetallic element that does not exist in nature in forms other than silicon dioxide (silica) or as silicates (Friedberg and Schiller 1988). Silicon has been reported to be important for the growth and development of bone and cartilage in animals; indeed, studies of silicon deprivation in growing animals have shown reduced growth and marked defects of bone and connective tissue (Jugdaohsingh and others 2002; Sripanyakorn and others 2004). Both the distribution of silicon in animals and the effect of silicon deficiency support the view that silicon functions as a biological cross-linking agent contributing to the architecture of connective tissue. Silicon is apparently also involved in bone calcification, but the mechanisms are unclear (EFSA 2004).

The essentiality of silicon for humans has not been established, and a functional role for silicon has not yet been identified (EFSA 2004). *In vitro* studies have shown that silicon increases type I collagen synthesis, and the differentiation of human osteoblast-like cells and dietary silicon has recently been shown to correlate with bone mineral density in men and in premenopausal women (Reffitt and others 2003; Jugdaohsingh and others 2004; Sripanyakorn and others 2004). Silicon supplementation was also shown to increase femoral bone mineral density in postmenopausal osteoporotic women (Eisinger and Clairet 1993). In addition, some researchers have suggested that silicon also may have an antiatheroma activity; reports have appeared suggesting that inadequate dietary silicon may contribute not only to some bone disorders, but also to some cases of atherosclerosis and hypertension, Alzheimer's disease, and the aging process (Nielsen 2000).

Dietary intake is the main source of silicon for humans (Varo and Koivistoinen 1990; Pennington 1991). Silicon occurs naturally in foods as silicon dioxide and silicates and may be added as an anti-caking and anti-foaming agent in the form of silica, silicates, and dimethylpolysiloxane. Silicon is also present in water as orthosilicic acid; silicic acid exists as monosilicic acid and also as oligomers and as polysilicic acid, which is colloidal (EFSA 2004).

Silicon is essentially nontoxic when taken orally (Nielsen 2000). Short-term oral ingestion of sodium or magnesium silicate produces adverse renal effects in dogs and guinea pigs, but not in rats; similar doses of silicon dioxide and aluminum silicate did not produce adverse renal effects in dogs or rats. Long-term oral administration of silica at high doses inhibits growth in rats and mice though this effect was not regarded as toxic, but rather as being due to a nutritional imbalance (EFSA 2004). There are no reports of toxic effects in humans after intake of silicon occurring naturally in food. Humans have for decades consumed low levels of silicates as food additives without any reported deleterious effects (Nielsen 2000) and also used silicon in the form of magnesium trisilicate as an antacid. Some reports have shown that the long-term administration of magnesium trisilicate induces urinary silica calculi in adult patients (Farrer and Rajfer 1984; Haddad and Kouyoumdjian 1986; Lee and others 1993). More recently, a few cases of silica stones in subjects not ingesting trisilicate antacid, and 1 case of renal silica calculi in a 10-mo-old boy were reported (Ichiyanagi and others 1998; Nishizono and others 2004). In the latter case, the etiology was ascribed to the silicate-rich mineral water used to dilute milk.

Information on the dietary intake of silicon and of its content in food is based on very few studies (Varo and Koivistoinen 1990; Pennington 1991; Deelstra and others 1995; Jugdaohsingh and others

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Table 1—Silica (SiO_2) and silicon (Si) contents of Italian mineral waters examined[a]

	Whole country (*n* = 207)	North (*n* = 96)	Center (*n* = 56)	South (*n* = 55)
mg SiO_2/L	20.6 ± 25.5 (0.3 to 100.1)	11.0 ± 11.4 (1.4 to 88.8)	21.3 ± 26.5 (1.7 to 96.0)	36.7 ± 33.5 (0.3 to 100.1)
mg Si/L	9.6 ± 11.9 (0.1 to 46.7)	5.1 ± 5.3 (0.7 to 41.5)	9.9 ± 12.4 (0.8 to 44.8)	17.1 ± 15.6 (0.1 to 46.7)

[a]Values are expressed as mean ± SD and (range). *n* = nr of samples.

2002) and to our knowledge no data about content of silicon in food or water in Italy are available, except a single study (Leoni and Fabiani 1999).

The consumption of bottled mineral water in Italy is widespread and has greatly increased in recent decades. The purpose of this study was to collect extensive data on the silicon content of mineral water that could be used, together with data relating to different foods, to study the overall dietary intake of silicon and to evaluate the potential risk associated with a high intake of this element.

Materials and Methods

Analytical data of 207 mineral waters were obtained from reports collected by our laboratory within the ambit of official control on mineral waters. Italian regulations envisage regular monitoring of the quality of mineral water, and manufacturers are required to check the chemical and microbiological characteristics of water at least once every year. Testing was performed by authorized laboratories in accordance with statutory sampling and analysis procedures (Health Ministry 1993a, 1993b). In particular, the sampling protocol requires that the water be drawn from the source and that the analytical method be based on molecular absorption spectrophotometry (molibdosilicate method). Silica reacts with ammonium molybdate at a pH of approximately 1.2 to form heteropoly acids. Oxalic acid is added to destroy any molibdophosphoric acid present, and the molybdosilicic acid (yellow color) is measured spectrophotometrically at 410 nm. The data are reported as silica (SiO_2) and are converted to silicon by multiplying by 0.47, according to the molecular weights; the data collected refer to 2003.

On the basis of their silicon contents, we calculated the contribution of different categories of mineral waters to total silicon consumption, taking into account both the average intake of water (fresh and mineral) by the Italian population (about 700 mL) and the recommended intake (1500 to 2000 mL). The 1st value was obtained from the 2nd nationwide food intake survey (Turrini and others 1999), and the recommended intake is that contained in the guidelines for healthy nutrition issued by the Natl. Inst. of Research for Foods and Nutrition (INRAN 2003).

Because fluids account for only a part of total silicon intake, we decided to estimate the overall ingestion of silicon for the Italian population. To obtain this value, we calculated the contribution from other beverages and solid food using the Italian food consumption pattern reported in the INN-CA Study (Turrini and others 2001), and silicon values (mg/100 g) for each food item obtained from data collated by Pennington (Pennington 1991).

Results and Discussion

The results relating to mineral waters are shown in Table 1. The concentration of silica or silicon varies widely (0.3 to 100.1 mg/L and 0.1 to 46.7 mg/L, respectively), that is in the same order of magnitude of a previous work (Leoni and Fabiani 1999). The same table also shows the mean values and ranges of the silicon content in waters from different geographic areas (North, Center, and South), from which it can be seen that the content of this element increases from North to South.

Table 2—Distribution of waters with a silicon content >25 mg/L in different geographic areas

Geographic area	Nr of samples	Range (mg silicon/L)
Verbania (North)	1	41
Roma (Center)	3	38 to 49
Viterbo (Center)	3	41 to 43
Terni (Center)	1	26
Caserta (South)	3	29 to 32
Potenza (South)	14	30 to 47

To investigate the reasons for these differences we arbitrarily divided the samples into 3 categories according to their silicon contents: low (less than 10 mg/L), medium (between 10 and 25 mg/L) and high (over 25 mg/L). As shown in Figure 1, 77% of all the examined samples have a low silicon concentration, and waters with medium and high silicon contents represent 10% and 13%, respectively. However, the situation varies between the different geographic areas of the country: the percentage of waters with high silicon levels increases from North (1%) to South (33%) and the percentage of waters with a low silicon content decreases (from 91% to 55%). It is known that silica levels are linked to the geological features of the areas in which the sources are located. In particular, waters with higher silicon levels usually originate from sources found in volcanic areas (Chetoni 2000). And in fact, all the waters we found with high silicon levels (Table 2) came from well-known volcanic zones, except for 1 from a mountain source in northern Italy.

No daily requirement for silicon has yet been established, but an estimate of 10 to 25 mg/d has been formulated on the basis of the 24-h urinary excretion of silicon (Jugdaohsingh and others

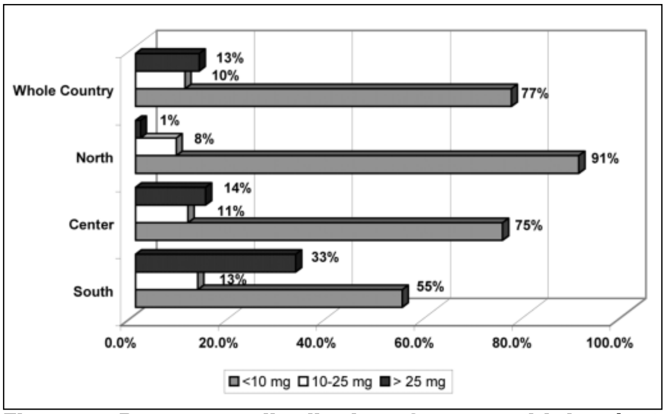

Figure 1—Percentage distribution of waters with low (<10 mg/L), medium (10 to 25 mg/L), and high (>25 mg) silicon content in different geographic areas

2002). Nor are suitable data available for establishing a tolerable upper intake level (EFSA 2004). The typical dietary intake has been estimated to be 20 to 50 mg silicon/d, corresponding to 0.3 to 0.8 mg/kg body weight/d in a 60-kg person; these intakes are unlikely to cause adverse effects (EFSA 2004). Intakes from the mineral waters examined, reported in Table 3, are between 3 and 30 mg silicon/d, except in individuals who consume 1500 mL of water with a high silicon content, in which case the intake could exceed 50 mg/d.

Nutrient intakes do not necessarily reflect nutrient bioavailability, but data reported in the literature, based on urinary excretion, suggest that silicon bioavailability from beverages is relatively high (Bellia and others 1994; Popplewell and others 1998; Reffitt and others 1999); in particular urinary silicon excretion from mineral waters was 50% to 86% (Jugdaohsingh and others 2002).

A rough estimate of the total dietary intake from different foods, calculated as reported in the Material and Methods section, was about 42 mg Si/d, excluding water (Table 4). This value is probably an underestimate because of the lack of data on the silicon content of some items. When the mean contribution of different types of mineral water (low, medium, and high) is added, the intake is in the range of 45 to 69 mg/d for a consumption of 700 mL and 48 to 99 mg/d for a consumption of 1500 mL. These values are near or above the upper limit of the typical dietary intake of 20 to 50 mg silicon/d that is regarded as unlikely to cause adverse effects; however, there is no evidence indicating the existence of risks associated with a higher intake.

Unlike adults, water is the main source of silicon for newborns, and the mean contribution of human milk and infant formula (reconstituted to 12% to 15%) to the dietary intake of silicon is low, that is, 0.1 and 0.7 mg/L, respectively (Bermejo-Barrera and others 2002). The assumption of silicon by newborns deserves particular attention, in view of their special sensitivity and the case of urinary silica calculi in an infant mentioned earlier, which was ascribed to the consumption of milk diluted with silicate-rich mineral water (Nishizono and others 2004). The report refers to a case of silica calculi in an infant that for 8 mo had been fed only milk powder dissolved in mineral water containing 172 mg SiO_2/L, corresponding to 81 mg Si/L, with an estimated daily intake of 172 to 206 mg SiO_2 (80 to 96 mg Si/d). The levels of silicon found in the waters we examined (maximum 46.7 mg Si/L) in no case reached the values reported in this case, although we considered it useful to calculate the daily intake of silicon from mineral waters with high silicon levels (>25 mg/L) by newborns of different weights. For this purpose we considered the different volumes of reconstituted formulas ingested by newborns in relation to their weights as reported in the literature (Maggioni and Signoretti 1978; Rota 1998). Data on silicon intake from 600 mL (3500 g, 1- to 2-wk-old infants) and 800 mL of water (5000 g, 4-mo-old infants) are shown in Table 5, and it can be seen that the values we found are far removed from those that caused the appearance of silica calculi. Silicon intakes by newborns older than 4 mo were not considered because after this age it is possible that foods other than milk are introduced and evaluation of the silicon intake becomes more complex.

Conclusions

The levels of silicon in Italian mineral waters are on the whole not particularly elevated, although some waters from volcanic areas could determine an intake of silicon in excess of 50 mg/d, depending on the volumes ingested. Adding intake due to mineral waters to dietary intake for the Italian population, the values obtained are near or above the upper limit of the range (20 to 50 mg/d) that is regarded as unlikely to cause adverse effects. Further studies on the physiological effects of such intakes could be useful.

Table 3—Daily intakes (mg/d) of silicon from mineral water in adult Italian population[a]

Silicon content	700 mL[b]	1500 mL[c]
<10 mg Si/L	2.9 (0.1 to 6.7)	6.2 (0.2 to 14.3)
10 to 25 mg Si/L	10.3 (7.0 to 15.0)	22.0 (15.1 to 32.1)
>25 mg Si/L	26.6 (18.3 to 32.7)	57.0 (39.2 to 70.1)

[a]Values are expressed as mean and, in parentheses, range.
[b]Representative daily intake of the Italian population (Turrini and others 1999).
[c]Minimum recommended daily intake of water (INRAN 2003).

Table 4—Silicon content of selected food items and estimated daily intake

Foods[a]	Daily consumption[a] (g/d)	Mean Si content[b] (mg/100 g)	Estimated daily intake (mg Si/d)
Cereals and tubers			
Bread and pizza	149.5	5.8	8.7
Crackers, bread sticks, rusks	8.9	6.3	0.6
Pasta not filled	47.1	6.0	2.8
Pasta made with eggs and filled	4.5	2.0	0.1
Rice	10.8	5.9	0.6
Grains and flour	8.1	113.0	10.3
Breakfast cereals	1.0	4.0	0.04
Potatoes, raw and cooked	40.8	0.6	0.4
Meat, fish, and seafoods, eggs			
Beef	45.2	0.7	0.3
Pork	8.0	0.9	0.1
Sheep meat	3.2	1.3	0.04
Horse meat	2.4	1.0	0.02
Poultry	30.1	1.2	0.4
Rabbit and other meat	6.7	0.5	0.03
Ham, salami, and so forth	26.2	1.2	0.3
Meat, preserved	0.8	1.3	0.01
Offal and unspecified meat	6.5	2.3	0.1
Fish and seafoods, fresh and frozen	31.8	0.5	0.2
Fish and seafoods, preserved	7.4	1.1	0.3
Eggs	13.8	0.3	0.04
Milk and dairy products			
Milk	129.7	0.3	0.4
Yoghurt	16.8	0.2	0.03
Cream	1.6	0.2	0.00
Cheese	43.2	1.5	0.6
Vegetables, fruit, and legumes			
Tomatoes	75.5	2.1	1.6
Vegetables, fresh and frozen	120.4	4.9	5.9
Vegetables, preserved	2.9	1.8	0.1
Legumes, fresh, frozen, dry, and tinned	20.9	3.6	0.3
Citrus fruit	36.9	0.2	0.1
Fruit, fresh	156.8	1.7	2.7
Fruit, preserved (including olives)	1.9	3.3	0.06
Nuts and dried fruit	2.2	6.8	0.1
Oil and fats	26.3	—	—
Sweet foods			
Cakes, biscuits, pastries, and so forth	43.0	3.5	1.5
Ice cream	14.7	0.5	0.1
Sugar	11.5	0.2	0.03
Honey, candies, jam, chocolate	8.1	1.0	0.1
Special foods and mixed dishes	60.0	—	
Beverages			
Soft drinks	35.2	0.4	0.1
Fruit juice	21.0	1.0	0.2
Wine and sparkling wine	83.7	1.5	1.3
Beer	27.2	4.1	1.1
Liquors	1.1	—	—
Tea, leaves	0.4	16.3	0.1
Coffee, powder	7.3	20.0	1.5
Infusions and coffee substitutes	0.6	—	—
Total	**1401.7**	**—**	**42.1**

[a]INN-CA Study (Turrini and others 2001).
[b]Mean values calculated from data collated by Pennington (Pennington 1991) taking into consideration only foods similar to those usually assumed in Italy. For values reported as less than a given value, the absolute value was taken for the calculation (for example, <0.2 mg/100 g = 0.2 mg/100 g).

Table 5—Daily intakes of silicon (mg/d) by 1- to 2-wk-old and 4-mo-old newborns from mineral waters with high levels of silicon (>25 mg Si/L) used for infant formula reconstitution

Mineral water	600 mL/d (1- to 2-wk-old newborn)	800 mL/d (4-mo-old newborn)
Mean	22.8	30.4
Minimum	15.7	20.9
Maximum	28.0	37.4

Vice versa, the amounts of silicon in these mineral waters do not represent a risk for newborns, at least at the usual volumes used to reconstitute formulas.

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