

A provisional database for the silicon content of foods in the United Kingdom

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Si may play an important role in bone formation and connective tissue metabolism. Although biological interest in this element has recently increased, limited literature exists on the Si content of foods. To further our knowledge and understanding of the relationship between dietary Si and human health, a reliable food composition database, relevant for the UK population, is required. A total of 207 foods and beverages, commonly consumed in the UK, were analysed for Si content. Composite samples were analysed using inductively coupled plasma–optical emission spectrometry following microwave-assisted digestion with nitric acid and H₂O₂. The highest concentrations of Si were found in cereals and cereal products, especially less refined cereals and oat-based products. Fruit and vegetables were highly variable sources of Si with substantial amounts present in Kenyan beans, French beans, runner beans, spinach, dried fruit, bananas and red lentils, but undetectable amounts in tomatoes, oranges and onions. Of the beverages, beer, a macerated whole-grain cereal product, contained the greatest level of Si, whilst drinking water was a variable source with some mineral waters relatively high in Si. The present study provides a provisional database for the Si content of UK foods, which will allow the estimation of dietary intakes of Si in the UK population and investigation into the role of dietary Si in human health.

Dietary silicon: Food composition: Human health

Si is the second most abundant element in the Earth's crust and although there has been interest in the biological role of Si since the beginning of the century, it is only in the last three decades that it has been suggested as an essential trace element (Carlisle, 1972, 1982; Schwarz & Milne, 1972). Si may have a role in a number of areas of human physiology and metabolism, especially bone and connective tissue formation (Jugdaohsingh *et al.* 2004), but possibly also gene expression and cardiovascular health (Schwarz, 1977; Carlisle, 1981; Institute of Medicine, 2001).

Si is rarely found in its elemental form as it readily reacts with atmospheric O₂ and water to produce silicates. These vary in composition from simple soluble orthosilicic acid (Si(OH)₄ ⇌ Si(OH)₃O[−] + H⁺) and oligomers through to less soluble colloids and gels, and insoluble solid-phase silicates (Iler, 1979). The latter constitute the vast majority of environmental silicates (for example, soil minerals), although natural waters contain soluble silicates (mostly orthosilicic acid) generally at 1–20 mg/l. Orthosilicic acid is the most readily absorbed form of Si and silicate in man (Jugdaohsingh *et al.* 2002). Plants take up orthosilicic acid from the soil, which is transported through the plant in this form, and is then mostly deposited in cell lumina and walls as solid amorphous silica deposits known as phytoliths. Therefore, in plants and plant-based foods, Si is present as insoluble phytolith silica, but intestinal uptake proceeds following luminal hydrolysis to orthosilicic acid (Reffitt *et al.* 1999). Meat and meat products contain very little Si (Pennington, 1991).

Very little data on the Si content of foods has been reported previously, primarily due to difficulties associated with the analytical procedures required for Si analysis (van Dyck *et al.* 2000). Existing published literature concentrates mainly on cereals and cereal products and there are limited data available for fruits and vegetables (Pennington, 1991; Bellia *et al.* 1994; Jugdaohsingh *et al.* 2002). Data for UK foods are especially limited (Bowen & Peggs, 1984).

Methods

Food sampling

A preliminary database for the Si content of foods was created by the principal investigator (J. P.) based upon collation of literature values of the Si content of foods and has been used previously to investigate Si intakes in the Framingham Heart Study cohorts (Jugdaohsingh *et al.* 2002). This preliminary database was used to identify food items that contributed most to Si intake and, in the present study, the number of foods analysed from the main Si-containing food groups was in approximate proportion to their contribution to Si intake in the Framingham Study, although a number of additional factors were also considered. First, a number of food items that are more frequently consumed in the UK than in the USA were identified (for example, porridge, oatcakes); second, alcoholic beverages were analysed in detail as

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Table 1. The silicon content of UK foods analysed by inductively coupled plasma–optical emission spectrometry and comparisons with published literature values (Pennington, 1991)

Food description	No. of food samples*	Present study		Published values (mg/100 g)
		mg/portion	mg/100 g	
			Mean	SD
Cereals and cereal products				
Biscuits, digestives, chocolate-covered	2 biscuits (36 g)	0.88	2.44	
Biscuits, digestives, plain	2 biscuits (30 g)	0.53	1.76	3
Biscuits, savoury, cream crackers	2 biscuits (14 g)	0.19	1.34	8
Biscuits, sweet, cream-filled	2 biscuits (24 g)	0.25	1.05	
Biscuits, sweet, shortbread, all-butter	2 biscuits (26 g)	0.31	1.19	3
Bran flakes	1 medium portion (30 g)	1.45	4.82	
Bread, brown	1 medium slice, large loaf (36 g)	2.22	6.17	6
Bread, brown, rolls	1 soft roll (48 g)	1.80	3.75	
Bread, naan	1 plain (160 g)	2.82	1.76	
Bread, pitta	1 large (95 g)	2.10	2.21	
Bread, white	1 medium slice, large loaf (36 g)	0.64	1.79	
Bread, white, rolls	1 soft roll (45 g)	1.68	3.73	
Bread, wholemeal	1 medium slice, large loaf (36 g)	1.72	4.78	
Bread, wholemeal, rolls	1 soft roll (48 g)	1.30	2.71	
Breads, buttery (for example, croissants or brioche)	1 croissant (60 g)	1.37	2.29	
Cornflakes	1 medium portion (30 g)	0.56	1.88	4
Cornflakes, honey and nut-coated	1 medium portion (30 g)	0.93	3.10	
Couscous	3 tablespoons (99 g)	0.54	0.55	
Crumpets	1 crumpet (40 g)	0.66	1.65	
Currant buns	1 individual (60 g)	2.36	3.93	
Flour, wheat, white	1 tablespoon (20 g)	0.86	4.29	
Flour, wheat, wholemeal	1 tablespoon (20 g)	0.61	3.04	
Granola cereals	3 tablespoons (60 g)	7.35	12.25	
High-fibre wheat bran cereal	4 tablespoons (28 g)	3.20	11.42	
Muesli, Swiss-style	$\frac{1}{2}$ 4 oz cup (50 g)	2.80	5.59	
Oat bran	2 tablespoons (14 g)	3.27	23.36	8.88
Oat cakes	2 round biscuits (26 g)	4.75	18.26	
Pasta, fusilli twists, white, cooked	1 medium portion (230 g)	1.86	0.81	
Pasta, spaghetti, white, boiled	1 medium portion (220 g)	1.45	0.66	
Pasta, spaghetti, whole-wheat, boiled	1 medium portion (220 g)	2.84	1.29	
Pasta, tricolore, cooked	1 medium portion (230 g)	3.63	1.58	
Pasta, white, egg, cooked	1 medium portion (230 g)	1.43	0.62	
Pasta, white, macaroni or penne, boiled	1 medium portion (230 g)	2.28	0.99	
Pearl barley, boiled	1 tablespoon (20 g)	0.37	1.84	9.0 (raw)
Polenta	1 tablespoon (33 g)	0.11	0.34	
Porridge oats, dry	2 tablespoons (30 g)	3.42	11.39	4.25
Puffed wheat	2 tablespoons (6 g)	0.13	2.19	
Rice cereal, chocolate-covered	1 medium portion (30 g)	1.51	5.02	
Rice cereal, toasted and crisped	1 medium portion (30 g)	0.94	3.13	
Rice, Arborio	3 heaped tablespoons (120 g)	1.06	0.88	
Rice, basmati, boiled	3 heaped tablespoons (120 g)	1.18	0.98	
Rice, brown, boiled	3 heaped tablespoons (120 g)	4.51	3.76	
Rice, jasmine, boiled	3 heaped tablespoons (120 g)	0.92	0.77	
Rice, white, boil in the bag, boiled	3 heaped tablespoons (120 g)	1.32	1.10	
Rice, white, easy-cook, boiled	3 heaped tablespoons (120 g)	2.34	1.95	
Rice, white, long-grain, boiled	3 heaped tablespoons (120 g)	2.23	1.86	
Rice, white, short-grain, boiled	3 heaped tablespoons (120 g)	1.18	0.98	
Shredded wholegrain wheat cereal biscuits	2 biscuits (45 g)	0.60	1.34	
Wheat and rice cereal flakes	1 medium portion (30 g)	1.38	4.60	
Wheat cereal biscuits	2 biscuits (40 g)	2.10	5.25	
Wheat bran	2 tablespoons (14 g)	1.54	10.98	9.03
Fruit				
Apples, cooking, fresh, peeled, cooked	1 average portion (85 g)	1.59	1.87	67.0, 26.0

Table 1. *Continued*

Food description	No. of food samples*	Present study			Published values (mg/100 g)
		mg/portion	mg/100 g		
			Mean	SD	
Apples, eating, raw	1 medium, without core (100 g)	0.21	0.21		0.2, 0.5
Apricots, fresh	1 medium, without stone (40 g)	0.44	1.11		0.5 (canned)
Avocado, fresh	$\frac{1}{2}$ small avocado, without skin or stone (50 g)	0.32	0.64		
Banana, raw	1 medium, without skin (100 g)	4.77	4.77		8
Blackberries, raw	10 berries (50 g)	0.12	0.23		
Cherries, raw, without stone	10 cherries, without stone (40 g)	0.41	1.03		
Clementines, raw, without skin	1 medium, without skin (60 g)	1.51	2.52		
Currants, dried	1 heaped tablespoon (25 g)	1.52	6.09		
Dates, dried	3 pieces, without stone (45 g)	7.47	16.61		
Fruit cocktail, in juice	1 average serving (115 g)	2.28	1.98		0.5
Fruit cocktail, in syrup	1 average serving (115 g)	0.47	0.41		0.5
Grapefruit, raw	$\frac{1}{2}$ medium, flesh only (80 g)	0.32	0.40		
Grapes, green and red	1 small bunch (100 g)	0.49	0.49		0.3
Guava, fresh, raw	6 halves (175 g)		ND		
Kiwi fruit, raw, without skin	1 medium, without skin (60 g)	0.13	0.22		
Lemon, fresh, raw	1 slice (20 g)	0.02	0.09		
Mandarin oranges, fresh, raw	1 medium, without skin (100 g)		ND		
Mango, canned in syrup	2 slices (135 g)	1.23	0.91		
Mango, fresh, raw, fibrous	1 medium, without stone or skin (150 g)	3.00	2.00		
Mango, fresh, raw, smooth	1 medium, without stone or skin (150 g)	4.73	3.15		
Melon, (cantaloupe, honeydew, galia)	1 slice, without skin (175 g)	3.19	1.82		
Olives, Italian, bottled in brine, drained, green and black	3 olives, without stone (9 g)	0.11	1.17		
Orange, fresh, raw	1 medium, without skin (160 g)		ND		< 0.2
Peaches, fresh, raw	1 medium, without stone (110 g)	0.70	0.64		0.4
Pears, raw	1 medium (160 g)	0.03	0.02		0.2
Pineapple, canned in juice	2 rings or 12 chunks (80 g)	1.42	1.77		9.0
Pineapple, canned in syrup	2 rings or 12 chunks (80 g)	3.62	4.53		9.0
Pineapple, fresh, raw	1 large slice, without skin (80 g)	3.14	3.93		
Plums, fresh, raw	1 medium, without stone (55 g)	0.14	0.25		0.4
Prunes, canned in juice	6 prunes, without stone (60 g)	0.70	1.16		2.0 (type unspecified)
Prunes, canned in syrup	6 prunes, without stone (60 g)	0.68	1.13		
Raspberries, fresh, raw	15 raspberries (60 g)	0.39	0.65		2.0 (frozen)
Redcurrants, raw	5 raw (2 g)	0.00	0.11		2.0
Strawberries, raw	10 pieces (120 g)	1.19	0.99		2.0
Sultanas	1 tablespoon (30 g)	2.67	8.91		Raisins (10.0, 11.6, 14.0)
Legumes and legume products					
Baked beans, canned in tomato sauce	1 tablespoon (40 g)	0.37	0.92		
Black-eye beans, boiled	2 tablespoons (60 g)	0.69	1.15		
Broad beans, canned or fresh and cooked	2 tablespoons (120 g)	0.46	0.38		
Butter beans, canned	2 tablespoons (60 g)	0.14	0.24		
Chickpeas, canned or dried and boiled	1 heaped tablespoon (35 g)	0.27	0.76		
Hummus	1 tablespoon (30 g)	0.29	0.97		
Lentils, green and brown, boiled	1 tablespoon (40 g)	0.78	1.95		
Lentils, red, boiled	1 tablespoon (40 g)	1.77	4.42		
Red kidney beans, canned or dried and boiled	1 heaped tablespoon (70 g)	0.80	1.14		
Soya beans, dried and boiled	2 tablespoons (60 g)	0.71	1.19		
Tofu	1 average serving (60 g)	1.78	2.96		
Milk and milk products					
Cheese, hard	1 medium chunk (40 g)	0.19	0.47		
Cheese, soft	1 medium chunk (40 g)	0.16	0.39		0.5
Milk, semi-skimmed	1 glass (200 g)	0.14	0.07		< 0.2 (skimmed)
Vegetables					
Aubergine, fresh, baked	$\frac{1}{2}$ aubergine, cooked (130 g)		ND		
Aubergine, fresh, boiled	$\frac{1}{2}$ aubergine, cooked (130 g)	0.38	0.29		

Table 1. Continued

Food description	No. of food samples*	Present study			Published values (mg/100 g)
		mg/portion	mg/100 g		
			Mean	SD	
Beans, green or French, fresh, boiled	1 medium serving (90 g)	7.86	8.73		10.0, 43.9 (raw); 5.0 (frozen)
Beans, runner, fresh, boiled	1 medium serving (90 g)	4.73	5.25		
Beetroot, pickled, drained	4 slices (40 g)	0.32	0.79		
Broccoli, green, fresh, boiled	1 medium serving (85 g)	0.66	0.78		0.5 (raw)
Brussels sprouts, fresh, boiled	9 sprouts (90 g)		ND		
Cabbage, red, fresh, raw	1/6th small cabbage (90 g)	0.25	0.28		< 0.2
Cabbage, regular, fresh, raw	1/6th small cabbage (90 g)		ND		0.5, 0.7, 0.8, 4.0, 17.1
Cabbage, savoy, fresh, raw	1/6th small cabbage (90 g)	0.64	0.71		
Cabbage, white, fresh, raw	1/6th small cabbage (90 g)	0.48	0.53		
Carrots, new and old, fresh, raw	1 tablespoon (40 g)	0.04	0.10		
Cauliflower, fresh, boiled	6 florets (60 g)	0.13	0.22		0.5
Celery, fresh, raw	1 stick (30 g)	0.09	0.29		5.5
Coriander, fresh, raw	1/2 tablespoon (2 g)	0.17	8.42		
Courgette, fresh, boiled	1 medium courgette (100 g)	0.95	0.95		
Cucumber, fresh, raw	1 inch piece (60 g)	1.52	2.53		3.0, 4.6
Kenyan or fine beans, fresh, boiled	1 medium serving (90 g)	9.00	10.00		
Leeks, fresh, boiled	1/2 medium leek (80 g)	0.28	0.35		6.0 (raw)
Lettuce, iceberg, fresh, raw	1 average serving in salad (80 g)	0.92	1.15		2
Lettuce, lamb's, fresh, raw	1 average serving in salad (30 g)	0.54	1.81		2
Lettuce, little gem, fresh, raw	1 average serving in salad (30 g)	0.33	1.11		2
Lettuce, rocket, fresh, raw	1 average serving in salad (30 g)	0.83	2.78		
Mange-tout, fresh, boiled	1 medium serving (90 g)	0.69	0.77		
Marrow, fresh, raw	1 average serving (65 g)	3	3.04	4.68	
Mushrooms, common and closed cup, fresh, raw	3 average mushrooms (30 g)			ND	0.01
Onion, normal, fresh, raw	1/2 small onion (30 g)			ND	1.0, 1.0, 3.0, 3.0
Onions, white, fresh, raw	1/2 small onion (30 g)			ND	0.5
Parsnips, fresh, peeled, boiled	1 tablespoon (50 g)	1.13	2.26		0.5 (raw)
Peas, fresh, boiled	2 tablespoon (60 g)	0.11	0.19		0.4 (raw)
Peas, frozen, boiled	2 tablespoon (60 g)	1.05	1.75		0.3 (frozen)
Peppers, green, fresh, raw	1/4 whole pepper (40 g)	0.12	0.29		
Peppers, red, fresh, raw	1/4 whole pepper (40 g)	0.09	0.22		0.2
Petit pois, frozen, boiled	2 tablespoon (60 g)	0.32	0.53		
Potato, fresh, peeled, boiled	1 medium potato (50 g)	0.17	0.34		< 0.5
Potato, oven chips, cooked	1 medium serving (165 g)	0.68	0.41		
Potatoes, new, peeled, boiled	1 medium potato (40 g)	0.22	0.56		0.2 (raw)
Radish, fresh	5 medium radishes (40 g)	0.16	0.39		0.1, 2.0, 5.1
Salad, mixed leaves, fresh, raw	1 average serving in salad (80 g)	1.41	1.76		
Spinach, fresh, boiled	2 tablespoons (80 g)	4.10	5.12		3.0, 5.0 (raw)
Spring greens, fresh, boiled	1 average serving (75 g)	1.36	1.81		
Spring onions, fresh, raw	1 spring onion (10 g)	0.24	2.43		
Swede, fresh, boiled	1 medium portion (60 g)	1.30	2.17		
Sweet potato, fresh, peeled, boiled	2 medium potatoes (130 g)	0.35	0.27		
Sweetcorn, canned, drained	2 tablespoons (60 g)	0.28	0.46		
Sweetcorn, on the cob, fresh, boiled	1 corn on cob, kernels only (125 g)	0.48	0.38		
Tomatoes, fresh, raw	1 medium tomato (85 g)		ND		< 0.2, 0.13, 6.1
Turnips, fresh, peeled, boiled	1 whole (110 g)	1.00	0.91		12.0 (raw)
Yam, fresh, peeled, boiled	Equivalent to 1 medium potato (130 g)	0.48	0.37		
Snack foods					
Chocolate, milk	1 average bar (50 g)	0.51	1.01		1
Corn chips†	1 packet (50 g)	2.22	4.44		
Crisps	1 small packet (30 g)	0.14	0.47		
Nuts and seeds					
Brazil nuts	6 whole (20 g)	0.06	0.28		

Table 1. *Continued*

Food description		No. of food samples*	Present study			Published values (mg/100 g)
			mg/portion	mg/100 g		
				Mean	SD	
Cashew nuts, roasted	1 small bag (25 g)		0.15	0.60		
Groundnuts, roasted and salted	1 small bag (25 g)		0.06	0.24	4.7	
Tahini	1 heaped teaspoon (19 g)		0.38	1.99		
Beverages†‡						
Bitter lemon	1 can (337 g)		0.47	0.14		
Carbonated beverages, other, canned	1 can (343 g)		0.41	0.12	0.3, 0.6, 0.3	
Cocoa, powdered, made up with water	1 mug (260 g)		1.04	0.40		
Coffee, instant, decaffeinated, made up with water	1 mug (260 g)		0.62	0.24		
Coffee, instant, made up with water	1 mug (260 g)		1.53	0.59	20	
Cola, canned	1 can (343 g)		0.69	0.20	0.2	
Cola, low-energy, canned	1 can (343 g)		0.38	0.11		
Drinking chocolate, powdered, low-energy, made up with water	1 mug (260 g)		10.3	3.96		
Drinking chocolate, powdered, made up with water	1 mug (260 g)		1.27	0.49		
Energy drinks, canned	1 slim can (260 g)		0.21	0.08		
Fruit drink, carbonated, canned	1 can (343 g)		0.38	0.11		
Fruit drink, carbonated, low-energy, canned	1 can (343 g)		1.03	0.30		
Fruit juice drink, carton	1 carton (260 g)		0.39	0.15		
Fruit juice drink, low-energy, carton	1 carton (260 g)		0.26	0.10		
Juice, apple, fresh	1 glass (160 g)		0.08	0.05		
Juice, apple, long-life	1 glass (160 g)		0.42	0.26		
Juice, orange, fresh	1 glass (160 g)		0.21	0.13		
Juice, orange, long-life	1 glass (160 g)		0.19	0.12		
Juice, pineapple, fresh	1 glass (160 g)		2.26	1.41		
Juice, pineapple, long-life	1 glass (160 g)		2.34	1.46		
Lemonade, canned	1 can (337 g)		0.64	0.19		
Lemonade, low-energy, canned	1 can (337 g)		0.40	0.12		
Malt-based drink, low-fat, powdered, made up with water	1 mug (260 g)		3.25	1.25		
Malt-based drink, powdered, made up with water	1 mug (260 g)		3.93	1.51		
Milk shake, powdered, made up with water	1 mug (260 g)		0.52	0.20		
Tea, black, decaffeinated, infusion	1 mug (260 g)		0.78	0.30		
Tea, camomile, infusion	1 mug (260 g)		0.68	0.26		
Tea, black, ordinary, infusion, leaves	1 mug (260 g)		0.33	0.81	0.2	
Tea, black, ordinary, infusion, tea bag	1 mug (260 g)		0.31	0.86	0.2	
Water, mineral, non-English, sparkling	1 bottle (330 g)	3	2.31	0.70	0.51	
Water, mineral or spring water, sparkling	1 bottle (330 g)	3	1.29	0.39	0.14	
Water, mineral or spring, still	1 bottle (330 g)	3	1.78	0.54	0.49	
Water, plain, bottled	1 bottle (330 g)		1.65	0.50		
Water, soda	1 can (170 g)		0.15	0.09		
Water, tap	1 glass (200 g)	4	0.50	0.25	0.11	
Water, tonic	1 can (170 g)		0.37	0.22	0.34 (Denver, USA); 0.02 (Wales, UK)	
Alcoholic beverages§						
Bitter or ale, bottled	1 bottle (300 g)	8	5.49	1.83	0.45	
Bitter or ale, canned	1 small can (333 g)	3	3.80	1.14	0.38	

0.34 (Denver, USA); 0.02 (Wales, UK)

3.0 (<2.25% alcohol)
3.0 (3–3.7% alcohol)

Table 1. Continued

Food description		No. of food samples*	Present study			Published values (mg/100 g)
			mg/portion	mg/100 g		
				Mean	SD	
Bitter or ale, draft	1 pint (574 g)	5	12.60	2.19	0.60	6.0 (3.7–4.5% alcohol)
Cider	1 pint (574 g)	3	2.30	0.40	0.07	
Lager, bottled	1 bottle (300 g)	5	6.21	2.07	0.36	
Lager, canned	1 small can (333 g)	4	5.46	1.64	0.51	
Lager, draft	1 pint (574 g)	3	16.30	2.84	1.05	
Stout, bottled	1 bottle (300 g)	2	5.28	1.76	0.12	
Stout, canned	1 small can (333 g)	4	6.06	1.82	0.59	
Wine, fortified, port	1 small glass (50 g)	2	0.62	1.24	0.15	
Wine, fortified, sherry	1 small glass (50 g)	3	0.63	1.26	0.06	
Wine, red	1 glass (125 g)	7	0.85	0.68	0.59	0.20–2.35
Wine, rosé	1 glass (125 g)	3	2.89	2.31	0.84	1.99
Wine, white	1 glass (125 g)	7	1.34	1.07	0.47	0.7

ND, non-detectable level of Si. For details, see p.810.

* For most foods, three samples of the food were used to provide a composite sample. However, for some foods a composite sample was not used and a number of individual foods were analysed; for these the mean and standard deviation are presented together with the number of food samples used.

† These products (particularly low-energy drinking chocolate) may contain non-bioavailable silicate additives leading to a high Si content.

‡ Mean Si content of water used to dilute was 0.196 mg/100 g.

§ Si levels were not related alcohol content in the present study or a previous study (Sripanyakorn *et al.* 2004).

recent data showed that some of these, such as beer, may be especially high in Si (Sripanyakorn *et al.* 2004). Third, a few plant-based foods that had not been adequately investigated in the literature, but could contain substantial amounts of Si, were also included for analysis (for example, nuts). Finally, drinking water, which may be a significant source of dietary Si and is used in beverages (for example, tea, coffee and cold drinks) and in homemade soups and sauces, was analysed for use with water intake and recipe calculations. Processed foods were not included in the analysis as they may have Si added in a relatively non-bioavailable form, typically as particulate silicates and aluminosilicates (Dobbie & Smith, 1982; Institute of Medicine, 2001), and their natural Si content can be calculated from knowledge of the ingredients. Meat, poultry, fish and seafood contain very little Si and therefore were not investigated here (Pennington, 1991).

Selected foods (Table 1) were bought from supermarkets and greengrocers at three different locations in Southeast England (i.e. each food was purchased in triplicate), with selection based upon supermarket availability (i.e. popularity of product) and the frequency of ingestion of the food item. Equal amounts of each food from the three sources were combined, taking care to form a representative composite (for example, outer and inner leaves of green vegetables at an appropriate ratio) and then homogenised in a food blender. Some foods were analysed without compositing, in order to observe within-food variations of Si content, but at least three different samples of the same food type were then analysed. Foods were generally prepared in their 'as eaten' form and a single large batch of tap water of known Si content was used to boil foods where appropriate.

Chemical analysis

Throughout the study no glassware was used, and to avoid excessive skin contact, powder-free, polythene gloves were used on all occasions. Samples were digested and analysed in the Gastrointestinal Laboratory (St Thomas' Hospital, London, UK). Sample preparation and analysis was performed in a class J clean air

room. Homogenised samples were placed into Si-free 10 ml polypropylene transport tubes (Medfor Products, Farnborough, UK). Acid-assisted microwave digestion was conducted using a Milestone Ethos Plus Microwave Digestion System (Milestone Analytical UK Ltd, Northwich, Cheshire, UK) using nitric acid (65%, w/v, ANALAR grade; Merck, West Drayton, UK) and H₂O₂ (30%, w/v, ARISTAR grade; Merck, West Drayton, UK). Approximately 0.25 g homogenised sample was added to a digestion vessel with 10 ml nitric acid and 1 ml H₂O₂ and the vessel sealed, heated (ramped) to 200°C over 10 min and maintained at 200°C for 15 min. Sample blanks were similarly prepared using 10 ml nitric acid (69%, w/v) and 1 ml H₂O₂ (30%, w/v). Digested samples and blanks were diluted with approximately 33 ml ultra-high purity water (18 MΩ/cm; Elga Ltd, High Wycombe, UK) and total final volumes, assessed accurately by weight, were recorded before analysis. Acid digestion was not needed for most fluids, apart from viscous samples (for example, port and sherry), as the majority could be analysed directly or with simple dilution with ultra-high purity water. Si analysis was performed using an inductively coupled plasma–optical emission spectrometer (Jobin-Yvon JY24; Instruments SA, Longjumeau, France) with a V-groove nebuliser and Scott-type double-pass spray chamber at 251.611 nm as previously described (Jugdohsingh *et al.* 2002). Analysis was by peak profile with a window size of 0.1 nm, fifty-four increments per profile, an integration time of 0.5 s and sample flow rate was 1 ml/min. Si standards were prepared from a stock ICP–DCP standard solution (1000 mg Si/l; Aldrich Chemical Company, Gillingham, UK) in matrix-matched solutions (i.e. sample-based standards). Standard reference materials do not exist for Si in foods or clinical samples, so spiking and recovery experiments were used as before for quality assurance (Sripanyakorn *et al.* 2004). Under these conditions of microwave digestion, certain solid-phase silicates, especially crystalline silica and silicates, may undergo only partial digestion and require hydrofluoric acid for full dissolution. However, dietary Si is not expected to occur in the form of crystalline silicates, while the conditions of microwave digestion far exceed

gastrointestinal digestion. Therefore, any small amounts of undissolved silicates are unlikely to be absorbed in the gastrointestinal tract.

To ensure that Si detected in the sample was from the digested food, and not from 'noise' or background, a sample detection limit was established. The mean ± 2 SD of the Si content of the sample blanks was determined on each day of analysis. These values were then used to calculate the minimum observable value for a 'positive result' in the digested food samples. If the food sample had a reading of less than the mean $+2$ SD of the blanks, then the Si content of the food was considered undetectable. Mean Si in the sample blanks was 47.8 (SD 16.4) parts per billion translating to a mean sample detection limit (wet weight), for the digested and diluted samples, of 14.3 g Si per g sample. Further analytical details are available in the Food Standards Agency Report (Powell & Bolton-Smith, 2003).

Precision of analysis depends on sample type (i.e. matrix). Precision was less than 3% for most cereal foods, 4.66 (range 0–22.6) % for fruit and vegetables and 3.34 (range 0–16.2) % for beverages. Overall, as expected, precision was greatest in samples with high Si content and poorest in those with low content. This is reported in detail in the Food Standards Agency Report (Powell & Bolton-Smith, 2003).

The Si content of each food is expressed per 100 g edible portion and by typical portion size in the UK (Davies & Dickerson, 1991; Ministry of Agriculture Fisheries and Foods, 1993). For foods where multiple samples were analysed rather than a composite sample, the mean and standard deviation of Si content of the food samples is provided.

Results

Table 1 presents the Si content of the 207 foods and beverages analysed. Comparisons with the published literature are also presented in Table 1 where relevant or appropriate values exist.

Almost half of the foods analysed (ninety-five items) had low levels of Si (<1.0 mg/100 g) and there were ten digested foods that had levels of Si that were indistinguishable from background levels (i.e. sample blanks nitric acid and H₂O₂ alone; see p. 809): A total of eighteen foods contained high levels of Si (>5.0 mg/100 g). The majority of these foods (eleven items) were from the breads and cereals group and related cereal products, with oat-containing products having the highest levels of all cereals and oat bran having the highest Si content of all items analysed. The remaining items were from the vegetables group (namely, Kenyan beans, green beans, runner beans, spinach and coriander) or were dried fruits. When results were expressed in terms of Si content per portion, those foods with a high Si content were predominantly beers (seven out of twelve items).

There was considerable variation in the Si content of vegetables, legumes and fruits. With respect to vegetables and legumes, as noted earlier, the richest sources of Si were Kenyan beans, French beans and runner beans, spinach and red lentils. The majority of other vegetables contained low or undetectable amounts of Si (<1.0 mg per 100 g). With respect to fresh fruits, the highest levels of Si were found in the banana, mango and pineapple.

Of the non-alcoholic beverages, drinking chocolate provided the highest mean Si content, although this is probably due to the addition of particulate silicate additives rather than a high natural Si content (Lomer *et al.* 2004). Tap water contained more Si per 100 g than the carbonated soft drinks while sparkling mineral

waters contained more Si than the still water samples. The Si content of juices (for example, orange, apple and pineapple juice) corresponded to the content of the fresh form of the fruit with apple and orange juices having low levels and pineapple juice showing higher levels. With respect to the alcoholic beverages, beer had higher mean Si content than wine, and cider had the lowest Si content, again corresponding to the Si contents of the major raw materials, namely barley, grapes and apples respectively.

The remaining food groups, including the milk and milk products and the nuts and seeds, all contained low levels of Si.

Discussion

Data presented in the present paper represent the first available food composition database for the Si content of UK foods. A total of 207 different foods were analysed covering all the major potential Si-containing foods and food groups for the UK population. Almost half of all the foods analysed had a low Si content and a small number had levels that were undetectable. The highest levels of Si were found in the cereals, especially less refined cereals and oat-based products. Fruit and vegetables were highly variable sources of Si, with substantial amounts present in green beans, dried dates, bananas and red lentils but undetectable amounts in tomatoes, oranges and onions.

For many plant foods, consideration of the botanical characteristics of the plant may explain their observed Si content. Overall, fruit and vegetables with trichomes or ultrafine hairs on their surface, which are potential locations for Si depositions, tend to have higher Si content. Further evidence supporting the contribution of these fine hairs to the Si content is available from the observed content of the mature seeds. For example, the French bean is consumed either as an immature fruit or pod, which has trichomes present on its surface and a high Si level, or is matured and eaten as the kidney bean (Southgate, 2000) where the pod has been removed resulting in a substantial decrease in the level of Si. Similarly, spinach contains a moderate level of Si, which may also be due to the numerous silicified trichomes on the leaf epidermis. In cereals, it is the silicification of inflorescence bracts, and the siliceous epicarp hairs at the brush end of the mature caryopsis that are responsible for the high Si levels observed (Hayward & Parry, 1980; Hodson & Sangster, 1988). Si has been found along the epicarp hairs of the mature caryopses of wheat, barley and oats, but was most concentrated on the surface and at the tips of the hairs (Bennet & Parry, 1981; Parry *et al.* 1984).

Alcoholic beverages, especially the beers and wine, were shown to have a moderate to high Si content. Beer provides a significant amount of absorbable Si obtained from the hot mashing technique that extracts soluble orthosilicic acid from phytolith silica in the barley husks which adhere to the grain (Sripanyakorn *et al.* 2004). Due to the relatively high consumption of beer among the UK population (Bellia *et al.* 1994), beer could contribute substantially to the mean daily Si intakes. For example, in 1990, consumption of beer in the UK was 194 pints per individual per annum, which would provide a daily Si intake of 6 mg/individual (Bellia *et al.* 1994).

With respect to wine, it is known that Si is taken up by the grape vines, and some is transferred to the grapes, but little is known about the balance between endogenous Si and Si from other sources in determining the final Si concentration of wine (Blaich & Grundhofer, 1997). For example, the presence of Si in wine may also be due to the spraying of the grapes with potassium

silicate to control powdery mildew before harvest or due to the use of clarifying agents, such as bentonite and colloidal silica gel (EC Council, 1999; Cabras & Angioni, 2000).

Although tap water had a relatively low Si content, it also has the potential to contribute a substantial amount to overall Si intake due to the amount normally consumed directly, as a diluent in other beverages and as an ingredient in many recipes. The Si content of tap water can vary according to the geographical region, with typically high Si levels in hard water areas and low levels in soft water areas (Seaborn & Nielsen, 1993). In a study carried out in Egypt, bottled water of all brands contained higher levels of Si than tap water (Saleh *et al.* 2001), which also was reflected in the findings here with higher Si levels in spring and mineral waters. This may well be because tap water treatment (i.e. by Al flocculation) decreases the Si content.

Manufacturing processes may also affect the Si content of the final food item. First, although cereals and related products were shown to have high levels of Si compared with other food items, the level of Si varied according to the level of refining, which determines how much of the original silicified plant material is preserved in the final food item. Second, the Si content of some fruits and legumes may have also been affected by processing. For example, dates accumulate Si in substantial quantities but the drying process further increases their Si content due to the loss of water (Holland *et al.* 1991; Cummings, 1992). Hence, dried fruits in the present study (for example, sultanas), as reported elsewhere in the literature (Pennington, 1991), have relatively high Si levels. In addition, Si may be added to some dried foods in the form of silica gel (SiO₂) (Hughes, 1987). The high Si content of red lentils was surprising when compared with related foods such as other legumes consumed as mature seeds or in the fresh form (peas, chick peas, etc.) which all had Si levels below 1 mg/100 g, suggesting that drying processes or storage may be responsible for the higher Si content of red lentils. Third, high levels of Si found in drinking chocolate and corn chips may relate to Si added as particulate and non-bioavailable silicates during processing, chiefly as anti-caking agents (Expert Group on Vitamins and Minerals, 2003; Lomer *et al.* 2004).

The Si content of foods analysed in the present study was compared with the published literature where appropriate or relevant data were available. The Si contents of the majority of beverages and cereals were comparable with values available in the published literature, except for three products (white flour, savoury biscuits and Weetabix), with the Si content of plain white flour reported in the literature being nearly double that found in the present study (Table 1). Comparisons between the literature and the present study were less consistent for fruit and vegetables. This may be due to variations in the plant cultivars grown in different countries, geographical variations in soil and water Si contents used in agriculture, and in variations in Si content of water used in cooking for cooked items. Finally, banana was shown here and in previous work to have a high Si content, in contrast to the majority of other fruits, although the reasons for its high Si content are unknown (Pennington, 1991). However, the importance of bananas in contributing to an individual's Si exposure is questionable, as little is thought to be bioavailable following consumption of the fruit (Jugdaohsingh *et al.* 2002).

Conclusions

The present study provides a provisional database for the Si content of foods based on laboratory analysis of carefully selected

UK foods. This database will allow the estimation of dietary intakes in the UK population and investigation into the role of dietary Si in human health.

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References

- Bellia JP, Birchall JD & Roberts NB (1994) Beer: a dietary source of silicon. *Lancet* **343**, 235.
- Bennet DM & Parry DW (1981) Electron-probe microanalysis studies of silicon in the epicarp hairs of the caryopses of *Hordeum sativum* Jess., *Avena sativa* L., *Secale cereale* L., and *Triticum aestivum* L. *Ann Bot* **48**, 645–654.
- Blaich R & Grundhofer H (1997) Uptake of silica by grapevines from soil and recirculating nutrient solutions. *Vitis* **36**, 161–166.
- Bowen HJM & Peggs A (1984) Determination of the silicon content of food. *J Sci Food Agric* **35**, 1225–1229.
- Cabras P & Angioni A (2000) Pesticide residues in grapes, wine, and their processing products. *J Agric Food Chem* **48**, 967–973.
- Carlisle EM (1972) Silicon: an essential element for the chick. *Science* **178**, 619–662.
- Carlisle EM (1981) Silicon: a requirement in bone formation independent of vitamin D. *Calcif Tissue Int* **33**, 27–34.
- Carlisle EM (1982) The nutritional essentiality of silicon. *Nutr Rev* **40**, 193–198.
- Cummings LS (1992) Illustrated phytoliths from assorted food plants. In *Phytolith Systematics – Emerging Issues*, pp. 175–192 [G Rapp and SC Mulholland, editors]. New York: Plenum Press.
- Davies J & Dickerson J (1991) *Nutrient Content of Food Portions*. Cambridge, UK: Royal Society of Chemistry.
- Dobbie JW & Smith MB (1982) Silicon: its role in medicine and biology. *Scott Med J* **27**, 1–2.
- EC Council (1999) Common Organisation of the Market in Wine. Official Journal of the European Communities L179 **42**, 1–84.
- Expert Group on Vitamins and Minerals (2003) *Safe Upper Levels for Vitamins and Minerals*. London: Food Standards Agency.
- Hayward DM & Parry DW (1980) Scanning electron microscopy of silica deposits in the culms, floral bracts and awns of barley (*Hordeum sativum* Jess.). *Ann Bot* **46**, 541–548.
- Hodson MJ & Sangster AG (1988) Silica deposition in the inflorescence bracts of wheat (*Triticum aestivum* L.). I. Scanning electron microscopy and light microscopy. *Can J Bot* **66**, 829–838.
- Holland B, Welch AA, Unwin ID, Buss DH, Paul AA & Southgate DAT (1991) *McCance and Widdowson's The Composition of Foods*, 5th ed. Cambridge, UK: Royal Society of Chemistry.
- Hughes C (1987) *The Additives Guide*. Chichester, UK: John Wiley and Sons.
- Iler RK (1979) *The Chemistry of Silica. Solubility, Polymerisation, Colloid and Surface Properties, and Biochemistry*. New York: John Wiley & Sons.
- Institute of Medicine (2001) *Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium and Zinc*. Washington, DC: National Academy Press.

- Jugdaohsingh R, Anderson SHC, Tucker KL, Elliott H, Kiel DP, Thompson RPH & Powell JJ (2002) Dietary silicon intake and absorption. *Am J Clin Nutr* **75**, 887–893.
- Jugdaohsingh R, Tucker KL, Qiao N, Cupples LA, Kiel DP & Powell JJ (2004) Dietary silicon intake is positively associated with bone mineral density in men and premenopausal women of the Framingham Offspring Cohort. *J Bone Miner Res* **13**, 297–307.
- Lomer MCE, Hutchinson C, Volkert S, Greenfield SM, Catterall A, Thompson RPH & Powell JJ (2004) Dietary sources of inorganic microparticles and their intake in healthy subjects and patients with Crohn's disease. *Br J Nutr* **92**, 947–955.
- Ministry of Agriculture Fisheries and Foods (1993) *Food Portion Sizes*, 2nd edition. London: The Stationery Office.
- Parry DW, Hodson MJ & Sangster AG (1984) Some recent advances in studies of silicon in higher plants. *Phil Trans R Soc London* **304B**, 537–549.
- Pennington JAT (1991) Silicon in food and diets. *Food Addit Contam* **8**, 97–118.
- Powell JJ & Bolton-Smith C (2003) *Interaction between Silicon Intake and Vitamin D and K Status on Markers of Bone Health in Older Women. Final Report to the Food Standards Agency*. Project No. 5034. London: Food Standards Agency
- Reffitt DM, Jugdaohsingh R, Thompson RPH & Powell JJ (1999) Silicic acid: its gastrointestinal uptake and urinary excretion in man and effects on aluminium excretion. *J Inorg Biochem* **76**, 141–147.
- Saleh MA, Ewane E, Jones J & Wilson BL (2001) Chemical evaluation of commercial bottled drinking water from Egypt. *J Food Comp Anal* **14**, 127–152.
- Schwarz K (1977) Silicon, fibre and atherosclerosis. *Lancet* **i**, 454–457.
- Schwarz K & Milne DB (1972) Growth-promoting effects of silicon in rats. *Nature* **239**, 333–334.
- Seaborn CD & Nielsen FH (1993) Silicon: a nutritional beneficence for bones, brains and blood vessels. *Nutr Today* **28**, 13–18.
- Southgate DAT (2000) Vegetables, fruits, fungi and their products. In *Human Nutrition and Dietetics*, [JS Garrow, WPT James and A Ralph, editors]. London: Churchill-Livingstone.
- Sripanyakorn S, Jugdaohsingh R, Elliott H, Walker C, Mehta P, Shouker S, Thompson RPH & Powell JJ (2004) The silicon content of beer and its bioavailability in healthy volunteers. *Br J Nutr* **91**, 403–409.
- van Dyck K, Robberecht H, van Cauwenbergh R, *et al.* (2000) Spectrometric determination of silicon in food and biological samples: an inter-laboratory trial. *J Anal At Spectrom* **15**, 735–741.