Community Dent Oral Epidemiol 2007; 35: 479–488

COMMUNITY DENTISTRY AND ORAL EPIDEMIOLOGY

Fluoride intake and urinary excretion in 6- to 7-year-old children living in optimally, sub-optimally and non-fluoridated areas

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Maguire A, Zohouri FV, Hindmarch PN, Hatts J, Moynihan PJ. Fluoride intake and urinary excretion in 6- to 7-year-old children living in optimally, sub-optimally and non-fluoridated areas. Community Dent Oral Epidemiol 2007; 35: 479–488. © 2007 The Authors. Journal compilation © 2007 Blackwell Munksgaard

Abstract – *Objectives:* This study was designed to measure total intake, urinary excretion and estimated retention of fluoride in children under customary fluoride intake conditions, living in either fluoridated or low-fluoride areas of north-east England. Subsidiary aims were to investigate the relationships between the variables measured. *Methods:* Using a randomized cluster design with schools as the sampling units, four schools from a non-fluoridated area and two from a fluoridated area were selected from the schools chosen to participate in the study. Fluoride intake from diet and toothbrushing was assessed using a 3-day food diary and fluoride analysis of expectorated saliva during toothbrushing. Samples of all foods and drinks consumed were measured for fluoride content using direct and indirect silicon-facilitated diffusion methods as appropriate. Urinary fluoride excretion and urine volume were measured over 24 h and estimation of fractional urinary fluoride excretion (FUFE) and fluoride retention made from collected data. Following descriptive analysis of variables, Pearson's correlations investigated relationships between fluoride content of home tap water, daily fluoride intake, excretion and retention. *Results:* Thirty-three children completed the study: 18 receiving non-fluoridated water [mean = 0.08 (±0.03) mg F/l], nine sub-optimally fluoridated water [mean = 0.47 (±0.09) mg F/l] and six optimally fluoridated water [mean = 0.82 (±0.13) mg F/l] at the time of the study. Complete data on F intake, excretion and retention were available for 29 children. Mean fluoride intake from diet and toothpaste ranged from 0.031 (±0.025) mg/kg body weight (bw)/day for the low-fluoride area to 0.038 (±0.038) and 0.047(±0.008) mg/kg bw/day for sub-optimally and optimally fluoridated areas respectively. Contribution of toothpaste to total fluoride intake ranged from 3% to 93% with mean values of 57%, 35% and 47% for children receiving low, sub-optimally and optimally fluoridated water respectively. FUFE ranged from a mean of 32% (±13%) for the optimally fluoridated area to 44% (±33%) for the low-fluoride area. Fluoride retention was not correlated with the fluoride concentration of home water supply, but was strongly positively correlated ($P < 0.001$) with total daily fluoride intake. *Conclusions:* In an industrialized country, total fluoride intake, urinary excretion and consequently fluoride retention no longer reflect residence in a community with a non-fluoridated or fluoridated water supply. Fluoride toothpaste contributes a significant proportion of total ingested fluoride in children, particularly in low-fluoride areas.

Key words: children; diet; excretion; fluoride; intake; retention; toothpaste

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Submitted 8 April 2006;
accepted 24 July 2006

doi: 10.1111/j.1600-0528.2006.00366.x

Recent studies in the USA have shown an increase in the prevalence of dental fluorosis in fluoridated and nonfluoridated communities (1, 2), suggesting that exposure of individuals to fluoride is increasing. Residence in a non-fluoridated community does not automatically ensure low fluoride intake, nor does living in a fluoridated community result in adequate or high fluoride intake, because food, drink or even bottled water produced in a fluoridated area may be transported to a non-fluoridated area and vice versa (3). A significant increase in the fluoride content of infant milk formulas, toddler cereals, fruit juices and popular beverages has been reported (4), because of the use of fluoridated water in their processing. Consequently, there is some concern that in children, total daily fluoride intake from diet and especially from unintentional ingestion of toothpastes containing fluoride might exceed the threshold for development of dental fluorosis. The aesthetically important upper central permanent incisors begin to form soon after birth and erupt at about 7 years of age. Their susceptibility to dental fluorosis would appear to be greatest during the first 4 years of life (5–7), although Burt et al. (8) cautioned against too precise definitions of age of greatest risk of fluorosis, because there is increasing evidence that developing tooth germs may be vulnerable to fluoride over a longer period (9, 10).

Information on total fluoride exposure is important for public health planners and healthcare professionals when planning effective community-based fluoride therapy for the prevention of dental caries, while avoiding dental fluorosis. Total fluoride intake and excretion, and the body's resultant fluoride retention are the most relevant factors associated with the occurrence of dental fluorosis. The difficulties involved in measuring total fluoride intake and retention in infants and young children are considerable. Fluoride intake in a community will vary depending on the environmental temperature and the volume of fluid intake, because the major proportion of dietary fluoride ingestion is from drinks. In addition, the concentration of fluoride in various foods might differ by area because of differences in the concentration of fluoride in the water supply used to prepare and cook the foods. Finally, there may be differences in dietary and toothbrushing habits in each community. With regard to fluoride excretion, obtaining a 24-h urine sample, especially from young children is difficult. In addition, some dietary factors can increase or reduce the absorption and excretion of ingested fluoride (11, 12), making the body's retention of fluoride an important yet variable consideration. A few studies have measured both total fluoride intake and urinary fluoride excretion in the same children (13–17) and found a wide variation in the proportion of ingested fluoride excreted through urine, ranging from 31% to 85% in 3- to 5-year olds. Fluoride retention represents the difference between uptake and elimination of fluoride from urine and faeces. Because of the practical difficulties in collecting faeces, fluoride retention is usually estimated. A net fluoride retention of 0.05 mg/day has been reported for children aged 3–4 years residing in a fluoridated community in California (13). However, Ekstrand et al. (18) reported that breast-fed infants were in negative balance (i.e. they excreted more fluoride than they ingested), whereas bottle-fed infants were found to retain more than half of their fluoride intake.

There has been no study of fluoride intake and excretion in children living in the UK, therefore this study was designed to measure total fluoride intake, urinary fluoride excretion and fluoride retention in children under customary fluoride intake conditions, living in either fluoridated or low-fluoride areas of north-east England. The subsidiary aims of the study were to investigate the associations between: (a) fluoride intake and fluoride retention; and (b) the fluoride concentration of the home tap water and (i) total fluoride intake, (ii) 24-h urinary fluoride excretion, and (iii) fluoride retention.

Materials and methods

Subjects

The study protocol was approved by the relevant Local Ethics Committees in the study areas. The study had a randomized cluster design using schools as the sampling units. A list of all primary schools located in a non-fluoridated and an artificially fluoridated area north-east of England was obtained from the relevant Education Authorities and each school was contacted by letter. Four schools from two towns in the non-fluoridated area and two schools from a city in the fluoridated area were selected from the schools prepared to participate in the study. The study was explained in a letter to the parents of all children aged 6 years, and written consent was obtained from those parents and children who agreed to participate.

In total, 33 healthy children were recruited: 18 from schools in the fluoridated area and 15 from schools in the non-fluoridated areas. These children were aged 6 years when recruited and had been living continuously in the selected areas and were not taking any fluoride supplements. After analysing three samples of home tap water from each individual's home and school, the subjects were categorized into three groups based on the fluoride content of their home tap water supply: those receiving optimally fluoridated (≥0.7 mg F/l), sub-optimally fluoridated (≥0.3 to <0.7 mg F/l) and non-fluoridated (<0.3 mg F/l) drinking water.

Anthropometric measurements

Anthropometric measurements were taken during a home visit. Height (to the nearest centimetre) was measured without shoes using a portable digital stadiometer. Weight (to the nearest 0.1 kg) was also measured using a portable digital scale.

Assessment of dietary fluoride intake

Dietary fluoride intake was assessed using a 3-day food diary, with full written and verbal instructions given on how to complete the food diary. The importance of recording all food and drink consumed over the 3-day period was emphasized. Children and their parents were then interviewed at home on the fourth day to ensure the accuracy of information recorded and, with the help of a food portion atlas (19), to determine portion size. An electronic version of the current UK food composition tables (20–25) was used to code the food diaries and the codes were then entered into a purpose-designed MS Access database to estimate dietary fluoride intake once information from the fluoride analysis of foods and drinks had been included in the tables.

Collection and analysis of food and drink samples

Samples of food and drink consumed by the children during the 3-day dietary assessment were collected. Samples of home-made food and drink were obtained from households and others were purchased from local shops as appropriate. Samples of school meals, including tap water, were obtained from the schools. The samples were individually homogenized and stored frozen at −20°C until the appropriate fluoride analysis.

The fluoride contents of samples of water and non-milk-based drinks were measured using a fluoride ion-selective electrode after addition of TISAB II by a direct method (26). A silicon-facilitated diffusion method (27, 28) was used for fluoride analysis of food and milk-based drink samples.

Assessment of fluoride intake from ingested toothpaste

During the home visit on the fourth day, children were asked to brush their teeth using their normal toothbrush and toothpaste, according to their usual habits. The amount of toothpaste dispensed onto the toothbrush was measured by weighing the toothbrush before and after dispensing the toothpaste onto the toothbrush. The brand of toothpaste used was recorded and its fluoride concentration determined from the manufacturer's labelling information. All expectorated saliva, liquids and toothpaste were carefully collected during toothbrushing and rinsing. Any toothpaste adhering to the face or hands was collected by using a spatula. The number of brushings per day was recorded. The samples were weighed, mixed and stored frozen at −20°C until the appropriate fluoride analysis based on a silicon-facilitated diffusion method (27, 28).

Assessment of 24-h urinary fluoride excretion

On the third day of the 3-day dietary record, a 24-h urine sample was collected from each child by providing a jug, a funnel and a plastic bottle containing chlorhexidine digluconate as preservative to the parents, and providing written and verbal instructions on how to collect urine during a 24-h period. The volume of urine produced was recorded, and three aliquots were stored in a freezer at −20°C until the appropriate fluoride analysis. Fluoride content of urine samples was determined using a fluoride ion-selective electrode after addition of TISAB II by a direct method (26).

Estimation of FUFE and fluoride retention

Fractional urinary fluoride excretion (FUFE) (%) was calculated by dividing the daily amount of fluoride excreted in the urine by the total daily fluoride intake (TDFI) and expressing it as a percentage. Total daily fluoride excretion (TDFE) through urine and faeces was estimated by assuming that a fraction of 10% of daily fluoride intake is excreted through faeces (18, 29) and adding this to the daily amount of fluoride excreted in the urine. Retention (%) was then estimated by the following formula: $[(TDFI - TDFE)/TDFI] \times 100$.

Validity of the methods employed

Mean energy intake and physical activity level [PAL = energy intake/predicted basal metabolic rate (BMR)] were used to estimate the validity of dietary information. The validity of the recorded 24-h urine volume was estimated by measuring creatinine excretion [mg/kg body weight (bw)/day] using the Jaffe method (30) and urinary flow rate (ml/h).

Validity and reliability of fluoride analysis

A known amount of fluoride was added to 16% of samples of food and drinks, in triplicate, and the percentage recovery of fluoride measured in order to evaluate the validity of the method. Ten per cent of food and drink samples were reanalysed to determine the reliability of measurements.

Data analysis

Descriptive analysis of variables was carried out using the SPSS statistical program to derive mean (SD) values for each group. No statistical comparison by fluoride concentration of water was performed as the study was not designed to test any hypotheses. The Pearson correlation coefficient was used to investigate the relationships between fluoride content of tap water supply, daily fluoride intake, excretion and retention.

Results

Subject characteristics

Thirty-three children (16 boys and 17 girls) completed the study. Eighteen children were receiving non-fluoridated water at home with a mean (SD) fluoride content of 0.08 (±0.03) mg/l, while nine children living in an 'optimally' fluoridated area were receiving sub-optimally fluoridated tap water at home with a mean fluoride content of 0.47 (±0.09) mg/l. This was due to fluoridation equipment supplying a number of water supply zones being taken out of service for replacement at the time of the study. The remaining six children received optimally fluoridated home tap water with 0.82 (±0.13) mg F/l. The mean (SD) age, height and weight of all children was 6.9 (±0.7) years, 119.8 (±5.7) cm and 23.7 (±4.4) kg, respectively.

Validity of the methods

Validity of 3-day food diary

The mean (SD) intake of energy was 7.0 (±1.5) MJ for boys and 7.1 (±1.2) MJ for girls. The mean energy intake of boys, in the present study, was slightly lower than the estimated average requirement (EAR) of 7.2 MJ for boys aged 4–6 years (31), although the mean energy intake of girls was higher than the EAR of 6.5 MJ. However, the mean energy intakes of boys and girls in the present study were higher than the values reported for British boys (6.4 MJ) and girls (5.9 MJ), aged 4–6 years, in the report of National Diet and Nutrition Survey (32). The mean (SD) PAL of 1.7 (±0.3) for the children in the present study was slightly higher than the mean PAL of 1.6 for 5- to 9-year-old children with a healthy Body Mass Index (BMI) found in industrialized countries (33). Overall, from these results it was concluded that the collection of dietary data was likely to be satisfactory in this study.

Validity of the 24-h urine volume

It has been suggested that creatinine excretion rates below 11.3 mg/kg bw/day in healthy white children should be suspected as being incomplete (34). However, it has also been reported that the decision to exclude a sample from analysis should not just be based on this cut-off excretion rate for creatinine, and a second criterion should be used. A urinary flow rate of <9 ml/h has also been suggested as indicating a urine sample as incomplete (35). In the present study, the 24-h urine sample of one child did not meet the creatinine excretion rate criterion and was excluded from further analysis although the child had a urinary flow rate of 9 ml/h, the minimum acceptable rate.

Validity of the methods of fluoride analysis

The recovery of fluoride added to 21 food samples before diffusion ranged from 87% to 106%, with a mean of 98%. The lowest recovery was obtained for samples of tuna in oil and for honey. Results of the duplicate analysis of 35 food samples were within 0.001 μg. The mean recovery of fluoride added to 10 drink samples before measuring with the F ion-selective electrode was 100% with a range from 94% to 108%. Results of the duplicate analysis of 15 drink samples were within <0.001 μg.

Completion rate

The completion rate for all parts of the study is presented in Table 1. All 33 children provided a satisfactory 3-day food diary. However, four subjects (three in the optimally fluoridated area and one in the sub-optimally fluoridated area), were excluded from final analysis: one because of suspicion of an incomplete 24-h urine sample and

Table 1. Completion rates for data collection for 33 children by fluoride content of home tap water supply

	Home tap water supply		
	Optimally fluoridated	Sub-optimally fluoridated	Non-fluoridated
Mean fluoride content of home water in mg/l (SD)	0.82 (0.13)	0.47 (0.09)	0.08 (0.03)
Total number of children recruited	6	9	18
Total number of children rejected from data analysis	3	1	0
Reasons for rejection:			
Incomplete 24-h urine data	3	1	0
Incomplete expectorated saliva data	1[a]	0	0
Total number of children who satisfactorily completed all aspects of the study	3	8	18

[a]One of the three children whose urine data were incomplete.

three because of missing urine and/or expectorated saliva data. Fluoride intake results are therefore given for 32 children, whereas results for fluoride excretion and retention are given for the 29 children for whom all data were complete.

Fluoride intake

For the 32 children for whom all intake data were complete, the mean daily fluoride intake from diet, toothpaste ingestion and both sources, given as mg F and on a body weight basis, is shown in Table 2 according to the fluoride content of home tap water. The fluoride concentration of toothpaste used by the children studied ranged between 400 and 1450 ppm F. The contribution to daily fluoride intake via toothpaste ingestion for all children ranged from 3% to 93% with a mean of 57% for children who received non-fluoridated water, 35% for children who received sub-optimally fluoridated water and 47% for those receiving optimally fluoridated water.

Table 3 shows the mean 24-h urine volumes and daily fluoride excretion by group for the 29 children for whom all data were complete. The mean 24-h urine volumes were fairly similar in the three groups, especially when expressed on a body weight basis: 23, 22 and 22 ml/kg bw/day for children who received optimally, sub-optimally and non-fluoridated tap water, respectively. Average urinary flow rates were also similar, being between 20 and 22 ml/h. Mean daily urinary fluoride excretion was 0.014, 0.011 and 0.008 mg/kg bw/day for children who received optimal, sub-optimal and low fluoride home tap water, respectively.

The mean values for FUFE and fluoride retention for the 29 children by fluoride content of home tap water are presented in Table 4. The mean FUFE figures were 32%, 40% and 44% for children who received optimally, sub-optimally and non-fluoridated tap water, while fluoride retention was 58%, 50% and 46%, respectively.

Table 2. Mean (SD) fluoride intake (mg/day), from diet and toothpaste ingestion, for 32 children according to fluoride content of home tap water supply

	Optimally fluoridated home tap water ($n = 5$)	Sub-optimally fluoridated home tap water ($n = 9$)	Non-fluoridated home tap water ($n = 18$)
Mean fluoride content in mg/l (SD)	0.82 (0.13)	0.47 (0.09)	0.08 (0.03)
Dietary F intake			
mg/day	0.565 (0.304)	0.349 (0.108)	0.188 (0.087)
mg/kg bw/day	0.025 (0.014)	0.016 (0.005)	0.008 (0.004)
F intake from toothpaste			
mg/day	0.478 (0.280)	0.534 (1.058)	0.549 (0.554)
mg/kg bw/day	0.022 (0.013)	0.022 (0.041)	0.023 (0.026)
Total F intake			
mg/day	1.043 (0.220)	0.883 (1.011)	0.736 (0.533)
mg/kg bw/day	0.047 (0.008)	0.038 (0.038)	0.031 (0.025)
% of total fluoride intake from:			
Food	53	65	43
Toothpaste	47	35	57

Table 3. Mean (SD) volume of 24-h urine (ml) and daily fluoride excretion (mg/day) for 29 children according to fluoride content of home tap water supply

	Home tap water supply		
	Optimally fluoridated (n = 3)	Sub-optimally fluoridated (n = 8)	Non-fluoridated (n = 18)
Mean fluoride content (SD) (mg/l)	0.82 (0.13)	0.47 (0.09)	0.08 (0.03)
Volume of 24-h urine			
ml/day	495 (143)	482 (140)	534 (164)
ml/kg bw/day	23 (7)	22 (6)	22 (6)
ml/h	21 (6)	20 (6)	22 (7)
Fluoride excretion			
mg/day	0.323 (0.184)	0.239 (0.108)	0.203 (0.099)
mg/kg bw/day	0.014 (0.006)	0.011 (0.005)	0.008 (0.004)
mg/h	0.013 (0.008)	0.010 (0.004)	0.008 (0.004)

Table 4. Mean (SD) daily fluoride retention (mg/day) of 29 children according to fluoride content of home tap water supply

	Home tap water supply		
	Optimally fluoridated (n = 3)	Sub-optimally fluoridated (n = 8)	Non-fluoridated (n = 18)
Mean fluoride content (SD) (mg/l)	0.82 (0.13)	0.47 (0.09)	0.08 (0.03)
Total F excretion[a] (mg/day)	0.420 (0.209)	0.333 (0.180)	0.277 (0.110)
FUFE[b] (%)	32 (13)	40 (26)	44 (33)
Fluoride retention (%)	58 (13)	50 (26)	46 (33)

[a]Assuming a constant average fluoride fraction of 10% excreted through faeces.
[b]Fractional urinary fluoride excretion: the proportion of fluoride intake which is excreted through urinary excretion [(daily amount of fluoride excreted in urine/total daily fluoride intake) × 100].

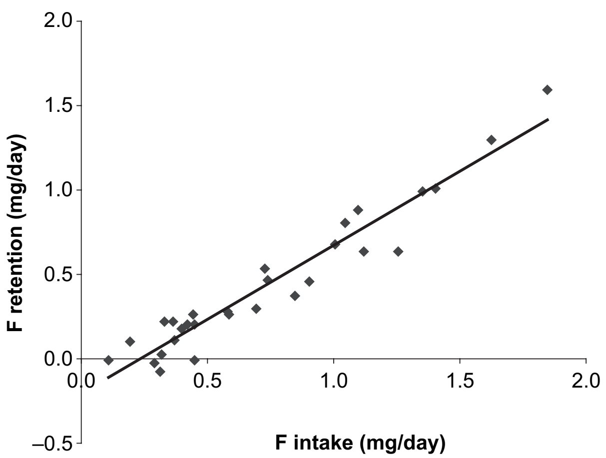

Fig. 1. Relationship between total daily F intake (mg/day) and F retention (mg/day); Pearson's correlation coefficient = +0.96, $P < 0.001$.

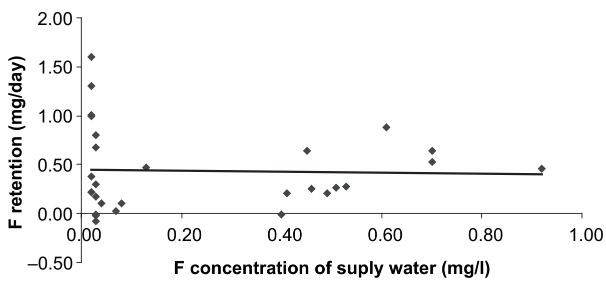

Fig. 2. Relationship between F concentration of home water supply (mg/l) and retention of fluoride (mg/day); Pearson's correlation coefficient = −0.32, P = 0.87.

As Fig. 1 shows there was a significant positive correlation (Pearson's correlation coefficient = +0.96, $P < 0.001$) between total daily fluoride intake (mg/day) and retention of fluoride (mg/day). In contrast, there was no correlation between fluoride concentration of supply water (mg/l) and total daily intake of fluoride (Pearson's correlation coefficient = +0.15, P = 0.42), 24-h urinary excretion of fluoride (Pearson's correlation coefficient = +0.27, P = 0.15), or, as Fig. 2 shows, daily retention of fluoride (Pearson's correlation coefficient = −0.32, P = 0.87).

Discussion

This study, for the first time, provides an accurate estimate of total daily fluoride intake and excretion in 6-year-old children in England under stable fluoride intake conditions, living in communities with optimally fluoridated sub-optimally fluoridated and non-fluoridated water.

All subjects who volunteered completed all aspects of the study; however, four children were excluded from data analysis because of an incomplete 24-h urine sample and missing urine and/or expectorated saliva data. The 3-day dietary diary method used was validated by comparing the energy intake of children with national standards and data and estimating PAL (energy intake/predicted BMR) which has been reported as a suitable and simple check on the validity of group estimates (36). The energy intakes and PALs of the children in the present study were in broad agreement with national standards, which confirms the previous validation of this method for use in children (37). In addition, the 3-day dietary method provided more information than the 'duplicate plate' method as it included sources of dietary fluoride intake.

As no fluoride supplements were taken by the children, diet and dentifrice ingestion were the main sources of total daily fluoride intake for all three groups of children. Daily fluoride intake estimated from dietary sources in the fluoridated area (mean 0.565 mg/day) was substantially higher than that in the non-fluoridated area (mean 0.188 mg/day). However, the differences in total daily fluoride intakes between areas were less, ranging from a mean of 0.736 mg/day (non-fluoridated) to 1.043 mg/day (optimally fluoridated).

The mean total fluoride intakes of children in non-fluoridated and sub-optimally fluoridated areas in the present study were lower than the so-called 'optimum' range of 0.05–0.07 mg F/kg bw/day for optimal dental health benefit (38), while the corresponding data for children receiving optimally fluoridated water were just below the lower end of the optimum range of fluoride intake; a level of fluoride intake which is therefore unlikely to put these children at risk of developing dental fluorosis.

There are several reports on children's fluoride intake from diet and toothpaste ingestion in the literature. However, differences in age groups studied, fluoride content of foods, drinks and tap water supplies, as well as quantities of food and drink items consumed, dietary habits, and methods of collection of dietary information make comparison between studies difficult.

The mean total intake of fluoride of the 6-year-old children receiving non-fluoridated home water in the present study (0.031 mg/kg bw/day) was higher than the reported mean intakes of 0.027 mg/kg bw/day for 3- to 4-year-old New Zealand children (39) and the 0.018 mg/kg bw/day for 5- to 6-year-old Japanese children (40), although it was lower than the 0.056 and 0.073 mg F/kg bw/day for two groups of 16- to 40-month-old children from Puerto Rico and Indiana (41), respectively, all living in non-fluoridated areas.

With regard to the children receiving sub-optimally fluoridated home tap water, their mean total fluoride intake (0.038 mg/kg bw/day) was higher than the 0.030 mg/kg bw/day reported for 4-year-old Iranian children receiving supply water containing 0.32 mg F/l (14), but lower than the 0.064 mg F/kg bw/day for Chilean children aged 3–5 years residing in an area with drinking water containing 0.5–0.6 mg F/l (15).

The mean total daily fluoride intake of children receiving optimally fluoridated water (0.047 mg/kg bw/day) was higher than the mean intake of 0.036 mg/kg bw/day for 3- to 4-year-old New Zealand children living in a fluoridated area (39), and lower than in other studies in children exposed to fluoride through either fluoridated water, fluoridated salt or fluoride tablets: 0.053 mg/kg bw/day for 3- to 6-year-old German children (16); 0.07 mg/kg bw/day for 16- to 40-month-old children from Indianapolis (41); 0.20 and 0.18 mg/kg bw/day for 15- to 36-month olds from Mexico City and Veracruz, Mexico respectively (42); and 0.098 mg/kg bw/day for 48- to 59-month-old Columbian children (43), although in this latter study only 27% of the total fluoride intake was from food prepared with fluoridated salt, with ingested toothpaste being the major contribution to fluoride intake.

Toothpaste also made the largest percentage contribution to total daily fluoride intake in children living in the low fluoride area in the present study, where it represented 57% of the total daily fluoride intake, which is consistent with other studies in children which have shown fluoridated toothpaste to be a major component of total fluoride intake in non-fluoridated areas. The contribution by toothpaste of almost 69% of total fluoride intake has been reported for New Zealand children aged 3–4 years (39), while contributions of 71% and 60% have been reported for children aged 16–40 months living in two negligibly fluoridated areas of Puerto Rico and Indiana, respectively (41). Contributions from toothpaste of 69% and 64% of total fluoride intake have also been reported for Colombian children aged 48–59 months (43), and

15- to 36-month-old Mexican children (42), respectively, living in negligibly fluoridated areas but consuming fluoridated salt, while large contributions (58% and 69%) from fluoride toothpaste have also been reported for two groups of Brazilian children aged 19–38 months living in areas with water fluoridated at a level of 0.7 mg F/l (44). In contrast, other studies have reported lower contributions from fluoride toothpaste in children from fluoridated (water or salt) communities: 29% for German 3- to 6-year olds (16), 22% for 6-year olds from Iowa (9), 47% for 3- to 4-year olds from New Zealand (39) and 44% for US (Indianapolis) children aged 16–40 months (41). These differences in contribution of toothpaste to total fluoride intake in different studies were probably due to age differences as younger children are more likely to swallow toothpaste, as well as differences in the fluoride concentration of the toothpaste used and the diet consumed.

The mean 24-h urine volumes for the three groups of children in the present study were fairly similar and in the range of 406–632 ml reported for children aged 3–6 years in the literature (14–16, 45, 46). In this study, the mean urinary fluoride excretion in children from the non-fluoridated area of 0.20 mg/day was similar to the mean of 0.21 mg/day reported for English children aged 1.8–5.2 years living in a non-fluoridated area (46), and 0.23 mg reported for 1.5- to 3.5-year olds from five European sites with a water fluoride concentration of <0.15 mg F/l (47).

For those children receiving sub-optimally fluoridated water (≥0.3 to <0.7 mgF/l), the mean urinary fluoride excretion of 0.24 mg/day was lower than the value of 0.36 mg/day reported for 3- to 5-year-old Chilean children receiving water with 0.5–0.6 mg F/l (15), and the 0.34 mg/day reported for 4-year-old Iranian children receiving 0.30–0.39 mg F/l in water (14).

The mean urinary fluoride excretion of 0.32 mg/day for the children receiving optimally fluoridated home tap water was similar to the 0.36 mg/day reported for Irish 1.8- to 5.2-year olds living in a fluoridated area (46) but lower than the 0.48 mg/day reported for German 3- to 6-year olds living in a non-fluoridated community but consuming fluoridated salt (16), and higher than the 0.23 mg/day reported for Swiss children aged 3 and 4 years consuming fluoridated salt (48).

Renal clearance of fluoride is directly related to urinary pH and urine flow rate (49) and differences in the composition of diet and the altitude of residence can influence urinary pH, and consequently fluoride excretion significantly. The fraction of the total daily fluoride intake excreted through urine has been estimated in a few studies (15, 46) and shown to have a wide range, from 35% in sub-optimally to 52% in optimally fluoridated areas for 3- to 6-year olds (15, 16, 50). The mean FUFE for the children receiving optimally and sub-optimally fluoridated water in the present study was within this range, but for non-fluoridated areas there are no data in the literature for comparison.

The mean fractional fluoride retention in this study was estimated to range from 46% to 58% for children receiving non-fluoridated and optimally fluoridated water, respectively; values much lower than a previous estimate of 70% published by the World Health Organization (51). However, the results of the present study are in good agreement with reported estimated fractional fluoride retentions of 54% for 3- to 5-year olds (15), 43% for toddlers aged 12–36 months (52), and 47% for infants (53). Even lower fluoride retentions of 12.5% (53), 20% (14), and 15% (13) have been reported in formula-fed infants and 4-year-old Iranian and North American children respectively. The rate of uptake of fluoride into bones and teeth is influenced by the stage of bone maturation and is quicker in newly formed bone compared with mature bone (54). Therefore, during periods of rapid growth and development, fluoride retention by the body is greater. The differences in the levels of fluoride retention between young children may be also attributed to the differences in their diet. Insoluble complex formation of calcium and magnesium with fluoride in the diet can significantly reduce fluoride absorption and its uptake into bone and teeth (54). In addition, dietary protein and fat increase fluoride absorption (54); therefore, a diet high in protein and/or fat may result in an increase in the proportion of fluoride intake retained in the body.

In this study, fluoride retention did not correlate with the fluoride concentration of the home water supply, whilst it was strongly positively correlated with total daily fluoride intake, suggesting that for children living in an industrialized country, total fluoride intake and excretion and, consequently fluoride retention, no longer reflect residence in a non-fluoridated or fluoridated community.

The work by Ekstrand et al. (18), carried out in infants aged 8–28 weeks living in a fluoridated area (1.0 mg F/l) found that almost 10% of fluoride ingested each day (11) was excreted through faeces.

As collecting 24-h faeces from young children is problematic, most fluoride retention studies (15, 55) have assumed that faecal fluoride accounts for 10% of fluoride intake and the same contribution was assumed in the present study to allow comparison. However, it has been suggested that fluoride elimination in faeces could be as high as 25% of daily intake (51). Therefore, further investigations on total fluoride excretion through both urine and faeces in different age groups and different areas are needed in order to measure faecal fluoride excretion and consequently fluoride retention in children.

Acknowledgements

The authors gratefully acknowledge the children and their parents for their participation and cooperation. This work was funded by the Borrow Foundation. The views expressed are those of the authors and not necessarily of the Borrow Foundation.

References

1. Pendrys DG, Stamm JW. Relationship of total fluoride intake to beneficial effects and enamel fluorosis. J Dent Res 1990;69(Spec No):529–38; discussion 56–7.
2. Szpunar S, Burt B. Fluoride exposure in Michigan schoolchildren. J Public Health Dent 1990;50:18–23.
3. Heilman JR, Kiritsy MC, Levy SM, Wefel JS. Assessing fluoride levels of carbonated soft drinks. J Am Dent Assoc 1999;130:1593–9.
4. Rao GS. Dietary intake and bioavailability of fluoride. Annu Rev Nutr 1984;4:115–36.
5. Evans RW, Stamm JW. Dental fluorosis following downward adjustment of fluoride in drinking water. J Public Health Dent 1991;51:91–8.
6. Evans RW, Stamm JW. An epidemiologic estimate of the critical period during which human maxillary incisors are most susceptible to fluorosis. J Public Health Dent 1991;51:251–9.
7. Bårdsen A, Klock KS, Bjorvatn K. Dental fluorosis among persons exposed to high- and low-fluoride drinking water in western Norway. Community Dent Oral Epidemiol 1999;27:259–67.
8. Burt BA, Keels MA, Heller KE. The effects of a break in water fluoridation on the development of dental caries and fluorosis. J Dent Res 2000;79:761–9.
9. Levy SM, Warren JJ, Broffitt B. Patterns of fluoride intake from 36 to 72 months of age. J Public Health Dent 2003;63:211–20.
10. Robinson C, Connell S, Kirkham J, Brookes S, Shore R. The effect of fluoride on the developing tooth. Caries Res 2004;38:268–76.
11. Ekstrand J. Fluoride Metabolism. In: Fejerskov O, Ekstrand J, Burt BA, editors. Fluoride in dentistry. 2nd edn. Copenhagen: Munksgaard; 1996:55–68.
12. Whitford GM. Metabolism and toxicity of fluoride. Basel: Karger; 1996.
13. Brunetti A, Newbrun E. Fluoride balance of children 3 and 4 years old. Caries Res 1983;17:171 (abstract 41).
14. Zohouri FV, Rugg-Gunn AJ. Total fluoride intake and urinary excretion in 4-year-old Iranian children residing in low-fluoride areas. Br J Nutr 2000;83: 15–25.
15. Villa A, Anabalon M, Cabezas L. The fractional urinary fluoride excretion in young children under stable fluoride intake conditions. Community Dent Oral Epidemiol 2000;28:344–55.
16. Haftenberger M, Viergutz G, Neumeister V, Hetzer G. Total fluoride intake and urinary excretion in German children aged 3–6 years. Caries Res 2001;35:451–7.
17. Grijalva-Haro MI, Barba-Leyva ME, Laborin-Alvarez A. Fluoride intake and excretion among children in Hermosillo, Sonora, Mexico. Salud Publica de Mexico 2001;43:127–34.
18. Ekstrand J, Hardell LI, Spak CJ. Fluoride balance studies on infants in a 1-ppm-water-fluoride area. Caries Res 1984;18:87–92.
19. Nelson M, Atkinson M, Meyer J. A photographic atlas of food portion sizes. London: Ministry of Agriculture Fisheries and Food; 1997.
20. Holland B, Unwin ID, Buss DH. Cereals and cereal products: the third supplement to McCance and Widdowson's The Composition of Foods. 4th edn. Cambridge: Royal Society of Chemistry, Ministry of Agriculture, Fisheries and Food; 1988.
21. Holland B, Welch AA, Buss DH. Vegetable dishes: the second supplement to the fifth edition of McCance and Widdowson's The Composition of Foods. Cambridge: Royal Society of Chemistry, Ministry of Agriculture, Fisheries and Food; 1992.
22. Holland B, Unwin ID, Buss DH. Fruit and nuts: the first supplement to the fifth edition of McCance and Widdowson's The Composition of Foods. Cambridge: Royal Society of Chemistry; Ministry of Agriculture, Fisheries and Food; 1992.
23. Holland B, Welch AA, Buss DH. Vegetable dishes: the second supplement to the McCance and Widdowson's The Composition of Foods. 5th edn. Cambridge: Royal Society of Chemistry, Ministry of Agriculture, Fisheries and Food; 1992.
24. Holland B, Brown J, Buss DH. Fish and fish products: the third supplement to the fifth edition of McCance and Widdowson's The Composition of Foods. Cambridge: Royal Society of Chemistry and Ministry of Agriculture, Fisheries and Food; 1993.
25. Food Standards Agency. McCance and Widdowson's The Composition of Foods. 6th Summary edn. Cambridge: Royal Society of Chemistry; 2002.
26. Martinez-Mier E, Cury J, Heilman J, Levy S, Li Y, Maguire A et al. Development of standard fluoride analytical methods: direct analysis. Caries Res 2004;38:372.
27. Taves D. Separation of fluoride by rapid diffusion using hexamethyldisiloxane. Talanata 1968;15: 969–74.
28. Soto-Rojas A, Cury J, Heilman J, Levy S, Li Y, Maguire A et al. Development of standard fluoride

analytical methods: precision/trueness testing for diffusion techniques. Caries Res 2005;39:313.
29. Ekstrand J, Fomon SJ, Ziegler EE, Nelson SE. Fluoride pharmacokinetics in infancy. Pediatric Res 1994;35:157–63.
30. Bones R, Taussky H. On the colorimetetric determination of creatinine by the Jaffe reaction. J Biol Chem 1951;158:581–91.
31. Department of Health. Dietary Reference Values for Food Energy and Nutrients for the United Kingdom. Report on Health and Social Subjects No. 41; London: HMSO; 1991.
32. Gregory J, Lowe S, Bates C, Prentice A, Jackson L, Smithers G et al. National Diet and Nutrition Survey: young people aged 4 to 18 years. London: The Stationery Office; 2000.
33. Brooks GA, Butte NF, Rand WM, Flatt JP, Caballero B. Chronicle of the Institute of Medicine physical activity recommendation: how a physical activity recommendation came to be among dietary recommendations. Am J Clin Nutr 2004;79:921S–930S.
34. Remer T, Neubert A, Maser-Gluth C. Anthropometry-based reference values for 24-h urinary creatinine excretion during growth and their use in endocrine and nutritional research. Am J Clin Nutr 2 2002; 75:561–9.
35. Marthaler TM, editor Monitoring of renal fluoride excretion in community preventive programmes on oral health. Geneva: World Health Organization; 1999.
36. Bingham S. The use of 24-h urine samples and energy expenditure to validate dietary assessments. Am J Clin Nutr 1994;59(Suppl. 1):227S–31S.
37. Hackett AF, Rugg-Gunn AJ, Appleton DR. Use of a dietary diary and interview to estimate the food intake of children. Human Nutr Appl Nutr 1983;37:293–300.
38. Burt BA. The changing patterns of systemic fluoride intake. J Dent Res 1992;71:1228–37.
39. Guha-Chowdhury N, Drummond BK, Smillie AC. Total fluoride intake in children aged 3 to 4 years – a longitudinal study. J Dent Res 1996;75:1451–7.
40. Kimura T, Morita M, Kinoshita T, Tsuneishi M, Akagi T, Yamashita F et al. Fluoride intake from food and drink in Japanese children aged 1–6 years. Caries Res 2001;35:47–9.
41. Rojas-Sanchez F, Kelly SA, Drake KM, Eckert GJ, Stookey GK, Dunipace AJ. Fluoride intake from foods, beverages and dentifrice by young children in communities with negligibly and optimally fluoridated water: a pilot study. Community Dent Oral Epidemiol 1999;27:288–97.
42. Martinez-Mier EA, Soto-Rojas AE, Urena-Cirett JL, Stookey GK, Dunipace AJ. Fluoride intake from foods, beverages and dentifrice by children in Mexico. Community Dent Oral Epidemiol 2003;31: 221–30.
43. Franco AM, Martignon S, Saldarriaga A, Gonzalez MC, Arbelaez MI, Ocampo A et al. Total fluoride intake in children aged 22–35 months in four Colombian cities. Community Dent Oral Epidemiol 2005;33:1–8.
44. Paiva SM, Lima YB, Cury JA. Fluoride intake by Brazilian children from two communities with fluoridated water. Community Dent Oral Epidemiol 2003;31:184–91.
45. Rugg-Gunn AJ, Nunn JH, Ekanayake L, Saparamadu KD, Wright WG. Urinary fluoride excretion in 4-year-old children in Sri Lanka and England. Caries Res 1993;27:478–83.
46. Ketley CE, Lennon MA. Urinary fluoride excretion in children drinking fluoridated school milk. Int J Paediatr Dent 2000;10:260–70.
47. Ketley CE, Cochran JA, Holbrook WP, Sanches L, van Loveren C, Oila AM et al. Urinary fluoride excretion by preschool children in six European countries. Community Dent Oral Epidemiol 2004;32(Suppl. 1):62–8.
48. Marthaler TM, Binder-Fuchs M, Baez R, Menghinin G. Urinary fluoride excretion in Swiss children aged 3 and 4 consuming fluoridated domestic salt. Acta Med Dent Helv 2000;5:89–97.
49. Ekstrand J, Fejerskov O, Silverstone LM, editors. Fluoride in dentistry. 1st edn. Copenhagen: Munksgaard; 1988.
50. Ketley CE, Lennon MA. Determination of fluoride intake from urinary fluoride excretion data in children drinking fluoridated school milk. Caries Res 2001;35:252–7.
51. World Health Organisation. Fluorides and oral health. Report of a WHO Expert Committee on Oral Health Status and Fluoride Use. World Health Organization Technical Report Series 1994;846:1–37.
52. Zohouri FV, Swinbank CM, Maguire A, Moynihan PJ. Is the fluoride/creatinine ratio of a spot urine sample indicative of 24-h urinary fluoride? Community Dent Oral Epidemiol 2006;34:130–8.
53. Ekstrand J, Ziegler EE, Nelson SE, Fomon SJ. Absorption and retention of dietary and supplemental fluoride by infants. Adv Dent Res 1994;8: 175–80.
54. Cerklewski FL. Fluoride bioavailability – nutritional and clinical aspects. Nutr Res 1997;17:907–29.
55. Zohouri FV, Rugg-Gunn AJ. Sources of dietary fluoride intake in 4-year-old children residing in low, medium and high fluoride areas in Iran. Int J Food Sci Nutr 2000;51:317–26.