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Relative effects of pre- and post-eruption water fluoride on caries experience by surface type of permanent first molars

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Abstract – Objectives: To determine the relative pre- and post-eruption exposure effects of fluoridated water on the caries experience of different surface types of first permanent molars. *Methods:* Parental questionnaires covering residential history of participants were linked to the oral examinations of 6–15-year-old Australian children conducted in 1992 by the School Dental Services of South Australia and Queensland. Percentage of lifetime exposed to optimally fluoridated water pre- (PRE) and post-eruption (POST) was calculated with respect to tooth eruption age. Combined pre- and post-eruption categories were created to test PRE against POST exposure: PRE and POST = 0, PRE < POST, PRE = POST and in the range 0–90% of lifetime exposure, PRE > POST and, PRE and POST $\geq$ 90% lifetime exposure. These categories were used as indicator variables in linear regression models with PRE and POST = 0 as reference in an analysis of first permanent molar DMFS scores overall and by surface type. *Results:* Participation rates were 69.7% in South Australia (n = 9690) and 55.6% in Queensland (n = 10 195). Compared with the reference, the categories PRE > POST ($\beta = -0.033$), PRE = POST ($\beta = -0.028$) in the range 0–90% and, PRE and POST $\geq$ 90% ($\beta = -0.055$) showed significantly lower caries overall ($P < 0.01$), with a similar pattern for pit and fissure surface caries ($\beta = -0.035$, -0.031 and -0.052, respectively). Only a high PRE and POST exposure decreased caries levels significantly in the approximal ($\beta = -0.038$; $P < 0.01$) and free smooth surfaces ($\beta = -0.023$; $P = 0.03$). *Conclusions:* Pre-eruption exposure was important for a caries preventive effect on first permanent molars in children 6–15 years old since post-eruption exposure alone could not lower caries levels significantly. For pit and fissure surfaces, a high pre-eruption exposure could decrease caries levels significantly. However, for other surface types, only a high pre- and post-eruption exposure produced a caries preventive effect.

Key words: caries; children; post-eruption; pre-eruption; surfaces types; water fluoridation

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Introduction

Following the discovery of the link between fluoride and caries, an attempt was made to define the optimal fluoride level at which caries was inhibited. A series of investigations known collectively as the '21 Cities Study' confirmed the association between fluoride and caries and helped establish a safe and optimal level of water fluoride for the purpose of caries prevention (1). Community fluoridation was initiated with the adjustment of water fluoride to the recommended concentration in Grand Rapids, Michigan in 1945 (2). Fluoride was then primarily seen as a pre-eruptive source of dental caries prevention. The pre-eruptive benefits were also shown in subsequent laboratory studies (3–5).

An opportunity to study variation of exposure by age was provided by relocation of participants by fluoridation status in Klein's study on the caries data of children aged between 8 and 14 years who were relocated from a fluoride-deficient to a naturally fluoridated area. The younger age groups with more recently erupted first molars benefited more from the fluoride exposure. For example, caries incidence was inhibited by 60% in the 8–10-year olds with respect to the incidence observed in the control group. Thus, the importance of an early post-eruptive exposure effect was seen (6) in the participants all of whose first molars were erupted before the relocation. That fluoride could have a dual action (i.e. having both pre- and post-eruptive effects) in deterring caries was recognized.

An alternative approach to relocating participants was to study effects of commencement or cessation of fluoridation. Of the numerous studies in the 1950s, 1960s and 1970s that separated the caries preventive effects of pre-eruptive exposure to fluoridated water from that of post-eruptive exposure by examining caries differences before and after the commencement and discontinuation of water fluoridation (7–16) the most important was that in Tiel–Culemborg. This study had a long observation period extending over three decades in which multiple cohorts of children were examined, providing data on different tooth groups and surfaces from children born in different years allowing analyses to determine the effects of the introduction of fluoride followed by its discontinuation two decades later. Conducted as a Dutch version of the American investigations into benefits of water fluoridation, the Tiel–Culemborg study showed that younger age classes on exposure to fluoridated water had a greater reduction in caries, suggesting that pre-eruptive exposure was important. This was particularly so for the pit and fissure, and mesial surfaces of the first permanent molars (9). The stage of exposure, whether pre- or post-eruptive, did not matter so much for the free smooth surfaces which showed a significant caries reduction of similar magnitude for both the 12-year olds who were born before fluoridation commenced in March, 1953 and the 9-year olds who were born 2 years after fluoridation was introduced in Tiel.

By the early 1970s, there were multiple sources of fluoride, particularly fluoridated toothpaste, available in addition to water fluoridation. With the widespread availability of fluoride, there has been a remarkable decline in caries levels since the 1980s (1, 17) especially pertaining to school-age children of developed countries, whereas most of the fluoridation studies looking into the before-and-after effects of water fluoridation or its cessation were conducted prior to the 1980s in periods of high caries levels.

The relative effects of pre- and post-eruption exposure on caries of first permanent molars have been described for Australian children in a period of low caries levels (18). This study identified geographic variation in fluoridation and residential movement between fluoridated and nonfluoridated areas so as to establish different patterns of pre- and post-eruptive exposure. The study found that pre-eruptive exposure was more strongly associated with caries prevention than post-eruptive exposure. However, the findings were not reported by surface type. There are important differences in the effects of fluoride by surface type: not only do the systemic and dietary factors leading to the development and progression of caries differ but the effect of fluoride in the prevention and progression of caries is not of equal extent in the different surface types (10, 19). A surface-specific analysis offers the opportunity to refine our understanding of the caries preventive effects of pre- and post-eruptive exposure to fluoride. The aim of this paper is to report the findings of the relative pre- and post-eruption exposure effects of fluoridated water in the prevention of caries by surface type of first permanent molars of Australian children aged 6–15 years, based on individual exposure histories and controlling for the effect of potential confounders.

Material and methods

Baseline data from the Child Fluoride Study (CFS), a multi-site, 3-year, prospective, longitudinal study of caries in children were collected between June 1991 and May 1992 through clinical examinations and parental questionnaires (20).

Sampling

Children attending school dental services for a routine examination in South Australia and Queensland were sampled for the study (20). There were two strata in each State: in South Australia (i) metropolitan Adelaide (fluoridated) and (ii) rest of South Australia (predominantly nonfluoridated), and in Queensland they were (i) metropolitan Brisbane (nonfluoridated) and (ii) the rural city of Townsville (fluoridated). Random sampling based on date of birth in any month was used with different sampling ratios to provide similar numbers of subjects from each stratum (21). All subjects attended school dental services, which conducted periodic dental examinations in addition to providing preventive, restorative and other nonspecialist dental services (e.g. professional fluoride applications, pit and fissure sealants).

Oral examinations

School dental staff (i.e. dental therapists and dentists) examined the sampled children according to the World Health Organization criteria for decayed, missing and filled teeth (22), adapted for primary (dmfs index) and permanent (DMFS index) tooth surfaces following the criteria of the US National Institute for Dental Research (23). Additional coding for surfaces that were sound and unrestored, or fissure sealed were used. All examiners were supplied with written descriptions of the criteria and procedures and the supervising staff met with the researchers for discussing the criteria. There were no additional procedures for standardization of examiners or assessment of examiner reliability through replicate examinations because of the large numbers of clinical staff involved (21).

Parental questionnaires

The parental questionnaire collected the child's date of birth and residential history since birth. Starting from the current place of residence, all areas where the subjects had lived in for longer than 6 months were recorded along with their respective usual sources of drinking water. Socioeconomic status (SES) measures and use of discretionary sources of fluoride were included in the questionnaire. The parents of sampled children who had not responded were sent up to two reminder notices (24).

Dependent variables

DMFS for the first permanent molars (DMFS6) was the dependent variable in the analysis for overall caries of the first molar (18). In the analyses, differentiating caries by surface type, the dependent variables were: $DMFS6_{\text{PIT \& FISSURES}}$ representing caries in the pit and fissure surfaces defined as occlusal surfaces of maxillary and mandibular molars, lingual surfaces of maxillary molars and buccal surfaces of mandibular molars; $DMFS6_{\text{APPROXIMAL}}$ representing caries in the approximal surfaces defined as mesial and distal surfaces of maxillary and mandibular molars; and $DMFS6_{\text{FREE SMOOTH}}$ representing caries in the free smooth surfaces defined as buccal surfaces of maxillary molars and lingual surfaces of mandibular molars.

Threshold age

A cut-off or threshold age was required before and after which PRE and POST exposure could be calculated for each subject. The average age of eruption of the first permanent molars was based on a South Australian study (25). The threshold ages were 80 months (6.67 years) for males and 78 months (6.50 years) for females. The period of life before and after the threshold ages represent pre- and post-eruption periods, respectively. Post-eruption exposure was taken as '0' for subjects whose age was less than or equal to the threshold age. Subjects whose total residence history did not add up to their current age, i.e. those who had missing residential history, were excluded from the analysis, as it was not always known whether the missing period was before or after eruption exposure.

Water fluoride exposure

The source of water intake at home recorded in the questionnaire could be one or more of: public supply, tank water and/or some other source. Tank water refers to rain water stored in tanks of houses and contains negligible fluoride. Public supply (i.e. tap water) was the only potential source of fluoride from water as nonpublic sources such as tanks, bores and bottled water were assumed to have <0.3 ppm fluoride. The fluoride level of the public water supply was collected from the water authority of each region. Although exposure to water fluoride was based on the fluoride concentration of townships and cities, data on individual residential histories and sources of water consumption were collected. There was no specific question on the quantity of water consumed, as it was assumed that there would be no systematic bias in the volume of water consumed by fluoridation status.

A postcode-fluoride database was used to map fluoride exposure to residential history. There was variation in the precision with which fluoride concentrations were specified because of the nature of the sources of information available to compile the database. Therefore, the fluoride concentrations in the public water supply were categorized as 0 ppm (where the listed concentration was <0.3 ppm), 0.5 ppm (listed concentrations in the range 0.3–0.7 ppm) or 1 ppm (listed concentrations above 0.7 ppm) which was the optimal exposure (21). The percentage of fluoride exposure was calculated based on the fluoride concentration of the public water supply and the source(s) of water intake (18).

Using the threshold age along with the duration of residence at different places, fluoride exposure and the age of the child, the percentage of lifetime pre- and post-eruptive exposure to optimally fluoridated water were calculated by the following formulae:

pre-eruptive:

$$\frac{\sum \text{time of residency (until subject was of threshold age)} \times \text{percentage of fluoride exposure (fluoride concentration of public water supply of that area and water source(s) used)}}{\text{threshold age}} \quad (1)$$

post-eruptive:

$$\frac{\sum \text{time of residency (threshold to current age)} \times \text{percentage of fluoride exposure (fluoride concentration of public water supply of that area and water source(s) used)}}{\text{age - threshold age}} \quad (2)$$

The products of time periods in different residential locations by their percentage of fluoride exposure were summed and divided by the total pre- or post-eruptive periods. The resulting estimate represented the fraction of pre- or post-eruptive period with optimal water fluoride exposure. This estimate was expressed as a percentage.

A cross-tabulation of pre-eruptive (PRE) versus post-eruptive (POST) exposure to fluoridated water showed that most participants had similar PRE and POST exposure, i.e. PRE exposure was strongly associated with POST exposure (18). Because of high collinearity ($r = 0.74$; $P < 0.01$) and the need to separate PRE and POST effects for comparison, a combined PRE and POST variable was created. The combined exposure variable was coded into five categories to create a set of ordered categories with varying degrees of exposure that would allow comparison of PRE and POST exposure while maintaining sufficient numbers in each category for analysis (Table 1). These five categories were basic to the requirement to test PRE against POST exposure. The five categories were defined in increasing order of PRE exposure: (1) both PRE and POST exposure of 0% lifetime; (2) PRE < POST exposure; (3) PRE = POST exposure; (4) PRE > POST exposure; (5) maximum exposure for PRE and POST. The second and fourth categories were created to test PRE against POST exposure. For a subject to belong to the second category the PRE exposure could be in the range 0 to <90% whereas POST exposure was in the range >0–100% with the condition that PRE < POST exposure. The subjects belonging to the third category were coded to have PRE and POST exposure in the range >0 to <90% with the condition that PRE = POST. The fourth category had reverse conditions from the second category for PRE and POST exposure. The fifth category had the combination of maximum PRE and POST exposure in the range ≥90–100%.

Confounding variables

Apart from the main exposure variable of interest, there were potential confounders such as age, SES and discretionary fluoride sources (18). The discretionary sources of fluoride were fluoride toothpastes, tablets/drops, and infant formula. Data on current brushing frequency and mouthrinsing were collected in the questionnaire and were coded as categorical variables in the analysis representing the frequency (fluoride tablets/drops, toothpastes

Table 1. Exposure categories of combined pre- and post-eruption exposure variable and their mean percentage of lifetime exposed to fluoridated water

Coding criteria with coding range	*n*	Coded exposure category (mean exposure)	Range after coding PRE	Range after coding POST
I PRE = 0.0; POST = 0.0	5679	PRE (0.0) = POST (0.0)	0.0–0.0	0.0–0.0
II 0.0 ≤ PRE < 90.0; 0.0 < POST ≤ 100.0	2452	PRE (40.1) < POST (77.4)	0.0–90.0	1.0–100.0
III 0.0 < PRE < 90.0; 0.0 < POST < 90.0	1797	PRE (60.0) = POST (60.0)	35.0–85.0	35.0–85.0
IV 0.0 < PRE ≤ 100.0; 0.0 ≤ POST < 90.0	4189	PRE (66.6) > POST (22.6)	1.0–100.0	0.0–90.0
V 90.0 ≤ PRE ≤ 100.0; 90.0 ≤ POST ≤ 100.0	3656	PRE (99.8) and POST (99.9) ≥ 90.0	90.0–100.0	90.0–100.0

and mouthrinses) and duration (fluoride tablets/ drops and mouthrinses) of their usage. For the purpose of the analysis, frequency of brushing was expressed as average number of times brushed per day and grouped into three categories: less than once a day; once to less than twice, twice or more. Professional fluoride treatment was also included as an explanatory variable as it could potentially alter the relationship between exposure to fluoridated water and caries experience. Age at which the child participant started toothbrushing was expressed categorically as: 0 to <2 years, 2–4 years and >4 years of age. Fluoridated toothpastes were assumed to be a source of post-eruption exposure to fluoride, although inadvertent swallowing by young children could contribute to a pre-eruptive effect. Another potential confounder in the association was use of fissure sealants that was described by the number of surfaces fissure sealed with categories: 0, 1–2 and 3–8 surfaces.

Indicator variables were created from the PRE and POST combined lifetime water fluoride exposure variable and potential confounders of age, parental income, age at which the child started brushing, frequency of brushing with fluoride toothpaste, professional fluoride treatment received, fluoride supplement use, use of infant formula, use of fluoride mouthrinses and number of surfaces fissure sealed. A reference group for each variable was selected against which significance of the indicator variables was determined using ordinary least squares regression. In this way, beta coefficients of indicator variables were also obtained, indicating the direction and strength of association with respect to the reference group.

Results

Subject participation

The children sampled whose parents gave their consent by signing and returning the consent form were regarded as participants. Of the 13 911 children sampled for the study in South Australia, 69.7% or 9690 participated. In Queensland, the participation rate of the 18 348 children sampled was lower at 55.6% so that the numbers participating were 10 195 (21). There were varying participation rates by age group and strata. In general, participation rates were higher among younger age groups so that the majority of children participating in the study were aged <12 years. Although 9690 + 10 195 = 19 885 children participated in total, there were 17 773 children of the age group 6–15 years whose returned questionnaires provided complete pre- and post-eruption residential history.

Caries distribution

There were a total of 17 031 participants who had one or more first permanent molars. The mean DMFS6 was 0.60 (SD 1.37) with a range of 0–20. Over 12 000 subjects had a DMFS6 score of 0. The distribution was highly positively skewed with a skewness of 3.46. The mean $\mathrm{DMFS6}_{\mathrm{PIT\ \&\ FISSURES}}$ was 0.53 (SD 1.16) with a range of 0–8. The distribution was positively skewed with a skewness of 2.70. The mean $\mathrm{DMFS6}_{\mathrm{APPROXIMAL}}$ was 0.05 (SD 0.31) with a range of 0–8. There was a high positive skewness of 9.03. The mean $\mathrm{DMFS6}_{\mathrm{FREE\ SMOOTH}}$ was 0.02 (SD 0.17) with a range of 0–4. There was a high positive skewness at 10.99.

Combined PRE and POST exposure variable

The five categories of the combined variable are described in Table 1, which provides the number of subjects in the categories and the ranges of PRE and POST exposure for each category. The category with no exposure to fluoridated water PRE or POST had the highest number of subjects with 5679. This was followed by the category with PRE > POST exposure with 4189 subjects. The category with the lowest count of 1797 subjects had each subject with equal PRE and POST exposure in the range >0 to <90% lifetime.

Bivariate linear regression

Group means for dependent variables: DMFS6, $\mathrm{DMFS6}_{\mathrm{PIT\ \&\ FISSURES}}$, $\mathrm{DMFS6}_{\mathrm{APPROXIMAL}}$ and $\mathrm{DMFS6}_{\mathrm{FREE\ SMOOTH}}$ by the indicator variables were calculated and bivariate linear regression analyses compared the mean values with a reference group for each independent variable. Table 2 lists the group mean values and standard errors and indicates the significant differences.

Amongst the exposure variables, the categories with PRE and POST $\geq$ 90% and PRE > POST had significantly lower DMFS6 scores compared with the reference category of no exposure. Caries experience increased with age, age at which a child started brushing, lower brushing frequency, higher numbers of professional fluoride treatments, mouthrinsing and use of infant formula, and decreased with increasing parental income. Use of fissure sealants on one to two surfaces was associated with significantly increased DMFS6

Table 2. Bivariate linear regressions for association of DMFS (means and standard errors) with explanatory variables

	DMFS6		Pit and fissure		Approximal		Free smooth	
Independent variables	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Combined exposure groups (% lifetime)								
PRE and POST = 0 (Ref.)	0.67	0.02	0.59	0.02	0.058	0.004	0.023	0.003
PRE < POST	0.68	0.03	0.61	0.03	0.056	0.006	0.021	0.003
PRE = POST	0.63	0.03	0.55	0.03	0.067	0.008	0.016	0.003
PRE > POST	0.51**	0.02	0.45**	0.02	0.046	0.006	0.015*	0.003
PRE and POST $\geq$ 90	0.48**	0.02	0.45**	0.02	0.025**	0.003	0.012**	0.002
Age (years)								
6–7 (Ref.)	0.15	0.01	0.14	0.01	0.007	0.001	0.005	0.001
8–9	0.39**	0.01	0.35**	0.01	0.023*	0.003	0.012*	0.002
10–11	0.79**	0.02	0.70**	0.02	0.065**	0.005	0.024**	0.003
12–13	1.15**	0.04	1.00**	0.03	0.116**	0.010	0.039**	0.005
14–15	1.62**	0.08	1.40**	0.06	0.170**	0.024	0.043**	0.010
Parental income (in $)								
Up to 20 000 (Ref.)	0.74	0.03	0.64	0.02	0.068	0.006	0.026	0.003
20 001–30 000	0.62**	0.02	0.55**	0.02	0.051*	0.005	0.018*	0.002
30 001–40 000	0.56**	0.02	0.50**	0.02	0.048**	0.005	0.015**	0.003
40 001–50 000	0.48**	0.03	0.44**	0.02	0.032**	0.005	0.011**	0.003
Above 50 000	0.46**	0.02	0.42**	0.02	0.028**	0.004	0.016*	0.003
Age at which child started brushing (years)								
0–2 (Ref.)	0.52	0.01	0.46	0.01	0.038	0.002	0.015	0.001
>2–4	0.72**	0.02	0.62**	0.02	0.070**	0.006	0.025**	0.003
>4	1.06**	0.06	0.92**	0.05	0.112**	0.017	0.034**	0.008
Brushing frequency (per day)								
Less than once	0.86**	0.05	0.73**	0.04	0.093**	0.015	0.034**	0.007
Once to less than twice	0.67**	0.02	0.59**	0.02	0.062**	0.005	0.021	0.002
Twice or more (Ref.)	0.54	0.01	0.48	0.01	0.040	0.003	0.016	0.001
Professional fluoride treatment (times)								
0 (Ref.)	0.47	0.01	0.42	0.01	0.034	0.003	0.015	0.002
1–2	0.55**	0.02	0.49**	0.01	0.044	0.004	0.014	0.002
3–4	0.73**	0.03	0.65**	0.02	0.058**	0.006	0.024*	0.004
5 or more	1.06**	0.05	0.90**	0.04	0.120**	0.013	0.039**	0.006
Fluoride supplement use (months)								
0 (Ref.)	0.58	0.01	0.52	0.01	0.047	0.003	0.017	0.001
>0–50	0.64	0.03	0.56	0.03	0.053	0.008	0.023	0.005
>50	0.57	0.04	0.51	0.03	0.041	0.008	0.020	0.005
Use of mouthrinse								
Yes	0.74**	0.04	0.67**	0.03	0.059	0.009	0.019	0.004
No (Ref.)	0.59	0.01	0.52	0.01	0.049	0.002	0.018	0.001
Use of infant formula								
Yes (Ref.)	0.63	0.01	0.56	0.01	0.049	0.003	0.018	0.002
No	0.54**	0.02	0.47**	0.01	0.050	0.004	0.020	0.002
Number of first molar surfaces fissure sealed								
0 (Ref.)	0.54	0.01	0.48	0.01	0.046	0.003	0.017	0.001
1–2	1.12**	0.03	1.00**	0.03	0.092**	0.008	0.026*	0.004
3–8	0.47*	0.02	0.41*	0.02	0.042	0.006	0.019	0.004

*$P < 0.05$; **$P < 0.01$.

scores and use on three to eight surfaces was associated with significantly decreased DMFS6 scores. There was no significant association with fluoride supplement use.

For pit and fissure surfaces, a similar trend in mean caries levels and significance compared with reference groups was noted both for the exposure variables and the confounding variables. The results of DMFS6$_{\text{APPROXIMAL}}$ bivariate linear regression by indicator variables and their group mean DMFS6$_{\text{APPROXIMAL}}$ scores are also shown in Table 2. Amongst the exposure variables, the only significant and also lowest score of 0.025 belonged to the group with the highest PRE and POST exposure. Among the confounding variables, caries experience increased with age, age at which child started brushing and professional fluoride treatment given three to four and more than five times. Caries experience decreased with increasing parental income and brushing frequency. There were no significant associations with professional fluoride treatment given one to two times, fluoride supplement use, mouthrinsing and use of infant formula.

Amongst the exposure variables from the associations between $DMFS6_{FREE\ SMOOTH}$ and indicator variables, the categories with PRE and POST $\geq$ 90% and PRE > POST had significantly lower scores compared with the reference group of no exposure (Table 2). Similar trends (to the approximal surfaces) in group mean values and significance were noted for associations of $DMFS6_{FREE\ SMOOTH}$ with age, age at which child started brushing and professional fluoride treatment. There was a linear trend of decreasing caries with increasing parental income until the second highest income category. There was a decrease in mean $DMFS6_{FREE\ SMOOTH}$ with increasing brushing frequency, and the middle category was almost significant at $P = 0.074$. As in the approximal surfaces, there were no significant associations with professional fluoride treatment given one to two times, fluoride supplement use, mouthrinsing and use of infant formula.

Testing PRE against POST exposure in the multivariate model

Table 3 shows the results of ordinary least squares regression for the dependent variables DMFS6, $DMFS6_{PIT\ \&\ FISSURES}$, $DMFS6_{APPROXIMAL}$ and $DMFS6_{FREE\ SMOOTH}$ with the fluoride exposure variables on controlling for potential confounders. This table shows standardized beta coefficients, which enable comparisons of variables of differing magnitudes and dispersions. The beta coefficient of a category of the exposure variable (e.g. PRE = POST) expresses the relative strength and direction of the difference in DMFS6 between the reference group and the category PRE = POST, after controlling for the effect of the potential confounders.

DMFS6 ordinary least square regression

The negative beta coefficients of the variables PRE = POST, PRE > POST, and PRE and POST = 90 showed significant preventive effects compared with the reference of no PRE and POST exposure. A pattern of decreasing DMFS6 scores with increasing PRE exposure (i.e. an exposure–response relationship) was observed. Among the potential confounders, mouthrinsing, use of infant formula, and use of fluoride supplements from >0–50 months were each nonsignificant. Caries increased with increasing age at which child started brushing, increasing number of times of professional fluoride treatment and decrease in brushing frequency. Use of fluoride supplements as drops or tablets for over 50 months duration was associated with decreased caries levels. Use of fissure sealants on one to two surfaces was associated with significantly higher DMFS6 scores compared with the reference group of no use of fissure sealants. Beneficial effects were evident on use on three or more surfaces indicated by the lower caries scores. Controlling for potential confounders, the lowest caries experience was associated with high PRE and POST exposure and exposure to a higher PRE than POST was more beneficial than exposure to a higher POST than PRE. The model R^2-value showed 11.8% of the variance in the DMFS first molar score could be explained by the independent variables.

$DMFS6_{PIT\ \&\ FISSURES}$ ordinary least square regression

A similar trend in beta coefficients and significance to the exposure variables in DMFS6 ordinary least square regression was observed. The coefficients were stronger here than of the model for overall DMFS6 in which the inclusion of the proximal and free smooth surfaces may have attenuated the association between caries and exposure. Among the beta coefficients of the potential confounders, those related to toothbrushing were weaker compared with overall DMFS6. Non-use of infant formula was associated with significantly lower caries levels compared with the reference group who used infant formula. Larger coefficients of indicator variables describing use of fissure sealants were noted for the pit and fissure surfaces than in the model for overall DMFS6. The model R^2 value was slightly higher (than for DMFS6), at 12.1%.

$DMFS6_{APPROXIMAL}$ ordinary least square regression

There were two exposure variables with negative beta coefficients: PRE > POST and PRE and POST $\geq$ 90%. Of these, only the beta coefficients

Table 3. Multivariate linear regressions for association of DMFS with explanatory variables

	DMFS6		Pit and fissure		Approximal		Free smooth	
Independent variables	β	P-value	β	P-value	β	P-value	β	P-value
Combined exposure groups (% lifetime)								
PRE and POST = 0	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.
PRE < POST	−0.001	0.936	−0.002	0.815	0.001	0.892	0.007	0.485
PRE = POST	−0.028	0.003	−0.031	0.001	0.001	0.923	−0.011	0.269
PRE > POST	−0.033	0.001	−0.035	0.000	−0.006	0.563	−0.015	0.156
PRE and POST ≥ 90	−0.055	0.000	−0.052	0.000	−0.038	0.000	−0.023	0.030
Age (years)								
6–7	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.
8–9	0.065	0.000	0.070	0.000	0.014	0.186	0.013	0.235
10–11	0.183	0.000	0.189	0.000	0.070	0.000	0.047	0.000
12–13	0.222	0.000	0.227	0.000	0.090	0.000	0.065	0.000
14–15	0.199	0.000	0.205	0.000	0.088	0.000	0.040	0.000
Parental income (in $)								
Up to 20 000	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.
20 001–30 000	−0.031	0.003	−0.030	0.004	−0.018	0.093	−0.015	0.181
30 001–40 000	−0.039	0.000	−0.039	0.000	−0.013	0.234	−0.022	0.041
40 001–50 000	−0.053	0.000	−0.050	0.000	−0.029	0.004	−0.029	0.005
Above 50 000	−0.058	0.000	−0.056	0.000	−0.036	0.001	−0.019	0.071
Age at which child started brushing (years)								
0–2	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.
>2–4	0.040	0.000	0.038	0.000	0.025	0.005	0.011	0.210
>4	0.053	0.000	0.050	0.000	0.041	0.000	0.012	0.171
Brushing frequency (per day)								
Less than once	0.033	0.000	0.028	0.001	0.035	0.000	0.016	0.066
Once to less than twice	0.031	0.000	0.027	0.001	0.028	0.002	0.014	0.119
Twice or more	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.
Professional fluoride treatment (times)								
0	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.
1–2	0.047	0.000	0.047	0.000	0.028	0.004	0.005	0.639
3–4	0.075	0.000	0.074	0.000	0.038	0.000	0.022	0.023
5 or more	0.096	0.000	0.089	0.000	0.077	0.000	0.026	0.010
Fluoride supplement use (months)								
0	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.
>0–50	0.002	0.841	0.003	0.741	−0.006	0.479	0.005	0.541
>50	−0.028	0.001	−0.028	0.001	−0.020	0.025	0.003	0.764
Use of mouthrinse								
Yes	−0.001	0.904	0.002	0.829	−0.009	0.319	−0.006	0.527
No	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.
Use of infant formula								
Yes	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.
No	−0.015	0.070	−0.022	0.009	0.013	0.142	0.007	0.427
Number of first molar surfaces fissure sealed								
0	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.	Ref.
1–2	0.081	0.000	0.089	0.000	0.025	0.006	−0.003	0.769
3–8	−0.052	0.000	−0.056	0.000	−0.012	0.174	−0.005	0.608

of PRE and POST ≥ 90% was significant. Among the confounders, the indicator variables describing age group 6–7 years, parental income ≤$30 000, fluoride supplement use for >0 to <50 months, mouthrinsing, use of infant formula or use of fissure sealants on three or more surfaces were not significant. Approximal caries increased significantly with increase in age starting from 10–11 years, increasing age at which child started brushing, increasing number of times of professional fluoride treatment, decrease in brushing frequency and use of fissure sealants on one to two surfaces, and decreased significantly with increasing income >$30 000 and fluoride supplement use >50 months. The model R^2 value showed 2.9% of the variance in $DMFS6_{APPROXIMAL}$ could be explained by the independent variables.

$DMFS6_{FREESMOOTH}$ ordinary least square regression

There were three exposure variables with negative beta coefficients i.e. PRE = POST, PRE > POST and PRE and POST $\geq$ 90%, of which the beta coefficient of PRE and POST $\geq$ 90% was significant. As in the previous model for $DMFS6_{APPROXIMAL}$, caries increased significantly with age from 10–11 years. Except in the lowest income group and highest income group which was nearly significant at $P = 0.071$, caries decreased significantly with increasing income. Unlike in the $DMFS6_{APPROXIMAL}$ model, age at which child started brushing, brushing frequency, use of fluoride supplements, professional fluoride treatment one or two times and use of fissure sealants on one or two surfaces showed no significant difference in caries levels in comparison with their reference groups. The model R^2 value was 0.7%.

Discussion

Sample size and precision

The multivariate model for caries of the pit and fissure surfaces reflects that of overall DMFS6 as the bulk of caries of the first permanent molar occurs in this surface type. As a result of the extremely low caries levels in the approximal and free smooth surfaces, the relative beneficial effects of pre- and post-eruption exposure could not be clearly shown in their multivariate models. A larger sample size would be required to enable the demonstration of significant differences at such low caries levels. The estimates of precision for mean caries levels as measured by the relative standard error were: 1.74% (DMFS6), 1.66% ($DMFS6_{PIT\ \&\ FISSURE}$), 4.71% ($DMFS6_{APPROXIMAL}$) and 6.84% ($DMFS6_{FREE\ SMOOTH}$). This indicated that the estimates were less precise for the smooth surfaces, showing a gradient in precision from the pit and fissure, approximal and free smooth surfaces. While this represented an adequate level of precision, reflecting the large sample size, the low caries levels among the smooth surfaces limited the ability to detect significant differences. For example, to detect a mean difference in DMFS of 15% with type I and type II error rates of 5% and 80%, respectively, would require estimated sample sizes in order of: 3540 (DMFS6), 3270 ($DMFS6_{PIT\ \&\ FISSURE}$), 26 400 ($DMFS6_{APPROXIMAL}$) and 55 000 ($DMFS6_{FREE\ SMOOTH}$). While for overall DMFS6 and $DMFS6_{PIT\ \&\ FISSURE}$ distributions the required sample sizes were much lower than the obtained ones, for the proximal and free smooth surfaces bigger sample sizes would be required.

Modeling issues

The percent of variance explained by the models ranged from 10% for fissure caries, 3% for approximal caries and 1% for free smooth surface caries. The interpretation of a given percentage of variance explained by a statistical model depends on the context of the study, where a value of 30% might be considered high by a social scientist while a value of 98% might be considered small by a physicist (26). Low psychosocial and organizational effects found in models from large-scale surveys have been attributed to a range of factors (27). These factors include the correlation of measures of disease with sociodemographic, attitudinal and behavioral variables leading to a reduction of their effects when simultaneously entered into a model (27).

Another modeling issue that warrants discussion is related to the skewness of the DMFS distribution. The fact that DMFS represents a count of the total number of tooth surfaces decayed, missing or filled because of caries, which were skewed in nature, lends itself more naturally to an analysis based on a Poisson or negative binomial regression approach. This alternative statistical approach is yet to be embraced as a standard technique, although it may be preferred on the basis of technical considerations. When the caries distribution with its skewed DMFS pattern was modeled using negative binomial regression, there was no alteration of the trend in beta coefficients of the exposure indicator variables. As the main findings of both statistical modeling approaches were similar and the results of the linear regressions appeared to be robust, a standard approach using ordinary least squares regression was used.

SES indicators

Socioeconomic status was measured as three indicators: educational attainment of parent(s) or guardian(s), occupation(s) of parent(s) or guardian(s) and the pre-tax annual household income. In order to achieve parsimony in the model as well as to avoid collinearity, the most suitable of the three was selected. Income was preferred as it was entered prior to the other SES indicators in the stepwise procedure.

Comparability of extremes in fluoride exposure

The extremes in lifetime fluoride exposure in this research, zero and maximal pre- and post-eruptive exposure are frequently associated with residence in rural versus major urban centers. Systematic social differences exist between these centers, potentially confounding the comparisons. This has been limited in this research through the inclusion of a range of SES indicators in the analysis presented.

Mobility of the population

Residential mobility among the child population was a substantial contributor to both variation and cross-over in exposure to water fluoridation in a child's lifetime. Some variation in exposure could also arise from a change in water source without residential movement. Residential mobility may not be evenly distributed in the child population, potentially biasing comparisons by fluoride exposure. In the research design employed in this study, such biases are unavoidable. However, the inclusion of a range of SES indicators in the analysis will have statistically controlled for variations in oral health because of bias in such social characteristics.

Surface classification

A methodological difference between the CFS and the Tiel–Culemborg study was in the surface classification of caries of the lower molar buccal and the upper molar palatal surfaces. In this study, the lower molar buccal and upper molar palatal surfaces along with the occlusal surfaces were categorized as pit and fissure surfaces because of the presence of the buccal pit and the extension of the disto-lingual fissure on these surfaces, respectively. Consequently, caries on these surfaces were treated as pit and fissure caries. Caries on these surfaces are predominantly located in pit and fissures so that the resulting misclassification would be minor. The overall DMFS6 would be unaffected by this. In the Tiel–Culemborg study where the initiation and progression of caries was examined to study increment, two sites of caries initiation were differentiated on these surfaces (i.e. fissure and free smooth surfaces) and the caries in them were counted separately as pit and fissure or free smooth surface caries.

Pre-eruptive effects

A Scottish study looked at the effect of cessation of fluoridation in 1980, 10 years after its introduction in the city of Stranraer (14). A comparison was made with parallel examinations (conducted in 1980 and 1986 in both cities) of 10-year olds in Annan, which had negligible fluoride in its public water supply. While the DMFT levels of 10-year olds declined by 33% in Annan, those of Stranraer increased by 4% in 1986, six years after the cessation of fluoridation. The caries decline in Annan was in line with the results of other studies in western countries whereas there was no such decline noted in Stranraer. However, the surveys in both years showed lower caries levels for the Stranraer children although the difference in DMFT levels had fallen from 50% in 1980 to 39% in 1986 (14). The 10-year-old cohort of 1986 had 4 years of exposure to fluoridated water in their pre-eruptive period and may have derived a residual benefit of this earlier exposure. However, this exposure did not extend up to the entire pre-eruptive period. Although one cannot differentiate a greater pre-or post-eruptive beneficial effect from this study, the importance of a continued exposure in the entire pre-eruptive period and beyond is suggested.

The findings of the present study showed a dominant PRE exposure caries preventive effect. The categories with high POST exposure and low PRE exposure did not have significantly lower mean caries scores with respect to the reference group. The category with PRE = POST exposure had mean lifetime percentage of exposure of 60.0% for both PRE and POST. Categories with PRE < POST and PRE > POST had mean PRE exposures of 40.1% and 66.6%, respectively. Correspondingly, there was an increasing strength of beta coefficients with increasing PRE exposure among these three significant categories for overall DMFS6 and for $DMFS6_{PIT\ \&\ FISSURE}$ so that the maximum caries preventive effect was achieved by high PRE and POST exposure. Although the category PRE < POST had a higher mean POST exposure of 77.4% lifetime exposure, the low PRE exposure was associated with a higher, nonsignificant DMFS6 score. Thus, high exposure to fluoridated water in the POST period did not suffice in restricting caries to low levels when PRE exposure was low, whereas a high PRE exposure resulted in lower overall DMFS6 and $DMFS6_{PIT\ \&\ FISSURES}$ scores when POST exposure was low. Only the high PRE and POST category showed significantly lower mean

$DMFS6_{APPROXIMAL}$ and $DMFS6_{FREESMOOTH}$ scores with respect to the reference group. However, the beta coefficients of the PRE < POST category were weak and positive in both their multivariate models.

Surface-specific effects

The Tiel–Culemborg study showed that different surface types were inhibited differently and in different stages by fluoride. In interpreting these findings, three successive stages of fluoride uptake by the tooth were identified: matrix formation and calcification, pre-eruptive maturation and post-eruptive maturation (9). Different surfaces were seen to have varying accessibility to fluoride ions in the three stages. As a result of this, an inhibition of the progression of caries may not have occurred in the pit and fissure surfaces in the same way as for smooth surfaces. Among the younger age group of 9-year olds who had 2 years of pre-eruptive exposure, a significant caries reduction of 29% in the pit and fissure surfaces was reported, whereas among the 12-year olds, who had no pre-eruptive exposure, no significant difference between Tiel and Culemborg was noted. Similarly the mesial surface of the first molar, which is not a free surface at the time of eruption, had less accessibility to fluoride so that the 12-year olds of Tiel and Culemborg did not show significant differences in the caries of this surface type. The caries experience in the mesial surfaces of the first molars in the 9-year olds of Tiel was 50% lower than those of Culemborg because of their 2 years of pre-eruptive exposure in Tiel. In the distal surface, which is a free surface at eruption, significant differences of 27% and 50% were noted for the 12- and 9-year olds, respectively (9).

The authors concluded that the pits and fissures have less favorable physical conditions (deep fissures) for the uptake of fluoride ions and this may explain a smaller beneficial effect in the occlusal than in the other surfaces from post-eruptive fluoride (9). For the free smooth surfaces the caries reduction is the same whether fluoridation started 2–3 years before or after the eruption of the tooth. However, the percentage of reduction decreases progressively for freely accessible surfaces of teeth that have erupted three or more years before fluoridation (10, 19).

The results of the Tiel–Culemborg study indicated that an inhibition of the progression of caries might not occur in the pits and fissures as for the smooth surfaces on exposure post-eruptively for reasons of lack of accessibility. Therefore, pre-eruption exposure may be important in inhibiting the initiation of caries in pit and fissure surfaces. This explanation may be applied to the results obtained from the CFS where PRE exposure had a dominant role in pit and fissure caries prevention and without which there was no significant reduction in caries.

Clinical significance of findings at population level

An interpretation of the observed statistical significance at an individual level can be projected at the population level since the findings relate to the community-wide benefit of fluoridated water (28). For example, in the multivariate model, the mean DMFS6 of children with maximum PRE and POST exposure was 0.055 less than the mean for children with no PRE or POST exposure in the 6–15-year age range. Practically this constitutes fewer 0.055 first molar surfaces per child belonging to the high PRE and POST exposure group compared with a child belonging to the no exposure group. However, if a population of approximately 200 000 children of this age range were to benefit from fluoridation, there would be 11 000 fewer surface caries in the permanent first molars alone. Hence, a substantial benefit is achieved when viewed at a larger scale, and an even greater benefit might be expected for a high-risk group.

Conclusions

The beta coefficient of the category with POST > PRE exposure was always the weakest. This itself could indicate the relatively greater importance of a PRE exposure to fluoridated water. The multivariate models for overall DMFS6 and $DMFS6_{PIT\ \&\ FISSURE}$ clearly depicted the significant role of a PRE > POST exposure as compared to PRE < POST exposure for caries prevention. As caries declines, a greater proportion of the remaining caries resides in the pit and fissure surfaces (17, 29), which gain more preventive benefit from PRE exposure. The role of PRE exposure through water fluoridation becomes more important in furthering the decline, because by fluoridating, an effective targeting and prevention of pit and fissure surface caries would be achieved. In this study, a significant preventive affect was seen in all surfaces by a continuous pre- and post-eruption exposure. Water fluoridation provides a mechanism for this continuous exposure for a benefit in all surfaces.

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