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ABSTRACT

Systematic reviews produce conflicting conclusions regarding dental caries-preventive effects of water fluoridation in adults. The authors investigated the relationship using data from the nationally representative 2004−2006 Australian National Survey of Adult Oral Health. Effects were compared between the pre-fluoridation cohort born before 1960 (n = 2,270) and the cohort born between 1960 and 1990 (n = 1,509), when widespread implementation of fluoridation increased population coverage from < 1% to 67%. Residential history questionnaires determined the percentage of each person's lifetime exposed to fluoridated water. Examiners recorded decayed, missing, and filled teeth (DMF-Teeth) and decayed and filled tooth surfaces (DF-Surfaces). Socio-demographic and preventive dental behaviors were included in multivariable least-squares regression models adjusted for potential confounding. In fully adjusted models, > 75% of lifetime exposure to fluoridation relative to < 25% of lifetime exposure was associated with 11% and 10% fewer DMF-Teeth in the pre-1960 ($p < .0001$) and 1960–1990 cohorts ($p = .018$), respectively. Corresponding reductions in DF-Surfaces were 30% ($p < .001$) and 21% ($p < .001$). Findings for intermediate fluoridation exposure suggested a dose-response relationship. Results were consistent in sensitivity analyses accounting for missing data. In this nationally representative sample of Australian adults, caries-preventive effects of water fluoridation were at least as great in adults born before widespread implementation of fluoridation as after widespread implementation of fluoridation.

KEY WORDS: community water fluoridation, health surveys, adult, DMF Index, cohort effect.

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INTRODUCTION

Despite being one of the United States' 10 greatest public health achievements of the 20th century (Centers for Disease Control and Prevention, 2000), community water fluoridation receives only qualified endorsement from some systematic reviews of its effectiveness in preventing dental caries. Authors of one review found that fluoridation reduces caries in children but were reluctant to quantify the effect, citing poor quality of many studies (McDonagh *et al*., 2000). For adult populations, they reported insufficient evidence to draw conclusions, a finding echoed in a U.S. consensus panel that made "no comment on primary prevention of … caries in adults, as no evidence was available to address these questions" (NIH Consensus Statement Online, 2001). The cited lack of evidence in adults hampers the development of health policy. For example, an economic evaluation of community water fluoridation in Australia initially assumed no caries-preventive benefit for adults, although cost-effectiveness changed substantially in a sensitivity analysis that assumed benefit (Cobiac and Vos, 2012).

Before 1990, few studies investigated the caries-preventive effects of fluoridation in adults (Rugg-Gunn and Do, 2012). This probably reflected a view, now outdated (Beltran and Burt, 1988), that fluoridated water was effective only when ingested prior to tooth eruption. It raises a pragmatic public health question that confronts a community contemplating the implementation of fluoridation: Will potential benefits be limited to people born after implementation, or might there be additional benefits for people born before implementation? We addressed this question in two cohorts of people studied in the 2004–2006 National Survey of Adult Oral Health (Appendix Fig. 1): people born before 1960, prior to widespread fluoridation (n = 2,270); and people born between 1960 and 1990, when population coverage increased from < 1% to 67%. Associations between percentage of lifetime exposed to fluoridated drinking water and dental caries experience were evaluated in each cohort, with the expectation that the association would be stronger in the 1960–1990 cohort.

MATERIALS & METHODS

The Australian 2004–2006 National Survey of Adult Oral Health (NSAOH) examined 5,505 people selected from all 8 states and territories (Slade *et al.*, 2007). People aged ≥ 15 yrs (hereafter "adults") were selected at random from the population by a stratified, clustered, random sampling procedure. Telephone interviews of potential participants established eligibility and collected socio-demographic and dental care information. Those with natural teeth were invited to an oral epidemiological examination, after completion of which they received a questionnaire by mail. The target sample size was calculated to address different survey aims, namely, 80% power with 5% type-I error in detecting reductions of 10% in age-group-specific mean DMFT since the 1987-1988 national survey.

The survey was approved by the University of Adelaide's Human Research Ethics Committee, and participants gave written informed consent. This manuscript is structured to address STROBE guidelines (von Elm *et al*., 2007).

Oral Epidemiological Examination

Thirty dentist-examiners trained in study procedures conducted examinations in dental clinics. They used mirrors and compressed air but not explorers or radiographs to evaluate all 32 teeth in each participant. For participants aged < 45 yrs, only teeth extracted because of dental caries or periodontitis were classified as missing due to disease. For older people, all absent teeth were recorded as missing due to disease. Dental caries was classified for 5 surfaces *per* tooth: mesial, buccal, distal, lingual, and occlusal/incisal. Decay was classified based on visual evidence of enamel cavitation and/or carious dentin. A surface was classified as filled if restored for the treatment of caries. As reported elsewhere (Mejia *et al.*, 2007), intra-class-correlation coefficients of reliability were 0.85 at the tooth level and 0.98 at the person-level among examiners, compared with the study reference examiner in masked, replicated examinations of 157 study participants.

Self-completed Mailed Questionnaire

The questionnaire asked people to record their residential location history from 1964 to 2003. Before 1964, only a few small towns had fluoridated water supplies. The questionnaire also asked about use of fluoride supplements in childhood and frequency of toothbrushing in the week before the survey.

Lifetime Exposure to Fluoridated Water

The exposure of interest was proportion of lifetime exposure to fluoridated drinking water (Grembowski, 1988). The fluoridation database maintained by the Australian Research Centre for Population Oral Health records fluoride concentration of public water supplies, classified geographically by postcode (Mahoney *et al*., 2008). It registers fluoride concentrations for 99.4% of the Australian population. We matched residential locations to water supplies in every year, coding fluoride concentrations as: (a) < 0.3 ppm F = 0; (b) 0.3 - < 0.7 ppm F = 0.5; and (c) ≥ 0.7 ppm F = 1.0. We assumed 0.5 ppm F for localities in New Zealand, Canada, or the United States and 0 ppm F for other foreign localities. The number of years at each concentration was multiplied by the concentration. The products were summed and divided by the person's age to yield the person's proportion of lifetime exposed to the equivalent of 1 ppm F in drinking water (hereafter "fluoridation exposure").

Data Analysis

Decayed and filled surfaces were aggregated to the tooth-level and added to the number of missing teeth to create a DMF-Teeth index. The DF-Surfaces was computed as the sum of decayed and filled tooth surfaces.

When a person had missing residential data for > 50% of the years investigated, his/her fluoridation exposure was treated as missing. For people with fewer missing data, the missing years were assumed to be their average observed fluoridation exposure. In sensitivity analysis, a second exposure variable assigned exposure of 0 ppm F to missing years in people with ≤ 50% of years with missing data.

Covariates were age in years, sex, country of birth (Australia, New Zealand, United Kingdom, other), usual reason for dental visits (check-up, dental problems), toothbrushing frequency (< 2 times/day, ≥ 2 times/day), use of fluoride supplements in childhood (yes or no, asked only of people age < 45 yrs), education (≤ year 12, certificate/diploma, university degree), and annual household income (< AUD40,000, AUD40,000 to < AUD80,000, ≥ AUD80,000). Covariates accounted for potential confounding of the fluoridation exposure and dental caries relationship in multivariate analyses.

Survey estimation procedures in SAS v9.2 generated weighted estimates for the Australian population. Complete case analysis was undertaken for participants with observed and assumed fluoridation exposure data. Means and percentages described distributions of dental caries experience and fluoridation exposure, respectively, within categories of each covariate. Analysis of covariance, with age in years as the covariate, compared age-adjusted mean DMF-Teeth and DF-Surfaces *per* person and components of caries experience at 4 levels of fluoridation exposure (≥ 75%, hereafter "prolonged"; 50 to < 75%; 25 to < 50%; and < 25%, hereafter "negligible"). Separate estimates were made of the relationship for the pre-1960 and 1960–1990 cohorts. Least-squares regression models were used because, in large samples, they produce valid estimates for non-normally-distributed data (Lumley *et al.*, 2002).

Further sensitivity analysis used hot-deck multiple imputation (Andridge and Little, 2010) to evaluate potential bias due to missing information. The method used 5 steps: (1) Data were cross-classified into i = 15 sampling strata and j = 6 age groups (15-24, 25-34, 35-44, 45-54, 55-64, and ≥ 65 yrs), creating 15 x 6 = 90 strata. Those stratification variables were selected because they were associated with both fluoridation exposure and likelihood of questionnaire non-response (Appendix Table 1). (2) For each of the 1,726 people with missing fluoridation exposure, one person with valid fluoridation exposure data was sampled from the same stratum with simple random sampling with replacement. (3) That person's fluoridation exposure became the imputed estimate, and imputed records were added to the records from 3,779 people who completed a questionnaire. (4) Fully adjusted regression models estimated the association between fluoridation exposure and caries experience. (5) The third and fourth steps were repeated 10 times, with independent random sampling in each repetition, and results from regression models were combined by the SAS MIANALYZE procedure.

Finally, additional sensitivity analysis used the multiply imputed dataset to evaluate potential differences between people sampled from capital cities *vs*. elsewhere and by limiting the analysis to Australian-born people.

Table 1. Dental Caries Experience and Exposure to Water Fluoridation in Australian Adults: 2004–2006 National Survey of Adult Oral Health

	Unweighted n (1)	Population %	Mean (s.e.) (2) DMFT	Mean (s.e.) DFS	% of Lifetime Exposed to Water Fluoridation			
					< 25%	25 to < 50%	50 to < 75%	≥ 75%
All people	3779	100.0	13.41 (0.27)	22.84 (0.57)	23.9	19.0	25.9	31.1
Age group, yrs								
15-24	246	15.1	2.98 (0.47)	3.81 (0.71)	26.4	4.1	6.9	62.6
25-34	416	17.1	5.33 (0.34)	8.57 (0.79)	21.8	4.5	9.4	64.4
35-44	765	20.5	10.27 (0.30)	18.42 (0.74)	22.7	13.5	24.4	39.4
45-54	792	19.5	18.47 (0.29)	34.61 (0.92)	22.3	18.0	46.1	13.6
55-64	842	14.5	21.78 (0.19)	38.59 (0.98)	25.2	28.0	46.8	0.0
≥ 65	718	13.4	23.84 (0.25)	35.12 (1.17)	26.7	54.7	18.6	0.0
Years of birth								
1960–1990	1509	55.0	6.95 (0.26)	11.62 (0.48)	23.8	8.2	14.9	53.1
Before 1960	2270	45.0	21.29 (0.17)	36.54 (0.64)	24.1	32.3	39.2	4.4
Region of state								
Capital city	2443	66.6	12.93 (0.32)	22.84 (0.72)	16.2	19.5	29.5	34.8
Remainder of state	1336	33.4	14.36 (0.51)	22.85 (0.95)	39.3	18.2	18.6	24.0
Sex								
Female	2321	51.5	13.82 (0.31)	24.16 (0.70)	24.0	18.7	25.6	31.8
Male	1458	48.5	12.97 (0.42)	21.45 (0.83)	23.9	19.5	26.2	30.5
Country of birth								
Australia	2929	79.5	12.93 (0.31)	22.16 (0.65)	22.6	16.5	24.7	36.2
New Zealand, UK	457	10.4	16.73 (0.62)	28.01 (1.46)	22.8	29.7	33.3	14.2
Other	393	10.1	13.75 (0.70)	22.87 (1.60)	35.2	28.4	27.8	8.6
Reason for dental visits								
Check-up	2186	59.6	12.99 (0.35)	23.98 (0.81)	23.7	19.1	25.3	32.0
Dental problem	1593	40.4	14.02 (0.36)	21.17 (0.68)	24.3	19.0	26.8	29.9
Toothbrushing frequency								
< 2 times/day	1447	41.5	12.35 (0.38)	19.77 (0.78)	22.2	16.0	25.1	36.6
≥ 2 times/day	2304	57.8	14.12 (0.32)	25.01 (0.71)	25.1	21.1	26.4	27.3
Not reported	28	0.7	17.78 (2.28)	26.00 (5.33)	26.1	25.7	23.6	24.6
Used fluoride supplements								
Yes	226	6.9	7.02 (0.50)	12.02 (1.06)	34.0	11.4	24.7	29.9
No	1109	42.5	6.65 (0.29)	10.97 (0.55)	21.1	7.7	13.2	58.1
Not reported	174	5.5	9.15 (0.71)	16.14 (1.55)	32.2	7.8	16.2	43.7
Not asked	2270	45.0	21.29 (0.17)	36.54 (0.64)	24.1	32.3	39.2	4.4
Annual income (AUD'000)								
< $40	1537	30.8	17.49 (0.40)	26.55 (0.84)	25.7	28.7	28.2	17.4
40–< 80	1185	32.9	12.43 (0.38)	22.59 (0.87)	25.9	15.9	24.0	34.2
≥ 80	841	27.1	11.29 (0.47)	20.97 (1.11)	17.5	13.1	30.2	39.2
Not reported	216	9.2	9.46 (0.90)	16.87 (1.86)	29.7	15.2	12.3	42.8
Highest level of education								
Year 12 or less	1272	35.4	12.53 (0.42)	18.78 (0.76)	26.2	17.6	22.0	34.2
Some college/diploma	1044	27.3	15.29 (0.43)	26.13 (0.97)	25.2	19.3	28.5	26.9
University degree	1463	37.3	12.87 (0.45)	24.30 (1.00)	20.8	20.3	27.6	31.3

(1) Numbers of people in sample are unweighted counts; all other statistics are weighted population estimates for the Australian adult dentate population.
(2) Standard errors of estimated means are shown in parentheses.

RESULTS

Of 5,505 examined people, 3,779 (69%) completed a questionnaire reporting at least 50% of their residential history and were used in complete case-analysis (Appendix Fig. 2). They reported 138,406 years of residence in locations with known fluoride exposure and 5,135 years at locations where fluoridation exposure was assumed to be their average exposure. Groups with complete and incomplete data differed by as much as 10 to 12% in distributions of dental attendance and income (Appendix Table 2).

Mean numbers of DMF-Teeth and DF-Surfaces increased 10-fold from youngest to oldest age groups, while the percentage with prolonged fluoridation decreased from 63% to 0% across age groups (Table 1). Groups classified according to

Table 2. Multivariable Models of Association between Exposure to Fluoride in Drinking Water and Caries Experience in Australian Adults Born between 1960 and 1990: 2004–2006 National Survey of Adult Oral Health

	Dependent Variable = DMFT		Dependent Variable = DFS	
	1960–1990 Cohort: β (95% CL)	Pre-1960 Cohort: β (95% CL)	1960–1990 Cohort: β (95% CL)	Pre-1960 Cohort: β (95% CL)
Fluoridation exposure (ref < 25% of lifetime)				
≥ 75% of lifetime	-1.14 (-2.09, -0.19)	-2.58 (-4.05, -1.11)	-3.44 (-5.28, -1.60)	-11.10 (-15.47, -6.72)
50 to < 75% of lifetime	0.27 (-0.87, 1.40)	0.09 (-0.61, 0.79)	0.18 (-2.19, 2.56)	-1.88 (-4.78, 1.02)
25 to < 50% of lifetime	0.75 (-0.73, 2.23)	-0.47 (-1.22, 0.28)	2.23 (-1.32, 5.77)	-2.72 (-6.01, 0.56)
Age in decades (centered)	3.89 (3.39, 4.39)	1.95 (1.57, 2.32)	7.73 (6.67, 8.79)	0.34 (-1.08, 1.75)
Region of state (ref = non-capital)				
Capital city	-0.65 (-1.61, 0.30)	-0.28 (-0.81, 0.26)	-0.08 (-1.85, 1.69)	2.80 (0.49, 5.11)
Sex (ref = Male)				
Female	0.42 (-0.37, 1.21)	1.89 (1.34, 2.43)	0.14 (-1.49, 1.77)	6.65 (4.40, 8.89)
Country of birth (ref = Australia)				
New Zealand, UK	0.39 (-1.08, 1.86)	-0.59 (-1.27, 0.09)	1.29 (-3.39, 5.96)	-3.22 (-5.84, -0.61)
Other	-0.27 (-1.51, 0.97)	-2.13 (-3.15, -1.11)	-1.78 (-4.53, 0.96)	-5.17 (-9.33, -1.02)
Reason for dental visits (ref = dental problem)				
Check-up	-0.34 (-1.16, 0.48)	-0.28 (-0.89, 0.33)	0.24 (-1.48, 1.97)	6.65 (4.55, 8.75)
Toothbrushing frequency (ref = ≥ 2 times/day)				
< 2 times/day	0.48 (-0.33, 1.29)	-0.02 (-0.63, 0.58)	0.25 (-1.38, 1.89)	-2.15 (-4.60, 0.31)
Not reported	4.35 (1.12, 7.58)	0.20 (-1.58, 1.97)	-0.11 (-8.10, 7.89)	1.28 (-9.19, 11.75)
Used fluoride supplements (ref = No)				
Yes	-0.93 (-1.97, 0.12)	n/a	-2.06 (-4.31, 0.19)	n/a
Not reported	1.23 (0.07, 2.38)		2.43 (-0.25, 5.12)	
Annual income (AUD’000) (ref >80)				
< 40	0.67 (-0.52, 1.87)	0.47 (-0.38, 1.32)	2.50 (0.14, 4.87)	-3.98 (-7.26, -0.70)
40–< 80	-0.03 (-1.11, 1.05)	0.54 (-0.31, 1.38)	1.57 (-0.36, 3.51)	0.53 (-2.73, 3.79)
Not reported	0.96 (-1.16, 3.08)	0.74 (-0.43, 1.92)	4.67 (0.79, 8.56)	0.13 (-5.02, 5.28)
Highest level of education (ref = University degree)				
Year 12 or less	1.15 (0.04, 2.25)	0.14 (-0.56, 0.84)	1.63 (-0.58, 3.85)	-7.66 (-10.49, -4.82)
Some college/diploma	1.00 (-0.13, 2.12)	0.63 (-0.06, 1.32)	1.54 (-0.89, 3.96)	-2.03 (-4.72, 0.67)

(1) Ref is the reference group used in the dummy variable model.
(2) β is the parameter estimate of the net difference in mean DMFT or DFS between the row-category and the reference category; 95% CL are 95% confidence limits for the parameter estimate. Values of 95% CL that do not overlap the null value of zero are statistically significant at the $p < .05$ threshold. Estimates are from complete-case analysis of 3,779 examined people who reported ≥ 50% of lifetime residential locations.

other covariates (*e.g.*, country of birth, income) had up to two-fold variation in fluoridation exposure, although differences in caries experience were relatively small. Differences based on dental attendance and income were attenuated considerably by age-adjusted measures of caries experience (Appendix Table 3).

In the pre-1960 cohort, the age-adjusted mean number of missing teeth was up to 1.5 times the age-adjusted mean number of filled teeth, whereas in the 1960–1990 cohort, the difference was four-fold (Appendix Table 4). Both cohorts revealed statistically significant lower age-adjusted mean numbers of DMF-Teeth, DF-Surfaces, and filled teeth among those with prolonged fluoridation exposure compared with those with negligible exposure.

These associations persisted in fully adjusted multivariable models (Table 2). Compared with people with negligible exposure, those with prolonged exposure had a net difference of 2.58 fewer DMF-Teeth in the pre-1960 cohort and 1.14 fewer DMF-Teeth in the 1960–1990 cohort. Net differences in numbers of DF-Surfaces were 11.10 and 3.44, respectively. For both cohorts, adjusted estimates of DMF-Teeth from the multivariable models revealed weak, inverse gradients across successive levels of fluoridation exposure (Fig., A). Gradients were more pronounced for DF-Surfaces (Fig., B), but were not monotonic.

Based on the preceding complete-case analyses, percentage differences in mean DMF-Teeth for people with prolonged *vs.* negligible fluoridation exposure were 12% in the pre-1960 cohort and 11% in the 1960–1990 cohort (Table 3). Those differences changed by no more than 1% under differing assumptions about fluoride exposure at unknown locations and after imputation for incomplete or unreported residential history. When measured as DF-Surfaces, relative differences associated with prolonged fluoridation were 30% and 21% based on complete case-analysis of the early and later cohorts, respectively. In sensitivity analysis, corresponding percentages in the two cohorts varied from 28 to 32% and from 19 to 25%. While point estimates showed greater percentage difference in the pre-1960

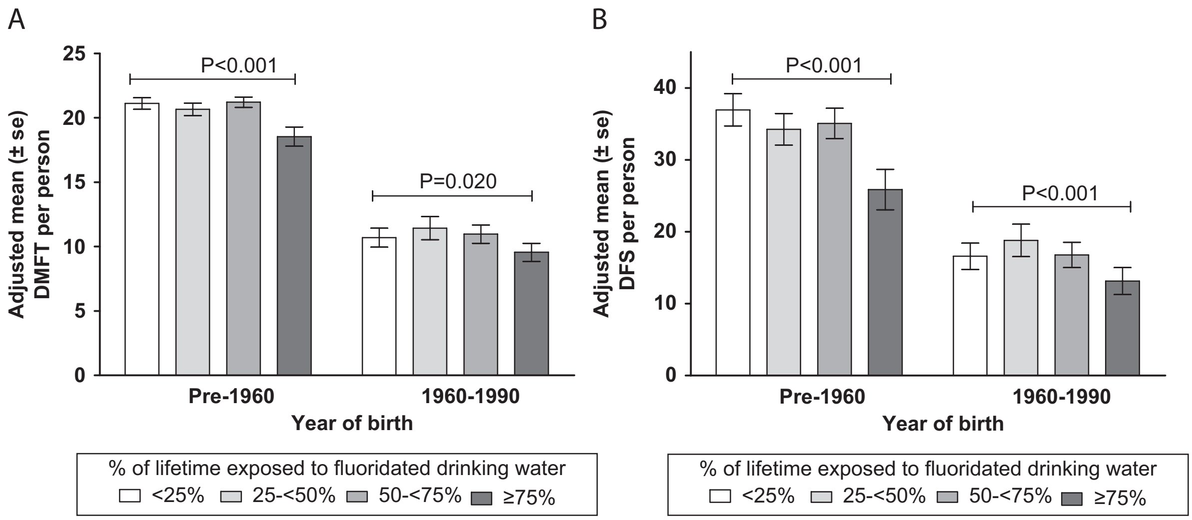

Figure. Adjusted estimates of caries experience and exposure to water fluoridation in two cohorts of Australia adults: 2004–2006 National Survey of Adult Oral Health. **(A)** Number of decayed, missing, and filled teeth *per* person (DMFT) in groups with 4 levels of fluoridation exposure, estimated from fully adjusted models (Table 2). **(B)** Number of decayed and filled tooth surfaces *per* person (DFS) in groups with 4 levels of fluoridation exposure, estimated from fully adjusted models (Table 2).

cohort compared with the 1960–1990 cohort, there was considerable overlap of the 95% confidence limits.

When cohorts were combined, the percentage difference in DF-surfaces associated with prolonged fluoridation was slightly smaller in capital cities (17%) than in other locations (23%). Restricting the analysis to Australian-born people yielded a similar difference of 22% in DF-Surfaces associated with prolonged fluoridation.

DISCUSSION

In this cross-sectional examination survey of a nationally representative sample of Australian adults, greater lifetime exposure to water fluoridation was associated with lower levels of caries experience. In both cohorts, relative reductions of approximately 11% in mean DMF-Teeth were observed in people with prolonged *vs*. negligible lifetime fluoridation exposure. When quantified by DF-Surfaces, the relative reduction was 30% in the pre-1960 cohort and 21% in the post-1960 cohort. An approximate inverse, dose-response gradient in DF-Surfaces was observed across successively greater levels of fluoridation exposure. The relationships remained consistent after adjustment for potential confounders and in sensitivity analyses that evaluated the impact of incomplete and missing fluoridation exposure data.

Missing data threaten the internal validity of health surveys. In this study, 31% of people were excluded from the complete-case analysis because of missing data, and their distribution of some covariates, including income, differed from that of the complete-case group. Meanwhile, fluoridation exposure could not be classified completely for all people. However, multiple imputation to account for missing data did not markedly alter estimated associations between fluoridation exposure and caries experience. Likewise, findings did not alter appreciably under various assumptions about unknown fluoridation exposure.

Missing teeth jeopardize internal validity by potentially misclassifying caries experience. Although dental caries is the main cause of tooth extraction in all age groups (Burt and Eklund, 2005), it is not clear how missing teeth should be handled in computations of surface-level caries experience (Lawrence *et al.*, 1996). We therefore included missing teeth in the DMF-Teeth index, but limited the surface-level measure to DF-Surfaces. The conclusions were similar, suggesting no serious bias. In this study, the fluoride content of water supplies was a proxy for individuals' fluoride consumption. While this creates misclassification of individuals' exposure, it is the appropriate marker of public health intervention. We did not inquire about fluoride content of toothpaste. Fluoride-containing toothpaste has been ubiquitous nationally since the 1970s (Spencer, 1986). Hence, it should not confound associations between fluoridation exposure and caries.

External validity of these findings is strengthened by the survey's generalizability to the Australian adult population. Indeed, we believe this to be the first nationally representative examination survey to evaluate the caries-preventive effectiveness of water fluoridation in adults. These results are also consistent with findings from 2 recent studies of Australian military recruits (Hopcraft and Morgan, 2003; Mahoney *et al.*, 2008). Meanwhile, a U.S. study specifically investigating tooth loss in adults found that it was less frequent among those born in fluoridated counties (Neidell *et al.*, 2010).

An important consideration is whether the association is causal. Typically cross-sectional designs cannot establish a temporal ordering between exposure and disease and therefore cannot contribute to causal interpretation. In principle, however, cross-sectional studies are informative about temporality under 2 conditions: (a) when studies compare lifetime-exposed and

Table 3. Sensitivity Analysis of Findings Comparing Caries Experience between Australian Adults with Prolonged and Negligible Levels of Fluoridation Exposure: 2004–2006 National Survey of Adult Oral Health

				Estimated Difference in Caries Outcome Measure between Prolonged— and Negligible-fluoridation-exposure Groups		
Stratum	Caries measure	Assumptions about Unknown Localities (1)	Analytic Dataset (2)	β (95% CL) (3)	*p* value (4)	% Difference (95% CL) (5)
Born pre-1960	DMFT	Average ppmF	Complete-case	-2.58 (-4.05, -1.11)	< .001	-12 (-19, -5)
Born pre-1960	DMFT	Average ppmF	Imputed	-2.54 (-4.19, -0.89)	.003	-12 (-20, -4)
Born pre-1960	DMFT	0 ppm F	Complete-case	-2.61 (-4.39, -0.84)	.004	-12 (-21, -4)
Born pre-1960	DMFT	0 ppm F	Imputed	-2.42 (-4.00, -0.84)	.003	-11 (-19, -4)
Born pre-1960	DFS	Average ppm F	Complete-case	-11.10 (-15.47, -6.72)	< .001	-30 (-41, -18)
Born pre-1960	DFS	Average ppm F	Imputed	-10.69 (-15.76, -5.62)	< .001	-28 (-42, -15)
Born pre-1960	DFS	0 ppm F	Complete-case	-12.11 (-16.49, -7.73)	< .001	-32 (-44, -21)
Born pre-1960	DFS	0 ppm F	Imputed	-10.91 (-16.10, -5.72)	< .001	-29 (-43, -15)
Born 1960–1990	DMFT	Average ppm F	Complete-case	-1.14 (-2.09, -0.19)	.018	-11 (-20, -2)
Born 1960–1990	DMFT	Average ppm F	Imputed	-1.26 (-2.25, -0.27)	.013	-12 (-21, -3)
Born 1960–1990	DMFT	0 ppm F	Complete-case	-1.37 (-2.34, -0.39)	.006	-13 (-22, -4)
Born 1960–1990	DMFT	0 ppm F	Imputed	-1.42 (-2.41, -0.42)	.005	-13 (-23, -4)
Born 1960–1990	DFS	Average ppm F	Complete-case	-3.44 (-5.28, -1.60)	< .001	-21 (-32, -10)
Born 1960–1990	DFS	Average ppm F	Imputed	-3.17 (-4.95, -1.39)	< .001	-19 (-30, -8)
Born 1960–1990	DFS	0 ppm F	Complete-case	-4.09 (-6.06, -2.13)	< .001	-25 (-36, -13)
Born 1960–1990	DFS	0 ppm F	Imputed	-3.58 (-5.38, -1.79)	< .001	-22 (-32, -11)
Capital city	DFS	Average ppm F	Imputed	-3.61 (-5.74, -1.48)	< .001	-17 (-27, -7)
Remainder of state	DFS	Average ppm F	Imputed	-5.65 (-8.63, -2.68)	< .001	-23 (-36, -11)
Australian born	DFS	Average ppm F	Imputed	-5.36 (-7.34, -3.38)	< .001	-22 (-31, -14)

(1) Average ppm F assumes that unknown localities conferred the person's observed, average lifetime fluoridation exposure; 0 ppm F assumes that unknown localities conferred no exposure to fluoridation.
(2) Unimputed, complete-case analysis of 3,779 people who were examined and had sufficient data to quantify fluoridation exposure. Imputed data are from hot-deck, multiple imputation for an additional 1,726 examined people who did not complete a questionnaire about residential history.
(3) β is the parameter estimate from a linear regression model equivalent to models in Table 2, estimating mean difference in caries outcome between groups with prolonged (> 75%) fluoridation exposure and negligible (< 25%) fluoridation exposure; 95% CL are 95% confidence limits for the parameter estimate.
(4) *p* value test of the null hypothesis that β = 0.
(5) Percentage difference is β divided by estimated caries outcome for the group with < 25% exposure to water fluoridation, multiplied by 100. 95% CL values are the 95% confidence limits of the percentage reduction.

lifetime-non-exposed people; and (b) when disease is quantified as lifetime, cumulative incidence. This principle was implicit in early studies of lifetime residents of U.S. towns with various concentrations of naturally occurring fluoride, where the DMF index was devised as a cumulative, lifetime measure of the disease. One such study of adults reported a three-fold difference in caries experience (McKay, 1948).

Unfortunately, this epidemiologic principle was overlooked in 2 systematic reviews of water fluoridation that excluded cross-sectional studies (McDonagh *et al*., 2000; Yeung, 2008). Their conclusions of insufficient evidence to evaluate fluoridation's effectiveness in adults conflict with findings from another systematic review that included cross-sectional studies, concluding that it reduced caries by 27% in adults (Griffin *et al.*, 2007). In the current study, there were too few people with 0% or 100% lifetime exposure to completely satisfy the principle's first condition, although contrasts between groups with negligible and prolonged lifetime exposure approximated it. There was also some evidence of a dose-response relationship between fluoridation exposure and caries, another prominent causal criterion. Evidence from experiments is another important causal criterion. While randomized controlled trials of community water fluoridation are not feasible, there is ample evidence of fluoride's efficacy in randomized controlled trials of its addition to toothpaste, mouthrinse, and gels (Marinho, 2009).

Based on this combined body of evidence, we believe that the current findings of an inverse association between water fluoridation and caries experience provide reasonable evidence of a causal, preventive effect in Australian adults. The caries-preventive effects of water fluoridation were at least as great in adults born before widespread implementation of fluoridation as after widespread implementation of fluoridation.

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