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Water Fluoridation and Dental Caries in U.S. Children and Adolescents

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Abstract

Fluoridation of America's drinking water was among the great public health achievements of the 20th century. Yet there is a paucity of studies from the past 3 decades investigating its dental health benefits in the U.S. population. This cross-sectional study sought to evaluate associations between availability of community water fluoridation (CWF) and dental caries experience in the U.S. child and adolescent population. County-level estimates of the percentage of population served by CWF (% CWF) from the Centers for Disease Control and Prevention's Water Fluoridation Reporting System were merged with dental examination data from 10 y of National Health and Nutrition Examination Surveys (1999 to 2004 and 2011 to 2014). Dental caries experience in the primary dentition (decayed and filled tooth surfaces [dfs]) was calculated for 7,000 children aged 2 to 8 y and in the permanent dentition (decayed, missing, and filled tooth surfaces [DMFS]) for 12,604 children and adolescents aged 6 to 17 y. Linear regression models estimated associations between % CWF and dental caries experience with adjustment for sociodemographic characteristics: age, sex, race/ethnicity, rural-urban location, head-of-household education, and period since last dental visit. Sensitivity analysis excluded counties fluoridated after 1998. In unadjusted analysis, caries experience in the primary dentition was lower in counties with ≥75% CWF (mean dfs = 3.3; 95% confidence limit [CL] = 2.8, 3.7) than in counties with <75% CWF (mean dfs = 4.6; 95% CL = 3.9, 5.4), a prevented fraction of 30% (95% CL = 11, 48). The difference was also statistically significant, although less pronounced, in the permanent dentition: mean DMFS (95% CL) was 2.2 (2.0, 2.4) and 1.9 (1.8, 2.1), respectively, representing a prevented fraction of 12% (95% CL = 1, 23). Statistically significant associations likewise were seen when % CWF was modeled as a continuum, and differences tended to increase in covariate-adjusted analysis and in sensitivity analysis. These findings confirm a substantial caries-preventive benefit of CWF for U.S. children and that the benefit is most pronounced in primary teeth.

Keywords: primary prevention, dental health surveys, United States, epidemiology, public health dentistry, drinking water

Introduction

Community water fluoridation (CWF) in the United States ranks among the great public health achievements of the 20th century for its effectiveness in preventing dental caries (Centers for Disease Control and Prevention 1999). The supporting evidence originated with scores of epidemiologic studies conducted predominantly during the mid-20th century (Burt and Eklund 2005). The 1 nationally representative observational study to investigate the relationship was conducted in 1986 to 1987. Results were reported in 1 article (Brunelle and Carlos 1990) and 1 abstract (Brunelle 1990), although the statistical significance of associations was not reported.

We know of only 2 U.S. studies of CWF reported since 1990. A 1996 to 1997 statewide study of 5- to 11-y-olds in Tennessee found that children living in fluoridated communities had approximately one-fifth less caries experience in primary teeth and permanent teeth than children living in nonfluoridated areas (Gillcrist et al. 2001). The other study, conducted in 1997 to 1999 among 7- to 9-y-olds in upstate New York, reported similar relative differences (Kumar et al. 2001). Nonetheless, this represents a dearth of U.S. epidemiologic evidence compared to the 57 studies reported from other countries between 1990 and 2010 (Rugg-Gunn and Do 2012).

Dental caries remains a serious public health problem for US children. Dental caries in the primary dentition affects one-quarter of 2- to 5-y-olds and one-half of 6- to 8-y-olds. In the permanent dentition, it affects one in five 6- to 11-y-olds—prevalence rates that have persisted since the 1990s (Dye et al. 2017). Conspicuous income-associated disparities in children's dental caries have likewise persisted for decades (Slade and Sanders 2017). Despite the shortage of recent supporting data from the United States, the US Preventive Services Task Force continues to endorse CWF (Community Preventive Services Task Force 2017), and the Healthy People 2020 initiative has an objective to extend CWF coverage (Healthy People 2020 2018).

This study aimed specifically to evaluate the association between availability of CWF and dental caries experience in the US child and adolescent population. The broader goal was to update evidence to inform public policy concerning fluoridation.

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A supplemental appendix to this article is available online.

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Materials and Methods

This manuscript follows STROBE (Strengthening The Reporting of Observational Studies in Epidemiology) guidelines (von Elm et al. 2008). The plans for analysis of de-identified data were deemed exempt from institutional review board review by the University of North Carolina Office of Human Research Ethics (study 15-2225) and by the National Center for Health Statistics (NCHS) Ethics Review Board (project 1776).

Study Design, Setting, and Participants

This was a cross-sectional study of 2- to 17-y-old participants in the 1999 to 2004 and 2011 to 2014 cycles of the National Health and Nutrition Examination Survey (NHANES). In each 2-y cycle, NHANES selected a stratified random sample representative of the U.S. civilian, noninstitutionalized population. For this analysis, participants born outside the United States and those living in the United States for 1 y or less were excluded due to uncertainty regarding their exposure to fluoridated drinking water.

Data Sources and Variables

Main Exposure Measure: County Fluoridation Status. The Water Fluoridation Reporting System (WFRS) provided county-level information about CWF. This database is maintained by the Centers for Disease Control and Prevention (CDC) in partnership with the Association of State and Territorial Dental Directors and is continually updated by state fluoridation managers. It contains information about fluoride concentration and population size served by each of approximately 54,000 US public water systems (Malvitz et al. 2009). The aggregate data are used to monitor national health objectives, and 36 states also provide public access to the information about individual water systems (Centers for Disease Control and Prevention 2017a). For this study, the CDC provided the authors county-level aggregated data as of March 2016 for 3,136 counties in all 50 states and the District of Columbia. Variables included the a) county's Federal Information Processing Standard (FIPS) code, b) number of people served by public water systems containing fluoride within the optimal concentration range (0.7 to 1.2 ppm fluoride [ppm F]) or higher, and c) annual county population estimates from the U.S. Census Bureau (US Census Bureau Population Division 2017). The derived exposure variable was the proportion of the county's population served by fluoridated water (b ÷ c). The authors updated the data set in 3 ways:

- FIPS codes for 55 counties in Virginia were updated for concordance with U.S. Census 2000 FIPS codes.
- Fluoridation status of 28 counties in California were updated using data reported by the California Department of Public Health (2009).
- Fluoridation status of 5 counties in Rhode Island absent from the WFRS were obtained from the state's water system report at My Water's Fluoride (Centers for Disease Control and Prevention 2017b).

Measures of Dental Caries Experience. Dental caries experience was assessed by NHANES dental examiners using visual and tactile criteria to evaluate the status of each tooth surface for participants aged 2 y and older. Dental decay was classified at the threshold of cavitation while a surface was classified as filled if the restoration was placed to treat dental caries. Permanent teeth missing due to decay were also recorded. Dental examiners were thoroughly trained in the NHANES examination protocol and exhibited high levels of interexaminer reliability (Dye et al. 2014). The outcome variable for the primary dentition was the number of decayed or filled primary tooth surfaces (dfs). Its calculation was limited to 2- to 8-y-olds because the index has doubtful clinical relevance in older children. The outcome variable for the permanent dentition was the number of decayed, missing, or filled permanent tooth surfaces (DMFS), computed for 6- to 17-y-olds.

Measures of Potential Confounders. Trained NHANES interviewers obtained information from an adult householder about the sampled child/adolescent, including age in years, sex (male, female), race/ethnicity (non-Hispanic White, non-Hispanic Black, Hispanic, other), educational attainment of head of household (less than high school, high school graduate, some college, college graduate or higher), and period since last dental visit (within the preceding year, 1 to 2 y ago, more than 2 y ago, or never). The latter was used to account for the possibility that dental visiting patterns might differ between fluoridated and nonfluoridated areas. The Rural-Urban Commuting Area codes, Version 2, used census-derived information about commuting distance and population size to classify rurality (urban, large rural, small rural, isolated) (U.S. Department of Agriculture Economic Research Service 2005).

Statistical Methods

Person-level NHANES data were merged with county-level fluoridation data using the FIPS code of the participant's county of residence and rural-urban classification using ZIP code of the participant's dwelling. Because NHANES public data sets released by the National Center for Health Statistics do not include geographic variables, these variables were accessed using the Triangle Federal Statistical Research Data Center.

Survey estimation procedures in SAS v9.2 (SAS Institute) generated weighted estimates for the U.S. population. For descriptive purposes, unadjusted estimates and 95% confidence limits (95% CLs) of mean dfs per participant and mean DMFS per participant were compared between 2 groups classified according to the percentage of county population served by public water containing ≥0.7 ppm F: a) <75% (hereafter "<75% fluoridated") or b) ≥75% ("≥75% fluoridated"). Absolute difference in means (a – b) and prevented fraction ([a – b]/a × 100) were also calculated.

Least squares regression models tested hypotheses about caries experience and county fluoridation. In large samples, such models produce valid estimates despite the nonnormal distribution of the dependent variable (Lumley et al. 2002), as

Table 1. Distribution of Counties, Population and Fluoridated Population According to County Fluoridation Coverage.

	Counties			2016 U.S. Population			Fluoridated Population		
% of County Fluoridated[a]	*n*	%	Cumulative %	*n* (Millions)	%	Cumulative %	*n* (Millions)	%	Cumulative %
≥87.5	566	18.0	18.0	107.2	33.3	33.3	103.9	50.2	50.2
75 to <87.5	336	10.7	28.8	61.5	19.1	52.4	50.4	24.3	74.5
62.5 to <75	368	11.7	40.5	29.4	9.1	61.5	20.7	10.0	84.5
50 to <62.5	342	10.9	51.4	30.0	9.3	70.8	16.6	8.0	92.5
37.5 to <50	276	8.8	60.2	14.9	4.6	75.5	6.4	3.1	95.6
25 to <37.5	288	9.2	69.4	17.2	5.3	80.8	5.4	2.6	98.2
12.5 to <25	235	7.5	76.9	13.3	4.1	84.9	2.4	1.2	99.4
<12.5	725	23.1	100.0	48.5	15.1	100.0	1.3	0.6	100.0
All	3,136	100.0		322.0	100.0		207.1	100.0	

Source: Fluoridations status for all U.S. counties from the Water Fluoridation Reporting System, 2016, merged with U.S. Census Bureau Annual Estimates of the Resident Population for Counties: April 1, 2010, to July 1, 2016.
[a]Percentage of county population served by public water systems with ≥0.7 ppm fluoride.

occurs for dfs and DMFS. Also, the models produced estimates that can be readily compared with previous reports. Separate models used fluoridation as a dichotomous exposure variable (≥75% fluoridated versus <75% fluoridated) or as a continuous proportion (0 to 1). One set of models adjusted only for NHANES cycle and demographic characteristics each modeled as dummy variables relative to a referent category. Another set of fully adjusted models also adjusted for rural-urban classification, education, and period since last dental visit (each modeled as dummy variables relative to a referent category). Sensitivity analysis repeated the fully adjusted models excluding participants living in counties that introduced fluoridation after 1998. The rationale was that the fluoridation status of those counties was uncertain at the time of NHANES examinations. Participants with 1 or more missing values for variables in a model were excluded from that model. We also explored potential effect-measure modification by race/ethnicity and by education, but there were no statistically significant interactions with fluoridation to justify reporting stratum-specific effects.

Sample Size

Calculations made when planning the study revealed >95% statistical power to detect, at a type I error threshold of $P < 0.05$, prevented fractions of 25% for mean dfs and 20% for mean DMFS given expected sample sizes of 7,000 and 12,000 participants, respectively. Both effects sizes were consistent with values reported for the 2 U.S. studies conducted in the 1990s (Gillcrist et al. 2001; Kumar et al. 2001) and were conservative, being at the lower quartile of the distribution of 65 effect estimates reported from studies conducted in other countries since 1990 (Rugg-Gunn and Do 2012).

Results

The WFRS data set contained data for 3,136 counties (Table 1) from the nationwide total of 3,142 counties. Although only 28.8% of counties were ≥75% fluoridated (i.e., ≥75% of the county population was served by public fluoridated water containing ≥0.7 ppm F), 52.4% of the U.S. population lived in those counties. As a consequence, those counties accounted for 74.5% of 207.1 million Americans served by fluoridated drinking water.

During the periods studied, NHANES examined 7,763 children aged 2 to 8 y, of whom 7,000 were included in the descriptive sample for analysis of primary dentition caries, and 6,633 had complete data for fully adjusted analytic models (Table 2). There were nearly twice as many 6- to 17-y-olds available for analysis of permanent dentition caries.

Descriptive Findings

The estimated percentage of U.S. children and adolescents living in ≥75% fluoridated counties did not vary appreciably according to age, sex, education, or period since last dental visit (Table 3). Non-Hispanic Blacks were more likely than other race/ethnic groups to live in ≥75% fluoridated counties, and only small percentages of participants living in small or large rural areas were served by fluoridated water. Dental caries experience was positively associated with age and rurality and negatively associated with educational attainment. Compared to non-Hispanic Whites and Blacks, Hispanics and "other" race/ethnicity groups had more caries experience in primary and permanent teeth. Recent dental visits were associated with greater caries experience, particularly in the primary dentition.

Unadjusted Associations

In unadjusted analysis of primary dentition caries in 2- to 8-y-olds, participants living in ≥75% fluoridated counties had 1.3 fewer dfs per child (95% CL = 0.6, 2.2) on average than those living in <75% fluoridated counties, a prevented fraction of 30% (95% CL = 11%, 48%) (Table 4). In the permanent dentition of 6- to 17-y-olds, the corresponding unadjusted estimate was 0.3 fewer DMFS per child on average (95% CL = 0.0, 0.5), a prevented fraction of 12% (95% CL = 1%, 23%; Table 4).

Table 2. Number of Study Participants.

Characteristic	Unweighted Number of Participants	
	2- to 8-y-olds	6- to 17-y-olds
All participants in NHANES 1999–2004 and 2011–2014	7,763	13,621
Excluded: no dental examination	699	884
Excluded: no fluoridation data or foreign born or residing in United States ≤1 y	64	133
Descriptive sample: examined participants with fluoridation data	7,000	12,604
Excluded: subjects living in isolated or unknown ZIP codes or with missing sociodemographic or dental visit covariates	367	633
Analytic sample: examined participants with valid residential + sociodemographic + behavioral covariates	6,633	11,971
Excluded: participants in counties fluoridated on/after 1999	1,804	3,218
Sensitivity analysis: analytic sample excluding counties fluoridated after 1998	4,829	8,753

NHANES, National Health Nutrition and Examination Survey.

Table 3. Descriptive Characteristics of U.S. 2- to 17-y-Olds: National Health and Nutrition Examination Survey 1999 to 2004 and 2011 to 2014.

Characteristic	Unweighted Number of Participants	Population%	Living in ≥75% Fluoridated Counties,[a] % (SE)	2- to 8-y-old dfs, Mean (SE)	6- to 17-y-old DMFS, Mean (SE)
All participants	16,718	100.0	49.3 (4.0)	3.9 (0.2)	2.1 (0.1)
Age group (y)					
2–5	4,114	24.2	49.6 (4.2)	2.6 (0.2)	NA
6–8	2,886	18.0	50.1 (4.7)	5.6 (0.3)	NA
6–11	5,649	37.7	50.3 (4.2)	NA	0.7 (<0.1)
12–17	6,955	38.1	48.3 (4.1)	NA	3.5 (0.1)
Sex					
Male	8,437	50.7	49.2 (4.1)	4.3 (0.2)	1.9 (0.1)
Female	8,281	49.3	49.5 (4.1)	3.5 (0.2)	2.2 (0.1)
Race/ethnicity					
Non-Hispanic Black	5,102	14.8	68.2 (4.8)	3.7 (0.2)	2.1 (0.1)
Hispanic	5,836	20.5	59.3 (4.7)	5.2 (0.3)	2.4 (0.1)
Other	1,466	7.4	55.8 (5.4)	4.8 (0.5)	2.5 (0.2)
Non-Hispanic White	4,314	57.3	40.1 (4.8)	3.4 (0.3)	1.9 (0.1)
Rural-urban classification					
Small rural	1,017	7.5	10.0 (6.8)	5.5 (0.8)	2.3 (0.3)
Large rural	1,326	11.9	20.1 (9.1)	5.3 (0.8)	2.2 (0.2)
Urban	14,126	78.3	58.9 (4.5)	3.6 (0.2)	2.0 (0.1)
Missing or isolated	249	2.4	5.3 (5.3)	6.8 (1.8)	2.9 (0.6)
Education of household referent					
Less than high school	5,252	21.1	53.1 (4.2)	5.8 (0.4)	2.7 (0.1)
High school graduate	3,884	23.4	42.1 (4.5)	4.8 (0.4)	2.2 (0.1)
Some college	4,157	27.6	46.9 (4.1)	3.6 (0.3)	2.1 (0.1)
College graduate or above	2,850	24.7	54.2 (5.3)	2.0 (0.2)	1.2 (0.1)
Missing	575	3.1	62.2 (6.0)	3.4 (0.6)	2.7 (0.3)
Period since last dental visit					
Within 1 y	11,600	73.9	47.3 (4.5)	5.0 (0.3)	2.1 (0.1)
1–2 y	1,529	7.9	46.3 (4.5)	4.7 (0.6)	2.1 (0.2)
More than 2 y or never	3,542	17.9	50.1 (4.1)	1.3 (0.1)	1.5 (0.1)
Missing	47	0.2	67.7 (11.9)	1.0 (0.5)	2.1 (0.7)

dfs, number of decayed or filled primary tooth surfaces per person; DMFS, number of decayed, missing, or filled permanent tooth surfaces per person; NA, not applicable; SE, standard error of population estimate.
[a]Counties in which ≥75% of the population is served by public water systems with ≥0.7 ppm fluoride.

Multivariable Associations with Binary Fluoridation Variable

Parameter estimates from multivariable models signified similar or larger absolute differences in caries experience associated with fluoridation (Table 5). For primary dentition caries, the absolute difference was 1.81 fewer dfs per child ($P < 0.01$) after adjustment for demographics, 1.39 dfs per child after additional adjustment for all covariates, and 1.79 dfs per child in the sensitivity analysis. Using as a reference the observed mean dfs of 4.6 in <75% fluoridated counties (Table 4), the 3 adjusted absolute differences in Table 5 are consistent with

Table 4. Unadjusted Mean Caries Experience According to Fluoridation Status among U.S. 2- to 17-y-olds: National Health and Nutrition Examination Survey 1999 to 2004 and 2011 to 2014.

	2- to 8-y-old dfs		6- to 17-y-old DMFS	
% of County Fluoridated[a]	*n*	Mean (95% CL)	*n*	Mean (95% CL)
<75% of county population (a)	2,914	4.6 (3.9, 5.4)	5,107	2.2 (2.0, 2.4)
≥75% of county population (b)	4,086	3.3 (2.8, 3.7)	7,497	1.9 (1.8, 2.1)
Absolute difference: (a) minus (b)		1.3 (0.6, 2.2)		0.3 (0.0, 0.5)
Prevented fraction: [(a) minus (b)]/(a) × 100 (%)		30 (11, 48)		12 (1, 23)

CL, confidence limit; dfs, number of decayed or filled primary tooth surfaces per person; DMFS, number of decayed, missing, or filled permanent tooth surfaces per person; *n*, unweighted number of participants in descriptive sample.
[a]Percentage of county population served by public water systems with ≥0.7 ppm fluoride.

Table 5. Regression Model-Adjusted Estimates of Association between Fluoridation Status and Dental Caries Experience among US 2- to 17-y-olds: National Health Nutrition and Examination Survey (NHANES) 1999 to 2004 and 2011 to 2014.

		2- to 8-y-old dfs			6- to 17-y-old DMFS		
Sample	Adjustment Variables	*n*	β (SE)	*P* Value	*n*	β (SE)	*P* Value
β = binary fluoridation status (≥75% vs. <75% of county population fluoridated[a])							
Descriptive	Demographics	7,000	–1.81 (0.46)	<0.01	12,604	–0.34 (0.12)	0.01
Analytic	All covariates	6,633	–1.39 (0.47)	<0.01	11,971	–0.25 (0.13)	0.06
Sensitivity	All covariates	4,829	–1.79 (0.50)	<0.01	8,753	–0.53 (0.15)	<0.01
β = continuous fluoridation variable (proportion of county population fluoridated)							
Descriptive	Demographics	7,000	–2.49 (0.56)	<0.01	12,604	–0.93 (0.23)	<0.01
Analytic	All covariates	6,633	–2.08 (0.54)	<0.01	11,971	–0.88 (0.24)	<0.01
Sensitivity	All covariates	4,829	–2.40 (0.57)	<0.01	8,753	–1.09 (0.24)	<0.01

βs are parameter estimates from linear regression models estimating associations between community water fluoridation exposure and extent of dental caries experience (dfs per child for 2- to 8-y-olds; DMFS per child for 6- to 17-y-olds). *P* value is from test of null hypothesis that β = 0. Demographic adjustments variables are age (continuous), sex (2 categories), race/ethnicity (4 categories), and NHANES cycle (5 categories). Models with all covariates add education (4 categories), period since last dental visit (3 categories), and rural-urban classification (3 categories). Parameter estimates and standard errors for all variables in the fully adjusted models are presented in Appendix Tables 1 to 4.
dfs, number of decayed or filled primary tooth surfaces per person; DMFS, number of decayed, missing, or filled permanent tooth surfaces per person; *n*, unweighted number of participants in descriptive sample; SE, standard error of β.
[a]Percentage of county population served by public water systems with ≥0.7 ppm fluoride.

prevented fractions in the primary dentition of 39%, 30%, and 39%, respectively. In the permanent dentition, adjusted net differences ranged from 0.25 ($P = 0.06$) to 0.53 ($P < 0.01$) (Table 5). Again, using the observed mean DMFS of 2.2 in <75% fluoridated counties as the reference, those absolute differences represent prevented fractions ranging from 11% to 24%.

Multivariable Associations with Continuous Fluoridation Variable

Across 8 categories of % CWF, there was an approximate inverse relationship between extent of fluoridation and caries experience (Appendix Fig. 1A, B). Additional multivariable models therefore assessed the proportion of county population fluoridated as a continuous variable, yielding statistically significant, inverse associations between fluoridation and caries experience for all 6 models (Table 5, $P < 0.01$ for all parameter estimates). In the primary dentition, parameter estimates ranged from –2.08 to –2.49, consistent with absolute differences of 2.08 and 2.49 (respectively) in mean dfs per child between counties with no fluoridation versus counties with 100% fluoridation. Those parameter estimates are approximately 40% greater (in absolute value) than the corresponding estimates for a binary indicator of ≥75% fluoridated counties in Table 5 (i.e., –1.39 to –1.81). In the permanent dentition, parameter estimates for fluoridation modeled as a continuous measure ranged from –0.88 to –1.09, which is more than double the corresponding parameter estimates using the binary indicator of fluoridation (i.e., –0.25 to –0.53; Table 5).

Discussion

Key Results

In this nationally representative sample of U.S. children and adolescents, greater availability of fluoridated drinking water was associated with significantly lower levels of dental caries experience. Conservatively, the prevented fraction was 30% in the primary dentition, using a threshold of ≥75% population coverage to create a binary classification of county fluoridation status. Effect estimates were at least as large (i.e., prevented fractions up to 39%) after adjusting for covariates and in sensitivity analysis. The prevented fraction for permanent dentition caries was smaller (12%), although as seen in the primary dentition, effect estimates generally increased (i.e., up to 24%) after adjustment for covariates and in sensitivity analysis. Effect estimates were greater when county fluoridation was modeled as a continuous variable to contrast 0% versus 100% population coverage.

The magnitude of effects is consistent with previous studies. The sole US national study to have investigated the association compared DMFS of 5- to 17-y-olds who were lifetime residents of either fluoridated or nonfluoridated communities, yielding an average prevented fraction of 18% (Brunelle and Carlos 1990). It increased to 25% when the analysis was restricted to children with no history of exposure to supplemental or topical fluorides. More recent US studies classified fluoridation exposure based on the school's water supply. The Kentucky study reported prevented fractions of 21% in the primary dentition and 25% in the permanent dentition (Gillcrist et al. 2001), while the New York study reported a prevented fraction of 14% for combined primary and permanent dentitions (Kumar et al. 2001). The prevented fractions observed here are in the lower quintile of studies reported internationally since 1990 (Rugg-Gunn and Do 2012), where prevented fractions were likewise generally greater for primary teeth than for permanent teeth. Consistent with previous NHANES findings (Beltran-Aguilar et al. 2005), this study found a strong inverse association between education and caries experience.

Limitations

Misclassification of fluoridation exposure occurred for several reasons. The binary CWF variable classified participants as exposed to CWF if they lived in a county where at least three-quarters of the population had fluoridated water. This represents exposure misclassification if the subject was among the remaining fraction of the county population. Conversely, participants in <75% fluoridated counties could have received fluoridated water. Fluoridation exposure was classified according to the participant's county of residence at the time of the NHANES examination, creating additional potential for misclassification had the child lived previously in a county with the opposing fluoridation status. In the decade 2001 to 2010, 1.7% of children aged 1 to 17 y relocated across state boundaries per year, down from 2.9% in the decade 1981 to 1990 (Switek 2016), although not all residential mobility results in a change in fluoridation exposure. Another source of exposure misclassification is the 15% of U.S. children and adolescents who report not using tap water (Sanders and Slade 2018). These sources of misclassification mean that these estimates of prevented fraction are akin to estimates from "intention-to-treat" analysis in clinical trials, where comparisons are made on the basis of treatment group allocation rather than treatment received.

Cross-sectional studies typically are limited for the purpose of causal inference, principally because the study design does not establish a temporal sequence between exposure and disease. That limitation is mitigated in studies that measure caries experience. Because dfs and DMFS indices capture active disease and cumulative disease history, the temporal sequence between exposure and disease is established for those participants who have used the same source of drinking water since birth.

Generalizability

This study has several important strengths. Its findings are generalizable to the U.S. child and adolescent population by virtue of NHANES probabilistic sampling method. Furthermore, NHANES data sets had few missing values and were linked to county-level CWF information for nearly all participants. The NHANES examination protocol is rigorous and applied uniformly over time and across geographical boundaries. By combining multiple NHANES cycles, the sample size provided sufficient statistical power to assess study aims. These findings fill a shortage in recent evidence about fluoridation, a shortage that has been criticized in a Cochrane systematic review (Iheozor-Ejiofor et al. 2015), although controversially (Rugg-Gunn et al. 2016), such reviews exclude evidence from cross-sectional studies.

The binary classification of ≥75% is a pragmatic public health goal, recognizing that most counties have a fraction of the population that is not on public water systems, making 100% fluoridation unattainable. However, when it is feasible for an entire county's population to receive fluoridated water, estimates from the continuous variable model are relevant because they signify the average prevented fraction expected for counties with 100% fluoridation compared to counties with 0% fluoridation.

Interpretation

When considered at the level of an individual, these effect estimates represent clinical benefits that are either small (1.3 fewer dfs per child) or negligible (0.3 fewer DMFS per child). However, caries experience indices are more meaningfully interpreted for groups, just as clinical trials report number needed to treat. For example, effect estimates from this study translate as 13 fewer primary tooth surfaces and 3 fewer permanent tooth surfaces developing caries for every 10 children who gain access to CWF. The potential public health benefit is substantial in the United States, where 115 million people currently do not have fluoridated tap water. The Healthy People 2020 objective OH-13, if met, would extend CWF to 20 million more (Healthy People 2020 2018), and 24% of them would be children and adolescents based on the national age distribution. Hence, if CWF were extended to 4.8 million children, and they experienced the prevented fractions found here, it would translate to 6.2 million fewer primary tooth surfaces developing caries and 1.4 million fewer permanent tooth surfaces developing caries.

As impressive as these figures appear, the potential for extending CWF is limited. Thirty-four million Americans live in places that do not have a public water supply (Centers for Disease Control and Prevention 2017a). Of the remaining 81 million people with nonfluoridated public water, many are served by water systems that are small or otherwise unsuited to fluoridation for engineering-related reasons. Furthermore, towns and cities contemplating adding fluoride to drinking water typically face fierce opposition (Allukian et al. 2017). Children's consumption of bottled water continues to climb in the United States (Popkin 2010) and potentially could reach many people whose drinking water is not fluoridated. However, very little bottled water contains fluoride at the optimal concentration.

Advocacy for fluoridated drinking water begins with sound scientific evidence that is communicated effectively to audiences that often have limited health literacy (Allukian et al. 2017). The current findings are consistent with earlier studies that established the scientific consensus that CWF is effective in preventing dental caries. They provide a valuable update of the evidence needed to support fluoridation as a core public health intervention promoting oral health.

Author Contributions

G.D. Slade, contributed to conception, design, data analysis, and interpretation, drafted and critically revised the manuscript; W.B. Grider, contributed to data analysis, critically revised the manuscript; W.R. Maas, contributed to conception and data acquisition, critically revised the manuscript; A.E. Sanders, contributed to conception, design, and data analysis, drafted and critically revised the manuscript. All authors gave final approval and agree to be accountable for all aspects of the work.

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Access to Underlying Research Materials

The county-level fluoridation data set analyzed in this study is available at the DataShare website maintained at UCSF by the data coordinating center that supports NIDCR's Oral Health Disparities collaborative: https://datashare.ucsf.edu.

Unrestricted variables from the National Health and Nutrition Examination Survey are available at https://www.cdc.gov/nchs/nhanes/index.htm.

Restricted variables, including the ZIP code and county of residence of study participants, must be accessed through the NCHS Research Data Center: https://www.cdc.gov/rdc/.

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