Impact of fluoride on associations between free sugars intake and dental caries in U.S. children

Melissa M. Melough[1], Sheela Sathyanarayana[1,2], Fatemeh Vida Zohoori[3], Hanna C. Gustafsson[4], Elinor L. Sullivan[4], Donald L. Chi[5,6], Steven M. Levy[7], Christy M. McKinney[1,5]

[1]Department of Child Health, Behavior, and Development, Seattle Children's Research Institute, Seattle, WA, USA
[2]Departments of Pediatrics and Environmental & Occupational Health Sciences, University of Washington, Seattle, WA, USA
[3]Centre for Public Health Research, School of Health and Life Sciences, Teesside University, Middlesbrough, UK
[4]Department of Psychiatry, Oregon Health & Science University, Portland, OR, USA
[5]Department of Oral Health Sciences, School of Dentistry, University of Washington, Seattle, WA, USA
[6]Department of Health Systems and Population Health, School of Public Health, University of Washington, Seattle, WA, USA
[7]Department of Preventive & Community Dentistry, College of Dentistry, and Department of Epidemiology, College of Public Health, University of Iowa, Iowa City, IA, USA

Knowledge Transfer Statement
Intake of free sugars, especially in the form of added sugars and specifically in beverages, was associated with higher dental caries in U.S. children in this study. Water fluoride exposure at CDC-recommended levels protected against caries, especially in the primary dentition. These findings suggest that household water fluoridation at CDC-recommended levels protects against the cariogenic potential of free and added sugars during childhood.

Abstract
Objective: Dental caries is the most prevalent chronic disease in U.S. children, with highest burden among Black and Hispanic youth. Sugars are a primary risk factor, but few studies have specifically measured intakes of free sugars and related this to dental caries, or explored the extent to which water fluoride mitigates the cariogenicity of free sugars. Furthermore, the cariogenicity of certain free sugars sources, such as extruded fruit and vegetable products, is unclear.
Methods: Using cross-sectional data on 4906 children aged 2-19 years in the U.S. National Health and Nutrition Examination Survey (NHANES) 2013-2016, we examined associations of free sugars intake with counts of decayed or filled primary tooth surfaces (dfs) and decayed, missing, or filled permanent surfaces (DMFS) in negative binomial regressions. Stratified models examined these associations in children with home water fluoride above or below the CDC-recommended level of 0.7 ppm.
Results: Free sugars accounted for 16.4% of energy, primarily contributed by added sugars. In adjusted models, a doubling in the percentage of energy from free sugars was associated with 22% (95% CI: 1%, 47%) greater dfs among children aged 2 to 8. A doubling in energy from added sugars was associated with 20% (95% CI: 1%, 42%) greater dfs and 10% (95% CI: 2%, 20%) greater DMFS in children aged 6-19. Beverages were the most important source of added sugars associated with increased caries. Other free sugars were not associated with dfs or DMFS. Associations between free sugars and caries were diminished among children with home water fluoride of 0.7 ppm or greater.

Conclusions: Free sugars intake, especially in the form of added sugars and specifically in sweetened beverages, was associated with higher dental caries. Water fluoride exposures modify these associations, reducing caries risk in the primary dentition of children whose home water meets recommended fluoride levels.

Abstract Word Count: 300; **Manuscript Word Count:** 3404
Figures: 1; **Tables:** 3
Keywords: sugar-sweetened beverages; children; adolescents; nutrition surveys; fluoridation; dietary sugars

Introduction

Dental caries is the most prevalent chronic disease in childhood (Benjamin 2010) with associated costs for U.S. children exceeding $8.7 billion per year (Bui et al. 2017). Consumption of free sugars is a primary risk factor for dental caries development (Moynihan and Kelly 2014). Free sugars are defined by the World Health Organization (WHO) as monosaccharides and disaccharides that are added to food and drinks or are naturally found in honey, syrups, fruit juices, and fruit juice concentrates (World Health Organization 2015b). Although the 2020-2025 Dietary Guidelines for Americans do not provide specific recommendations regarding free sugars, they recommend limiting added sugars, a major source of free sugars, to no more than 10% of energy intake (U.S. Department of Agriculture and U.S. Department of Health and Human Services 2020).

U.S. children exceed added sugars recommendations, with recent estimates showing children aged 2 to 19 years consume an average of 71.5 grams daily, or nearly 18 teaspoons, accounting for 14.8% of energy intake (Welsh et al. 2018). Free sugars are regarded as the most important risk factor for dental caries, as these sugars can be metabolized by oral microbiota to produce acid that demineralizes tooth enamel and dentin (Pitts et al. 2017). There is debate about the roles of different sources of free sugars in dental caries development. Most studies in the U.S. have focused on the roles of added sugars or sugar sweetened beverages (SSBs) (Park et al. 2015; Valenzuela et al. 2021) and have found compelling evidence of their cariogenicity. The role of naturally-occurring free sugars and other specific sources of free sugars (e.g., desserts, candy) is less clear (Liska et al. 2019). For example, some limited evidence suggests that 100% fruit juices may be cariogenic (Jensen et al. 2000; Marshall et al. 2003), yet others have associated them with reduced dental caries (Chankanka et al. 2015; Ghazal et al. 2015). These findings have yet to be fully clarified, but may reflect a lower cariogenic potential of fruit juices compared to SSBs (Marshall et al. 2003), which may be displaced in the diets of juice consumers. Furthermore, few studies have examined whether the cariogenic potential of free sugars – or specific sources of free sugars – may be mitigated by fluoridated water exposure. A 2015 systematic review found that water fluoridation reduces dental caries in children; however, the majority of studies available for this review were conducted prior to 1975 (Iheozor-Ejiofor et al. 2015). Little research has directly examined whether water fluoridation confers benefits by reducing the impact of particular dietary risk factors (Armfield et al. 2013), and little is known about the relationships of free sugars, fluoride, and dental caries in the context of the modern U.S. diet, which has seen recent decreases in SSB consumption (Marriott et al. 2019).

The objectives of this study were to examine the associations of free sugars and their sources with dental caries in U.S. children and to evaluate the extent to which fluoridated water exposure may mitigate the cariogenic potential of free sugars. We hypothesized that free sugars would be associated with increased dental caries and that some sources of free sugars (e.g., added sugars and SSBs) may be associated with greater risk than other sources. We anticipated that these associations would be less pronounced in individuals with household water fluoride at concentrations recommended by the U.S. Centers for Disease Control and Prevention (CDC, ≥ 0.7 ppm) (U.S. Public Health Service 2015) compared to their counterparts in households with water fluoride below the CDC recommendation.

Methods

Study Population: This cross-sectional study included data from participants aged 2 to 19 years in the National Health and Nutrition Examination Survey (NHANES) 2013-2014 and 2015-2016, the cycles in which household water fluoride concentration was measured. NHANES is a nationally representative survey of the noninstitutionalized U.S. civilian population. Participants who completed two 24-hour dietary recalls were included in descriptive analyses of sugar intake. Of 4906 children with complete dietary data, 4649 (94.8%) additionally had dental examination and fluoride data available and were included in the main analyses.

Dietary Assessment: All participants were eligible for two 24-hour dietary recalls conducted by trained interviewers using the Automated Multiple Pass Method (Blanton et al. 2006). The first was conducted in-person and the second was conducted by telephone 3 to 10 days later. Sample weights that adjust for non-response to the dietary component and differences in intake between weekdays and weekends were applied to analyses. For participants aged <6 years, interviews were conducted with a proxy respondent who was knowledgeable about the child's intake. A proxy assisted with interviews of children aged 6 to 11. Participants ≥12 years reported their diets themselves.

Estimation of Nutrient Intake: The USDA Food and Nutrient Database for Dietary Studies (FNDDS) contains nutrient values for foods and beverages reported in NHANES dietary interviews (USDA 2021). The FNDDS was used to determine participants' nutrient intakes including total energy.

Estimation of Free Sugars Intake: Free sugars are not reported in the FNDDS, so intake was estimated using a definition based on those established by the WHO (World Health Organization 2015a) and the UK National Diet and Nutrition Survey (Swan et al. 2018). We defined free sugars as all added sugars and all sugars naturally present in honey, syrups, and fruit and vegetable juices, purées, and similar extruded products. Data on added sugars were gathered from the Food Patterns Equivalents Database (FPED), which converts foods and beverages in the FNDDS to 37 USDA Food Patterns components (e.g., total vegetables, starchy vegetables, oils, etc.) (Bowman et al. 2013). Added sugars are defined in the FPED as sugars, syrups, or caloric sweeteners added to foods during food processing or manufacturing, during preparation at home or restaurants, or added at the table (Bowman 2017). This definition includes all types of syrups, brown sugar, cane sugar, dextrose, fructose, glucose, sucrose, lactose, galactose, maltose, molasses, honey, and others (Bowman 2017). All other sources of free sugars that were not classified as added sugars in the FPED are hereafter referred to as other free sugars and were estimated as follows. First, we examined ingredients listed in the USDA National Nutrient Database for Standard Reference (SR) (Haytowitz et al. 2019), a database that contains all the ingredients that compose complex FNDDS items such as stew or lasagna. SR items such as juices, purées, and pastes of fruits and vegetables were identified and the amount of free sugars contributed by these ingredients to each FNDDS item was calculated using information on the SR ingredient makeup of each FNDDS item. Individuals' consumption of other free sugars was calculated by summing the contributions from each item in their dietary recalls. The percentages of total energy intake from free sugars were calculated for each dietary recall by multiplying grams of free sugars by 4 kilocalories per gram, and then dividing by the total energy intake in the 24-hour recall. Daily percentages were averaged for each participant across two recalls. Descriptive statistics for free sugars (including added and other free sugars) were calculated for the full sample and among aged 2-5, 6-11, and 12-19 years to reflect stages with varying clinical recommendations and practices, as well as changes in children's school attendance and environment.

Categorization of Free Sugars Sources: Intakes of free sugars were also estimated by food source. Intakes of added sugars from the following sources were estimated: beverages (e.g., regular soda, sports drinks, sweetened dairy-based beverages); desserts (e.g., cakes, cookies, pudding, pie); coffee and tea; candy and sugars (e.g., syrups, table sugar, caramels, candy bars, etc.); and other sources (e.g., condiments, crackers, soups). Hereafter, the term "SSBs" is used to refer to beverages containing added sugars. Intakes of other free sugars from two sources were estimated: 100% fruit or vegetable juices, and other sources such as purées and pastes of fruits or vegetables.

Dental Caries: NHANES participants aged 1 year and older were eligible for oral health examinations conducted by calibrated licensed dentists trained in the NHANES protocol with high interrater reliability (Dye et al. 2014). Tooth surfaces were assessed for untreated cavitated-level decay, restorations placed to treat dental caries, and teeth extracted due to dental caries (Center for Health Statistics 2013). Missing primary teeth, which are often difficult to distinguish as exfoliated versus extracted due to dental caries, were scored as unerupted permanent teeth rather than missing teeth. The main outcomes considered in this study, based on typical ages for primary tooth exfoliation and permanent tooth eruption, were the number of primary tooth surfaces that had decay or were filled (dfs) among children aged 2-8 years and the number of decayed, missing, or filled surfaces of permanent teeth (DMFS) among children aged 6-19, as has been done in other NHANES studies (Slade et al. 2018).

Assessment of Covariates: Trained interviewers gathered demographic data from participants 16 years and older, and from proxy respondents for participants <16 years. Educational attainment of the household reference person (an adult household member who owns or rents the residence) was self-reported along with income, which was used to determine the ratio of family income to poverty (PIR). Oral health questionnaires were used to gather data on the time since the participant's last dental visit and frequency of toothbrushing. Frequency of eating or drinking was determined through a count of the distinct eating/drinking occasions in each dietary recall, which was averaged across 2 recalls.

Household Water Fluoride: Household water fluoride was assessed in NHANES 2013-2016 for participants aged ≤19 years who had a water sample collected from their homes. Approximately 10 mL of water was collected from the household tap after allowing the water to run for 5-10 seconds. Samples were stored at 2-8°C until analysis; fluoride concentrations were measured electrometrically using the ion-specific electrode at Georgia Regents University (NHANES 2017).

Statistical Methods: Analyses were performed using SAS version 9.4 (Cary, NC). Descriptive statistics were calculated using SAS PROC SURVEYMEANS to account for the complex survey design of NHANES. Negative binomial regression modeling using the macro %SURVEYGENMOD (Ricardo Da Silva 2017) was used to examine the associations of free sugars with dfs and DMFS. To optimize model fit, free sugars intakes were modeled as the base-2 logarithm of the percentage of energy derived from free sugars. Because each source of free sugars had some non-consumers, the log(x+1) transformation was used. Potential confounders were selected a priori based on knowledge of their relationships with diet and dental caries, and included age, sex, education, PIR, time since last dental visit, toothbrushing frequency, and daily eating occasions. Confounders were retained if they changed the effect estimates for the dietary exposure of interest by at least 10% (VanderWeele 2019). The final list of covariates included age as a continuous variable and race, sex, education, and time since last dental visit using the classifications presented in Table 1. To describe the associations of free sugars with dental caries among participants with differing water fluoride exposures, we constructed models in stratified samples after separating those with water fluoride concentrations that met/exceeded or fell below the CDC-recommended level of 0.7 ppm (U.S. Public Health Service 2015). Due to concerns related to potential limitations in power, we constructed interaction models by adding water fluoride concentration and an interaction term between sugars and fluoride to the models as supplemental analyses. Because we were limited to the existing available data, we did not conduct a power calculation. We followed the STROBE guidelines for our study. A P value of <0.05 was used to determine statistical significance in all analyses.

This work was exempt from review by the institutional review board, as NHANES data are de-identified.

Results

Free sugars intake

Free sugars accounted for a mean of 16.4% of children's energy intake (Table 1). Added sugars were the primary source of free sugars in children's diets, contributing a mean of 13.9% of energy, whereas other free sugars accounted for 2.6% of energy (additional details in Supplemental Table 1). Children from households with the highest PIR and educational attainment consumed slightly less free sugars than others. Intakes of free sugars were generally lower among children who visited the dentist most recently and those who practiced more frequent toothbrushing.

Free sugars accounted for means of 16.0%, 16.4%, and 16.6% of total energy among children aged 2-5, 6-11, and 12-19 years, respectively. With greater age, added sugars contributed more to intake of free sugars whereas other free sugars contributed relatively less. Shifts in beverage consumption across age groups helped explain this pattern, with older children consuming relatively greater amounts of SSBs and relatively less 100% fruit juice than younger groups (Figure 1).

Dental caries experience and household water fluoridation

Mean household water fluoride concentration among children aged 2-19 was 0.50 ppm (standard error, SE: 0.03). In those aged <8 years, mean dfs was 4.08 (SE: 0.41), but higher dfs counts were observed in those with household water fluoride <0.7 ppm (mean: 4.42, SE: 0.49) compared to water fluoride ≥0.7 ppm (mean: 3.24, SE: 0.47) (Table 2). Among all children aged 6-19, mean DMFS was 2.44 (SE: 0.15), and means in the lower and higher household water fluoridation settings were 2.46 (SE: 0.25) and 2.43 (SE: 0.19), respectively.

Associations between free sugars and dental caries

Because unadjusted and adjusted models were similar, we present results of adjusted models only in Table 3. Adjusted models showed that among children aged 2 to 8 years, a doubling in the percentage of energy from free sugars was associated with 22% (95% CI: 1%, 47%) greater dfs counts. A doubling in energy from added sugars was associated with 20% (95% CI: 1%, 42%) greater dfs. Individual sources of added sugars were not significantly associated with dfs, except for beverages. A doubling in the percentage of energy from SSBs was associated with 13% (95% CI: 2%, 25%) greater dfs counts. Intake of other free sugars was not associated with dfs.

A doubling of energy from added sugars or SSBs was associated with 10% (95% CI: 2%, 20%) greater or 6% (95% CI: 1%, 12%) greater DMFS counts in children aged 6-19 years, respectively. Other sources of added sugars and other free sugars were not associated with DMFS.

Impact of household water fluoride on the association between free sugars and dental caries

Among children with household water fluoride <0.7 ppm, a doubling in the percentage of energy from free sugars was associated with 28% (95% CI: 2%, 61%) greater dfs, whereas no significant association was noted among children with water fluoride ≥0.7 ppm (Table 3). This trend was similar and statistically significant for dfs for added sugars and SSBs. Similarly, added sugars, SSBs, and candies were associated with greater DMFS among children aged 6-19 years with lower water fluoride, but not among those with water fluoride ≥0.7 ppm.

Among children with household water fluoride ≥0.7 ppm, neither free sugars nor added sugars were associated with greater dfs or DMFS. However, a doubling in other free sugars from sources excluding

100% fruit juice was associated with reduced DMFS [-32% (95% CI: -48%, -10%)] in children aged 6-19 with household water fluoride ≥0.7 ppm.

In our statistical tests for interaction, greater household water fluoride concentration reduced the associations of both free sugars and added sugars with dfs counts in children aged 2-8 years (p-values for interaction both <0.01) (Supplemental Table 2). Interaction coefficients for other sources of free sugars and in DMFS models were not statistically significant.

Discussion

We found that intake of free sugars, especially in the form of added sugars, was positively associated with dental caries and that SSBs were the sugars source with the most pronounced association. Greater household water fluoride concentration reduced the associations of free sugars with dental caries. Free sugars were associated with increased dfs counts in children with household water fluoride <0.7 ppm but not among those with water fluoride ≥0.7 ppm. Added sugars were associated with greater dfs and DMFS in lower water fluoride settings but not in households with water fluoride ≥0.7 ppm. Our findings suggest that, in the current U.S. dietary context, individual-level exposure to fluoridated water at CDC recommended levels is protective against dental caries among children, especially in the primary dentition.

Most studies that examine the impact of water fluoride on dental caries involve pre-post examination of community water fluoridation (CWF) (Iheozor-Ejiofor et al. 2015). A few recent studies had sufficient variability in water fluoride to examine its impacts within a single cohort. One study linked county-level estimates of CWF coverage with NHANES 1999-2004 and 2011-2014 data and found that CWF was protective against dental caries in U.S. children and adolescents, particularly in the primary dentition (Slade et al. 2018). A study of CWF in Australia also found that fluoride reduced the impact of SSBs on dental caries (Armfield et al. 2013). Our findings, based on household fluoride, a more granular and direct measure, are consistent with these studies.

Our findings are also consistent with a recent systematic review showing a dose-response relationship between SSBs and dental caries, with greater risk among primary compared to permanent dentition (Valenzuela et al. 2021). Our analysis builds on these findings, suggesting that even in the context of recent decreases in SSB consumption in the U.S. (Marriott et al. 2019), free sugars – especially in the form of added sugars and in SSBs – remain an important risk factor for childhood dental caries, and that water fluoridation continues to substantially ameliorate this association.

Our analysis revealed that 100% fruit juices contribute a large portion of all free sugars to the diets of young children. In contrast to added sugars, other free sugars such as those in 100% juice did not appear to increase caries risk in this analysis, possibly related to its content of phytochemicals that may reduce cariogenic bacterial growth (Tabasco et al. 2011). We observed a protective association such that greater intake of other free sugars (excluding 100% juice) was associated with lower DMFS counts in those with higher water fluoride. It is possible that these sugars, often derived from items such as tomato paste and fruit purée, are consumed as part of complex dishes containing other foods and components that could protect against dental caries. For example, milk and yogurt may promote favorable (dental caries-protective) changes in the oral biofilm microbiota (Anderson et al. 2020).

This study has several strengths. Few studies have examined the association between free sugars and dental caries in the U.S. during recent years in which intakes of added sugars have declined. Energy intake from SSBs among U.S. children aged 2-19 years declined by more than 50% between 2003-2004 and 2015-2016 (from 211 kcal/day [SE: 8] to 94 kcal/day [SE: 3]) (Marriott et al. 2019). Additionally, many studies have used simple dietary screeners (Park et al. 2015) or food frequency questionnaires (Vega-López et al. 2018) to estimate intake of particular foods (e.g., SSBs) or total sugars, or have been limited to a single 24-hour dietary recall (Heller et al. 2001). Others have used multiple 24-hour recalls (Welsh et al. 2018), but have not examined specific types of sugars or estimated free sugars. Leveraging the detailed nutritional data from NHANES, we were able to provide specific estimates of free sugars intake overall and by source.

Limitations include the cross-sectional design of NHANES. We do not know the duration or consistency of exposure to the measured water fluoride levels. However, it seems unlikely that length of time living at the residence would differ by household fluoride concentrations. We do not know if children's reported diets were reflective of their usual intake during the period in which dental caries may have developed. The NHANES dietary data collection procedures, which utilize two 24-hour dietary recalls, have been extensively studied and validated (Ahluwalia et al. 2016), yet a series of three 24-hour recalls has been shown to be a preferred method to estimate total energy intake in young children (Burrows et al. 2010). Our study was limited to NHANES data from 2013-2016 since these were the only years in which household water fluoride concentrations were measured.

Sugars are the primary driver of dental caries (Sheiham and James 2013). We found that though free sugars were associated with dfs, this appeared to be driven primarily by added sugars. Therefore, for the prevention of dental decay, it may be most efficacious to continue focusing on interventions and/or policies that reduce intakes of added sugars. Stricter guidance, such as the conditional recommendation of the WHO to limit the intake of free sugars to no more than 5% of energy intake (World Health Organization 2015) may support this goal. Our findings exist even given the recent trends of decreasing sugars intake and a decrease in childhood dental caries (Centers for Disease Contron and Prevention 2019). Importantly, U.S. children continue to consume excessive free and added sugars, and reduction of sugars intake must remain a key priority for dental caries prevention. This study provides evidence that in the U.S., household water fluoridation at CDC-recommended levels protects against the cariogenic potential of free and added sugars during childhood.

Acknowledgements: This research received no specific grant from any funding agency. The authors declare no potential conflicts of interest with respect to the authorship and/or publication of this article.

Author contributions: MM Melough contributed to conception, design, data acquisition, analysis, and interpretation, and drafted and critically revised the manuscript. S Sathyanarayana contributed to conception, data analysis and interpretation, and critically revised the manuscript. FV Zohoori, HC Gustafsson, EL Sullivan, and DL Chi contributed to design, analysis, interpretation, and critically revised the manuscript. SM Levy contributed to interpretation and critically revised the manuscript. CM McKinney contributed to conception, design, data acquisition, analysis, and interpretation, and drafted and critically revised the manuscript. All authors gave their final approval and agree to be accountable for all aspects of the work.

Figure Titles:

Figure 1. Dietary sources of free sugars intake among U.S. children by age group.

References

Ahluwalia N, Dwyer J, Terry A, Moshfegh A, Johnson C. 2016. Update on NHANES Dietary Data: Focus on Collection, Release, Analytical Considerations, and Uses to Inform Public Policy. Adv Nutr. 7(1):121–134. doi:10.3945/an.115.009258. https://academic.oup.com/advances/article/7/1/121/4524042.
Anderson AC, Rothballer M, Altenburger MJ, Woelber JP, Karygianni L, Vach K, Hellwig E, Al-Ahmad A. 2020. Long-Term Fluctuation of Oral Biofilm Microbiota following Different Dietary Phases. Appl Environ Microbiol. 86(20):e01421-20.
Armfield JM, Spencer AJ, Roberts-Thomson KF, Plastow K. 2013. Water fluoridation and the association of sugar-sweetened beverage consumption and dental caries in Australian children. Am J Public Health. 103(3):494–500. doi:10.2105/AJPH.2012.300889.
Benjamin RM. 2010. Oral Health: The Silent Epidemic. Public Health Rep. 125(2):158–159. doi:10.1177/003335491613100202.
Blanton CA, Moshfegh AJ, Baer DJ, Kretsch MJ. 2006. The USDA Automated Multiple-Pass Method accurately estimates group total energy and nutrient intake. J Nutr. 136(10):2594–9. doi:136/10/2594 [pii]. http://www.ncbi.nlm.nih.gov/pubmed/16988132.
Bowman SA. 2017. Added sugars: Definition and estimation in the USDA Food Patterns Equivalents Databases. J Food Compos Anal. 64(July):64–67. doi:10.1016/j.jfca.2017.07.013.
Bowman SA, Clemens JC, Thoerig RC, Friday JE, Shimizu M, Moshfegh AJ. 2013. Food Patterns Equivalents Database 2009-10 : Methodology and User Guide [Online]. (September). http://www.ars.usda.gov/ba/bhnrc/fsrg.
Bui AL, Dieleman JL, Hamavid H, Birger M, Chapin A, Duber HC, Horst C, Reynolds A, Squires E, Chung PJ, et al. 2017. Spending on children's personal health care in the United States, 1996-2013. JAMA Pediatr. 171(2):181–189. doi:10.1001/jamapediatrics.2016.4086.
Burrows TL, Martin RJ, Collins CE. 2010. A Systematic Review of the Validity of Dietary Assessment Methods in Children when Compared with the Method of Doubly Labeled Water. J Am Diet Assoc. 110(10):1501–1510. doi:10.1016/j.jada.2010.07.008. http://dx.doi.org/10.1016/j.jada.2010.07.008.
Center for Health Statistics N. 2013. Oral Health Examiners Manual 2013. https://wwwn.cdc.gov/nchs/data/nhanes/2013-2014/manuals/Oral_Health_Examiners.pdf.
Centers for Disease Contron and Prevention. 2019. Trends in Dental Caries and Sealants, Tooth Retention, and Edentulism, United States. www.cdc.gov/oralhealth.
Chankanka O, Levy SM, Marshall TA, Cavanaugh JE, Warren JJ, Broffitt B, Kolker JL. 2015. The associations between dietary intakes from 36 to 60 months of age and primary dentition non-cavitated caries and cavitated caries. J Public Health Dent. 75(4):265–273. doi:10.1111/j.1752-7325.2012.00376.x.
Dye BA, Li X, Lewis BG, Iafolla T, Beltran-Aguilar ED, Eke PI. 2014. Overview and quality assurance for the oral health component of the National Health and Nutrition Examination Survey (NHANES), 2009-2010. J Public Health Dent. 74(3):248–256. doi:10.1111/jphd.12056.
Ghazal T, Levy SM, Childers NK, Broffitt B, Cutter GR, Wiener HW, Kempf MC, Warren J, Cavanaugh JE. 2015. Factors associated with early childhood caries incidence among high caries-risk children. Community Dent Oral Epidemiol. 43(4):366–374. doi:10.1111/cdoe.12161.
Haytowitz DB, Ahuja JKC, Wu Z, Somanchi M, Nickle M, Nguyen QA, Roseland JM, Williams JR, Patterson KY, Li Y, et al. 2019. USDA National Nutrient Database for Standard Reference, Legacy Release. Nutr Data Lab Beltsv Hum Nutr Res Center, ARS, USDA. [accessed 2021 Jul 1]. https://data.nal.usda.gov/dataset/usda-national-nutrient-database-standard-reference-legacy-release.
Heller KE, Burt BA, Eklund SA. 2001. Sugared soda consumption and dental caries in the United States. J Dent Res. 80(10):1949–1953. doi:10.1177/00220345010800101701.
Iheozor-Ejiofor Z, O'Malley LA, Glenny AM, Macey R, Alam R, Tugwell P, Walsh T, Welch V, Worthington H V. 2015. Water fluoridation for the prevention of dental caries. Cochrane Database Syst Rev. 2015(6):CD010856. doi:10.1002/14651858.CD010856.

Jensen ME, Donly K, Wefel JS. 2000. Assessment of the Effect of Selected Snack Foods on the Remineralization/Demineralization of Enamel and Dentin. J Contemp Dent Pract. 1(3):1–12.
Liska DA, Kelley M, Mah E. 2019. 100% fruit juice and dental health: A systematic review of the literature. Front Public Heal. 7(190). doi:10.3389/fpubh.2019.00190.
Marriott BP, Hunt KJ, Malek AM, Newman JC. 2019. Trends in intake of energy and total sugar from sugar-sweetened beverages in the United States among children and adults, NHANES 2003-2016. Nutrients. 11(9):1–13. doi:10.3390/nu11092004.
Marshall TA, Levy SM, Broffitt B, Warren JJ, Eichenberger-Gilmore JM, Burns TL, Stumbo PJ. 2003. Dental caries and beverage consumption in young children. Pediatrics. 112(3):e184–e191. doi:10.1542/peds.112.3.e184.
Moynihan PJ, Kelly SAM. 2014. Effect on caries of restricting sugars intake: Systematic review to inform WHO guidelines. J Dent Res. 93(1):8–18. doi:10.1177/0022034513508954.
NHANES. 2017. NHANES 2015-2016 Laboratory Procedure Manual: Water Fluoride. https://wwwn.cdc.gov/nchs/data/nhanes/2015-2016/labmethods/FLDEW_I_MET.pdf.
Park S, Lin M, Onufrak S, Li R. 2015. Association of Sugar-Sweetened Beverage Intake during Infancy with Dental Caries in 6-year-olds. Clin Nutr Res. 4(1):9–17. doi:10.7762/cnr.2015.4.1.9.
Pitts NB, Zero DT, Marsh PD, Ekstrand K, Weintraub JA, Ramos-Gomez F, Tagami J, Twetman S, Tsakos G, Ismail A. 2017. Dental caries. Nat Rev Dis Prim. 3(May):1–16. doi:10.1038/nrdp.2017.30.
Ricardo Da Silva A. 2017. %SURVEYGENMOD Macro: An Alternative to Deal with Complex Survey Design for the GENMOD Procedure. SAS Tech Pap.:1–28. [accessed 2021 Jun 10]. https://support.sas.com/resources/papers/proceedings17/0268-2017.pdf.
Sheiham A, James WPT. 2013. A new understanding of the relationship between sugars, dental caries and fluoride use: Implications for limits on sugars consumption. Public Health Nutr. 17(10):2176–2184. doi:10.1017/S136898001400113X.
Slade GD, Grider WB, Maas WR, Sanders AE. 2018. Water Fluoridation and Dental Caries in U.S. Children and Adolescents. J Dent Res. 97(10):1122–1128. doi:10.1177/0022034518774331. https://doi.org/10.1177/0022034518774331.
Swan GE, Powell NA, Knowles BL, Bush MT, Levy LB. 2018. A definition of free sugars for the UK. Public Health Nutr. 21(9):1636–1638. doi:10.1017/S136898001800085X.
Tabasco R, Sánchez-Patán F, Monagas M, Bartolomé B, Victoria Moreno-Arribas M, Peláez C, Requena T. 2011. Effect of grape polyphenols on lactic acid bacteria and bifidobacteria growth: Resistance and metabolism. Food Microbiol. 28(7):1345–1352. doi:10.1016/j.fm.2011.06.005. http://dx.doi.org/10.1016/j.fm.2011.06.005.
U.S. Department of Agriculture, U.S. Department of Health and Human Services. 2020. Dietary Guidelines for Americans, 2020-2025. 9th Edition. https://www.dietaryguidelines.gov/sites/default/files/2020-12/Dietary_Guidelines_for_Americans_2020-2025.pdf.
U.S. Public Health Service. 2015. U.S. Public Health Service Recommendation for Fluoride Concentration in Drinking Water for the Prevention of Dental Caries. Public Health Rep. 130(August):318–331.
USDA. 2021. FNDDS Documentation and Databases. Food Surv Res Gr Beltsville, MD. [accessed 2018 Nov 3]. https://www.ars.usda.gov/northeast-area/beltsville-md-bhnrc/beltsville-human-nutrition-research-center/food-surveys-research-group/docs/fndds-download-databases/.
Valenzuela MJ, Waterhouse B, Aggarwal VR, Bloor K, Doran T. 2021. Effect of sugar-sweetened beverages on oral health: a systematic review and meta-analysis. Eur J Public Health. 31(1):122–129. doi:10.1093/eurpub/ckaa147.
VanderWeele TJ. 2019. Principles of confounder selection. Eur J Epidemiol. 34(3):211–219. doi:10.1007/s10654-019-00494-6. https://doi.org/10.1007/s10654-019-00494-6.
Vega-López S, Lindberg NM, Eckert GJ, Nicholson EL, Maupomé G. 2018. Association of added sugar

intake and caries-related experiences among individuals of Mexican origin. Community Dent Oral Epidemiol. 46(4):376–384. doi:10.1111/cdoe.12378.
Welsh JA, Wang Y, Figueroa J, Brumme C. 2018. Sugar intake by type (added vs. naturally occurring) and physical form (liquid vs. solid) and its varying association with children's body weight, NHANES 2009–2014. Pediatr Obes. 13(4):213–221. doi:10.1111/ijpo.12264.
World Health Organization. 2015a. Guideline: Sugars intake for adults and children. https://www.who.int/publications/i/item/9789241549028.
World Health Organization. 2015b. Information note about intake of sugars recommended in the WHO guideline for adults and children. :1–6. https://www.who.int/nutrition/publications/guidelines/sugar_intake_information_note_en.pdf.

Table 1. Mean intakes of free sugars as a percentage of total energy intake among U.S. children 2-19 years of age, NHANES 2013-2016

		Free Sugars (all)[1] (% energy intake)		Added Sugars (% energy intake)		Other Free Sugars (% energy intake)	
	n	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**
All	4906	16.4	0.2	13.9	0.2	2.6	0.1
Sex							
Male	2456	16.7	0.2	14.1	0.3	2.6	0.1
Female	2450	16.2	0.3	13.6	0.2	2.6	0.1
Race and Ethnicity							
Hispanic	1635	15.5	0.3	12.7	0.3	2.9	0.1
Non-Hispanic White	1355	16.8	0.3	14.5	0.3	2.3	0.1
Non-Hispanic Black	1172	18.1	0.3	14.9	0.3	3.3	0.2
Non-Hispanic Asian	420	12.2	0.3	10.1	0.3	2.0	0.2
Other Race or Multiracial	324	16.5	0.7	13.8	0.8	2.7	0.3
Age Group							
2-5 years	1072	16.0	0.4	11.8	0.2	4.1	0.2
6-11 years	1730	16.4	0.2	13.8	0.2	2.6	0.1
12-19 years	2104	16.6	0.3	14.8	0.3	1.8	0.1
Education level[2]*							
HS graduate or less	2206	16.7	0.3	14.1	0.3	2.6	0.1
Some college or AA degree	1487	17.0	0.3	14.4	0.3	2.6	0.1
College graduate or above	1074	15.7	0.4	13.1	0.4	2.6	0.2
Poverty Income Ratio[3]**							
PIR < 1.3	2009	16.7	0.2	13.8	0.3	2.8	0.1
PIR ≥ 1.3 and < 1.85	632	16.5	0.5	14.1	0.5	2.4	0.2
PIR ≥ 1.85 and < 3.5	1001	16.8	0.3	14.3	0.3	2.5	0.2
PIR ≥ 3.5	909	16.1	0.4	13.6	0.4	2.5	0.2
Meal Frequency							
≤ 3 per day	370	16.2	0.5	14.2	0.5	2.1	0.2
> 3 and ≤ 5 per day	2360	16.1	0.2	13.7	0.2	2.4	0.1
> 5 and ≤ 7 per day	1810	16.6	0.3	13.9	0.3	2.7	0.1
> 7 per day	366	18.0	0.7	14.7	0.6	3.3	0.2
Survey Cycle							
2013-14	2582	17.1	0.2	14.4	0.2	2.6	0.1
2015-16	2324	15.8	0.3	13.3	0.3	2.5	0.2
Toothbrushing frequency**							
< once per day	62	17.4	0.9	15.6	1.0	1.8	0.5
once per day	1435	17.5	0.4	15.3	0.4	2.2	0.1
twice per day	2710	16.0	0.2	13.5	0.2	2.5	0.1
> twice per day	314	15.7	0.6	12.7	0.7	2.9	0.3
Time since last dental visit*							
≤ 6 months	3006	16.3	0.2	13.8	0.2	2.5	0.1
> 6 months and ≤ 1 year	837	16.8	0.4	14.3	0.4	2.5	0.1
> 1 year	664	16.8	0.5	14.5	0.6	2.3	0.2
Never	383	15.7	0.5	12.1	0.5	3.6	0.3

HS, high school; AA, Associate in Arts; PIR, poverty income ratio.

[1]Free sugars include all added sugars and all sugars naturally present in honey, syrups, and fruit and vegetable juices, purées, and similar extruded products.
[2]Education level refers to educational attainment of the head of household.
[3]Poverty income ratio (PIR) was defined as the ratio of the reported family income to the poverty threshold, calculated based on the poverty guidelines of the Department of Health and Human Services and accounting for family size, year, and state.
*Variable missing data for <5% of sample.
**Variable missing data for 5% to 10% of sample.

Table 2. Unadjusted mean caries experience among U.S. children ages 2-19 overall and according to level of household water fluoride concentration, NHANES 2013-2016 (total n = 4649[1])

	dfs among children ages 2-8		DMFS among children ages 6-19	
	n	Mean (SE)	n	Mean (SE)
Overall	1837	4.08 (0.41)	3634	2.44 (0.15)
Household water fluoride <0.7 ppm	1261	4.42 (0.49)	2536	2.46 (0.25)
Household water fluoride ≥0.7 ppm	576	3.24 (0.47)	1098	2.43 (0.19)

[1]822 children ages 6-8 years included in both dfs and DMFS analyses due to mixed dentition in this age range.

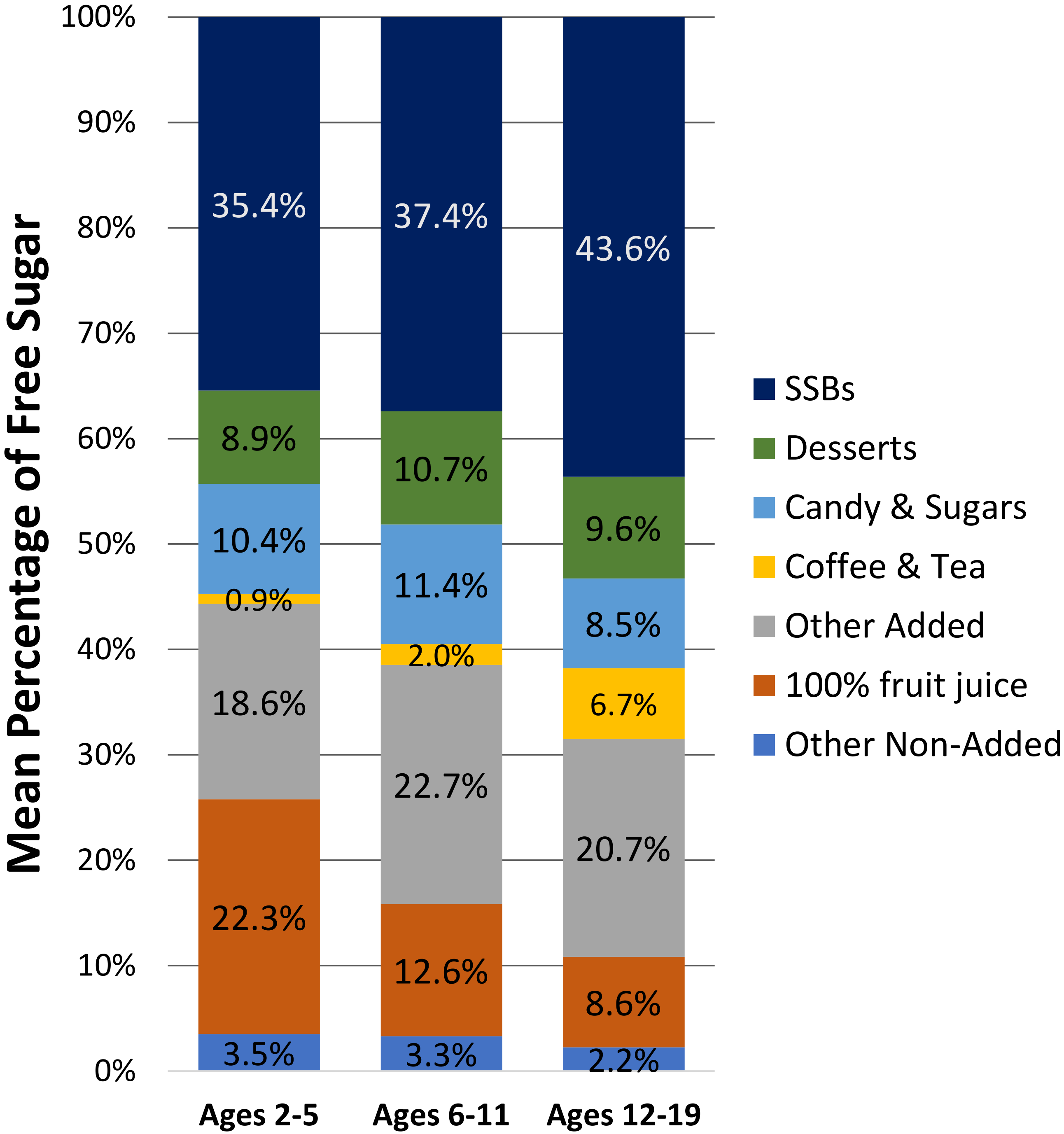
Table 3. Expected change in dfs and DMFS counts (with 95% confidence intervals) for a doubling in the percentage of energy intake from free sugars or major sources of free sugars in U.S. children by age group and household water fluoride concentration[1]

	dfs among children ages 2-8			DMFS among children ages 6-19		
	all (n = 1837)	<0.7 ppm F (n = 1261)	≥0.7 ppm F (n = 576)	all (n = 3634)	<0.7 ppm F (n = 2536)	≥0.7 ppm F (n = 1098)
Free Sugars (all)	**22% (1%, 47%)**	**28% (2%, 61%)**	8% (-24%, 54%)	6% (-4%, 16%)	10% (-2%, 25%)	-1% (-16%, 17%)
Added Sugars	**20% (1%, 42%)**	**26% (4%, 53%)**	-3% (-32%, 37%)	**10% (2%, 20%)**	**16% (5%, 31%)**	-2% (-15%, 14%)
SSBs	**13% (2%, 25%)**	**18% (4%, 32%)**	0% (-18%, 22%)	**6% (1%, 12%)**	**7% (1%, 15%)**	4% (-6%, 15%)
Desserts	-4% (-14%, 8%)	-6% (-17%, 7%)	4% (-17%, 30%)	2% (-4%, 8%)	0% (-6%, 8%)	5% (-6%, 18%)
Candy & Sugars	7% (-5%, 20%)	6% (-7%, 21%)	4% (-19%, 34%)	7% (0%, 15%)	**8% (1%, 14%)**	11% (-1%, 24%)
Coffee & Tea	11% (-11%, 38%)	10% (-14%, 41%)	9% (-32%, 73%)	7% (-1%, 15%)	6% (-2%, 16%)	7% (-8%, 23%)
Other added	-2% (-17%, 16%)	0% (-17%, 22%)	16% (-19%, 66%)	8% (-1%, 17%)	9% (-2%, 21%)	6% (-8%, 23%)
Other Free Sugars	0% (-9%, 10%)	-2% (-13%, 10%)	15% (-5%, 40%)	3% (-3%, 10%)	7% (-1%, 16%)	-6% (-16%, 6%)
100% fruit juice	4% (-5%, 14%)	2% (-8%, 13%)	18% (-2%, 41%)	6% (0%, 13%)	10% (2%, 18%)	-1% (-11%, 10%)
Other non-added	-16% (-33%, 5%)	-12% (-32%, 14%)	-14% (-45%, 36%)	-12% (-23%, 2%)	-5% (-17%, 12%)	**-32% (-48%, -10%)**

dfs, decayed filled surfaces in primary dentition; DFMS, decayed, filled, missing surfaces in permanent dentition; SSB, sugar-sweetened beverage.

[1]Models adjusted for sex, age, head of household education (high school or less, some college or Associate in Arts, college grad or above), race (Hispanic, Non-Hispanic White, Non-Hispanic Black, Non-Hispanic Asian, Other or Multiracial), and time since last dental visit (>1 year, 6 months to 1 year, <6 months, never).

Bolded values represent findings with p-values <0.05.


Mean Percentage of Free Sugar
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
35.4%
8.9%
10.4%
0.9%
18.6%
22.3%
3.5%
37.4%
10.7%
11.4%
2.0%
22.7%
12.6%
3.3%
43.6%
9.6%
8.5%
6.7%
20.7%
8.6%
2.2%
Ages 2-5
Ages 6-11
Ages 12-19
SSBs
Desserts
Candy & Sugars
Coffee & Tea
Other Added
100% fruit juice
Other Non-Added

Supplemental Material

Impact of fluoride on associations between free sugars intake and dental caries in U.S. children

Melissa M. Melough, Sheela Sathyanarayana, Fatemeh Vida Zohoori, Hanna C. Gustafsson, Elinor L. Sullivan, Donald L. Chi, Steven M. Levy, Christy M. McKinney

Supplemental Table 1. Distributions of energy (in kilocalories) and free sugars intakes (in percentage of total energy intake) among U.S. children 2-19 years of age, NHANES 2013-2016

	% consumers	Mean	SE	Minimum	Maximum
Energy	100.0%	1838	21	264	6364
Free Sugars (all)	100.0%	16.4	0.17	0.0	61.5
Added Sugars	99.9%	13.9	0.18	0.0	61.4
SSBs	92.4%	6.8	0.17	0.0	57.7
Desserts	59.9%	1.6	0.05	0.0	21.9
Candy & Sugars	63.5%	1.6	0.06	0.0	34.0
Coffee & Tea	16.3%	0.6	0.08	0.0	60.1
Other added	99.6%	3.4	0.09	0.0	21.9
Other Free Sugars	93.7%	2.6	0.10	0.0	35.0
100% fruit juice	52.0%	2.1	0.10	0.0	34.6
Other non-added	83.6%	0.5	0.02	0.0	16.0

SSB, sugar-sweetened beverage.

Supplemental Table 2. Interaction coefficient estimates for the interactions of free sugars intake with water fluoride concentrations in models of dfs and DMFS counts among U.S. children[1]

	dfs among children ages 2-8		**DMFS among children ages 6-19**	
	Estimated Interaction Coefficient (SE)	**P-value**	**Estimated Interaction Coefficient (SE)**	**P-value**
Free Sugars (all)	**-0.56 (0.22)**	**0.01**	-0.01 (0.13)	0.91
Added Sugars	**-0.51 (0.19)**	**0.01**	-0.05 (0.11)	0.57
SSBs	-0.24 (0.13)	0.05	-0.03 (0.07)	0.65
Desserts	0.19 (0.14)	0.16	0.11 (0.08)	0.18
Candy & Sugars	-0.23 (0.16)	0.15	-0.10 (0.08)	0.22
Coffee & Tea	-0.04 (0.32)	0.91	-0.04 (0.10)	0.70
Other added	-0.26 (0.23)	0.27	-0.13 (0.11)	0.23
Other Free Sugars	0.01 (0.12)	0.96	-0.11 (0.09)	0.19
100% fruit juice	0.03 (0.11)	0.77	-0.11 (0.08)	0.18
Other non-added	-0.45 (0.26)	0.08	-0.38 (0.21)	0.07

SSB, sugar-sweetened beverage.

[1]Models included terms for sex, age, head of household education (high school or less, some college or Associate in Arts, college grad or above), race (Hispanic, Non-Hispanic White, Non-Hispanic Black, Non-Hispanic Asian, Other or Multiracial), time since last dental visit (>1 year, 6 months to 1 year, <6 months, never), water fluoride concentration, percentage of energy from the given free sugar category, and interaction of free sugar with water fluoride concentration. Interaction coefficients represent the dependence of the sugar-caries relationship on fluoride concentration, with negative coefficients suggesting a reduced DMFS or dfs count associated with a given free sugar intake as fluoride concentration is increased.

p-values <0.05 shown in bold.