


## RESEARCH ARTICLE


# Total added sugar consumption is not significantly associated with risk for prediabetes among U.S. adults: National Health and Nutrition Examination Survey, 2013–2018

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**Data Availability Statement:** Data used for this study are publicly available at the NHANES website at <https://wwwn.cdc.gov/nchs/nhanes/> and the SAS macros used for the National Cancer Institute (NCI) method are available at the NCI website <https://epi.grants.cancer.gov/diet/usualintakes/macros.html>.

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## Abstract

Prediabetes affects 38% of U.S. adults and is primarily linked to added sugars consumed from sugar-sweetened beverages. It is unclear if total dietary intake of added sugar also increases the risk for prediabetes. This study examined if total (g/day) and percent intakes of <10%, 10–15%, or >15% added sugar increase the odds for prediabetes in U.S. adults. A cross-sectional, secondary analysis using 2013–2018 NHANES data was conducted. This study included data from U.S. adults  $\geq 20$  years with normoglycemia ( $N = 2,154$ ) and prediabetes ( $N = 3,152$ ) with 1–2 days of dietary recall information. Prediabetes was defined as a hemoglobin A1c of 5.7%–6.4% or a fasting plasma glucose of 100–125 mg/dL. Survey-weighted logistic regression was used to estimate odds ratios of prediabetes based on usual intakes of added sugar (total and percent intakes) using the National Cancer Institute Method. Differences in prediabetes risk and total and percent intakes of added sugar were compared by race/ethnicity. The sample's total energy intake from added sugar was 13.9%. Total (unadjusted: OR: 1.01, 95% CI: .99–1.00,  $p = .26$ ; adjusted: OR: 1.00, 95% CI: .99–1.00,  $p = .91$ ) and percent intakes of added sugar (unadjusted [ $<10\%$ : (ref); 10–15%: OR: .93, 95% CI: .77–1.12,  $p = .44$ ;  $>15\%$ : OR: 1.03, 95% CI: .82–1.28,  $p = .82$ ] and adjusted [ $<10\%$ : (ref); 10–15%: OR: .82, 95% CI: .65–1.04,  $p = .09$ ;  $>15\%$ : OR: .96, 95% CI: .74–1.24,  $p = .73$ ]) were not significantly associated with an increased odds of prediabetes. Prediabetes risk did not differ by race/ethnicity for total (unadjusted model [ $p = .65$ ]; adjusted model [ $p = .51$ ]) or percent (unadjusted model [ $p = .21$ ]; adjusted model [ $p = .11$ ]) added sugar intakes. In adults  $\geq 20$  years with normoglycemia and prediabetes, total added sugar

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consumption did not significantly increase one's risk for prediabetes and risk estimates did not differ by race/ethnicity. Experimental studies should expand upon this work to confirm these findings.

## Introduction

Prediabetes is a relatively asymptomatic, but serious medical condition characterized by insulin resistance and intermittent hyperglycemia [1] that affects approximately 96 million U.S. adults [2] and is a precursor to type 2 diabetes (T2D) [1]. Significant disparities in the prevalence of prediabetes are observed among minority populations, particularly for non-Hispanic Black, and Hispanic adults, in comparison to non-Hispanic White adults (32%, 35.3% vs 31%, respectively) [3]. Prediabetes can be largely prevented with lifestyle modifications that include diet change [4, 5]. Yet, roughly 70% of adults with prediabetes will go on to develop T2D within their lifetime [6, 7]. Increased consumption of carbohydrates have been implicated in the rising incidence of T2D [8]. During the late 1970s [9] the first published U.S. Dietary Guidelines began encouraging reductions to dietary fat (i.e., 40% to 30% calories/day) while increasing carbohydrate intake to 55% - 60% calories/day [10]. In line with this change, food manufacturers began substituting carbohydrates in lieu of fats, largely in the form of added sugars across a multitude of foods and beverages [11], which have become a mainstay of the current U.S. diet [12]. This shift paralleled a drastic rise in obesity and diabetes rates across the 1980s and 1990s [13], a trend which persist today [14, 15].

Current dietary guidelines recommend consuming 10% or less of one's daily calories from added sugars, yet the average American consumes around 270 calories per day (~13% of one's daily calories) [16]. Added sugars, which are caloric sweeteners added to foods and beverages during processing, preparation, or prior to consumption [11], include forms such as sucrose, used predominately in solid foods, and high-fructose corn (HFCS), used predominately in sugar-sweetened beverages (SSBs) [17]. Large cohort studies have consistently found a significant positive correlation between SSB consumption and T2D risk that is often dose dependent with greater consumption associated with a higher risk for T2D [18–21]. Research suggests that chronic consumption of diets high in added sugar (i.e., ~15–25% total energy intake) [22] are primarily responsible for T2D risk [23, 24] and are independent of total energy intake or body mass index (BMI) [24–27]. However, studies assessing the relationships between added sugar consumption and prediabetes are limited with most having used added sugar proxies (i.e., SSBs, HFCS, and fructose-sweetened beverages) instead of assessing total intake from all dietary sources (i.e., foods and beverages) [24, 28–37].

Also of concern is that minority populations demonstrate significant health disparities in obesity and T2D prevalence in comparison to non-Hispanic White individuals [3, 38]. Moreover, consumption of a high carbohydrate diet in minority populations (i.e., non-Hispanic Black adults) has been shown to promote an exaggerated insulin response that occurs independent of overweight/obesity status [39]. Non-Hispanic Black adults consume the greatest quantities of added sugar followed by non-Hispanic White adults, Hispanic adults, and non-Hispanic Asian adults (19 teaspoons (tsp), 17 tsp, 16 tsp, and 10 tsp respectively) [40] raising the question as to whether differences in dietary intake from added sugar may contribute to these health disparities.

To date, no studies have examined if total dietary intake of added sugar increases the risk for prediabetes and if so, how much (e.g., >15% total caloric intake) may be responsible for

the increased risk observed. Also, it is unclear whether added sugar uniquely influences the risk for prediabetes by race and ethnicity, particularly among those that consume high quantities of added sugar (i.e., non-Hispanic Black adults). Therefore, the main objective of this study was to examine whether total added sugar consumption was associated with prediabetes in a large nationally representative sample of U.S. adults  $\geq 20$  years. Second, this study examined if total added sugar consumption, as a percentage of total energy intake ( $< 10\%$ ,  $10\text{--}15\%$ ,  $> 15\%$ ), was associated with differing risk probabilities for prediabetes. Last, this study assessed if the associations between total and percent intakes of added sugar and prediabetes risk differed by race/ethnicity. The study's guiding a priori hypothesis was that positive associations between total and percent added sugar intakes and prediabetes risk would be observed, including greater risk at higher added sugar intakes (e.g.,  $> 15\%$  total energy), and that significant risk differences would be observed by race/ethnicity with increased risk among high T2D risk groups.

## Materials and methods

### Study design

This study used data from the National Health and Nutrition Examination Survey (NHANES) which is a repeated cross-sectional survey that employs a complex, multistage, probability sampling design to collect health and nutrition information from  $\sim 5,000$  noninstitutionalized U.S. civilians (age 0 years and older) annually [41, 42]. NHANES is supported by the National Center for Health Statistics (NCHS) and Centers for Disease Control and Prevention [43]. Specific details about the design and operations of NHANES, including sampling and data collection procedures, have been previously described elsewhere [42, 44]. A cross-sectional analysis was conducted and included data collected from NHANES respondents  $\geq 20$  years during the 2013–2014, 2015–2016, and 2017–2018 NHANES cycles. NHANES study protocols are approved by the NCHS Research Ethics Review Board [45] and are compliant with the Health and Human Services Policy for Protection of Human Research Subjects (45 CFR part 46) [42, 46]. Only de-identified, publicly-available data were analyzed, therefore the study was designated as 'Not Human Subjects Research' by the University of Alabama at Birmingham [47].

### Analytic sample

The analytic sample included respondents  $\geq 20$  years of age with fasting plasma glucose (FPG) or Hemoglobin A1c (HbA1c) defined prediabetes or normoglycemia. Details about NHANES data collection processes and prediabetes classification and laboratory procedures are described in the supporting information file (S1 Appendix in [S1 File](#)). Respondents represented the following NHANES racial and Hispanic origin groups: Hispanic (including Mexican American and other Latino populations), non-Hispanic Black, non-Hispanic White, Asian American, and Other Race which included persons not self-identifying with any of the prior categories. Appropriate sampling weights were applied to all analyses to account for the complex survey design and to ensure representativeness of the NHANES sample which includes non-institutionalized U.S. civilians [48]. The initial weighted sample (taken from the fasting subsample) [44] included a total of 5,888 respondents  $\geq 20$  years of age that excluded pregnant and lactating women ( $n = 115$ ) and those taking insulin or diabetic medications ( $n = 963$ ). An additional 167 respondents with T2D having either a HbA1c  $\geq 6.5\%$  (48 mmol/mol) or a FPG  $\geq 126$  mg/dL (7.0 mmol/L) were excluded resulting in 5,721 adults. Next, 415 adults were excluded due to not having at least 1 day of dietary recall information that contained a value for added sugar. The final sample included 5,306 adults with 3,152 respondents identified as having prediabetes (HbA1c 5.7% - 6.4% [39–47 mmol/mol] and FPG 100–125 mg/dL [5.6–6.9

mmol/L]) and 2,154 identified as having normoglycemia (HbA1c <5.7% [ $<39$  mmol/mol] and FPG <100 mg/dL [ $<5.6$  mmol/L]).

### Dietary intake assessment

Dietary intake data, including added sugars and total calories, were collected for the dietary assessment component of NHANES which uses the 24-hour dietary recall method [49]. Diet recalls are pre-announced and performed by trained interviewers using the validated U.S. Department of Agriculture's Automated Multiple-Pass Method (AMPM) previously described elsewhere [42, 49]. The first diet recall is administered in-person during the mobile examination center visit (on either weekdays or weekends) and the second is administered over the phone 3–10 days later [42].

Added sugars are defined as sugars, syrups, fruit juice concentrates, or caloric sweeteners added during processing, preparation, or prior to food and beverage consumption that exclude natural sugars present in dairy and fruit (including whole fruit and 100% fruit juice) [50]. Estimates for added sugar were obtained from the Food Patterns Equivalents Database (FPED) of the Food and Nutrient Database for Dietary Studies [51]. Added sugars were reported in teaspoon equivalents consumed per subject, per day calculated from foods/beverages [50]. Total calories from day 1 and day 2 dietary recalls were obtained from the NHANES nutrient intake files and were reported in kilocalories (kcal). The FPED files were merged with NHANES total nutrient intake files to combine estimates for added sugar and total calories. For this study, to reflect updates to nutrition facts labeling [52], added sugar was converted from teaspoon equivalents to grams (1 teaspoon equivalent = 4.2 grams) and from grams to calories (1 gram = 4 kilocalories) for day 1 and day 2 dietary recalls before the final dataset merge [52, 53]. Once all 2013–2018 data files were merged, percent intake was calculated by dividing grams of added sugar by total calories which was categorized into three groups (<10%, 10–15%, and >15%). The groups represent dietary guideline recommendations (<10%), average U.S. intake (~13%), and above average intake (>15%) respectively [16].

### Statistical analysis

All analyses were performed using SAS Studio version 3.8, Enterprise Edition [54]. NHANES analytic guidelines [44] were followed using SAS procedures [55] appropriate for complex survey designs. Survey data from 2013–2014, 2015–2016, and 2017–2018 were combined and appropriate sampling weights (from the fasting subsample WTSAF2YR) were created for the combined dataset and applied to all models prior to analyses to account for differential nonresponse and planned oversampling of certain subgroups [44]. Data on characteristics were reported using means and standard errors for continuous variables and percentages and standard errors for categorical variables. Characteristics were reported for the overall sample and by normoglycemia or prediabetes status. Rao Scott chi square tests were used to examine differences in sample characteristics for categorical variables by normoglycemia and prediabetes status. Ordinary least squares regression was used to examine differences in sample characteristics for continuous variables by normoglycemia and prediabetes status.

The National Cancer Institute (NCI) method [56, 57] was used to estimate usual intake of added sugar and total caloric intake using day one and day two 24-hour dietary recall data. The NCI method requires two or more dietary recalls on nonconsecutive days for a random subset of the population to account for between- and within-person variation in intake and can be used to correct for measurement error when estimating usual intake of nutrients [56]. A 2-step process was used to estimate usual intake of added sugar and total daily calories using the MIXTRAN and INDIVIT macros provided by the NCI [56, 58]. In step 1, the MIXTRAN

macro was used to generate an "amount-only" model of daily consumed nutrients (i.e., added sugar) using 24 hour dietary recall data on a transformed scale [58]. Intake day of the week [59] was included as a covariate in the MIXTRAN model to account for possible weekday or weekend day effects on dietary intake [60]. In step 2, INDIVINT was used to estimate usual intake for total calories and added sugar with parameters estimated from step 1. The INDIVINT macro was selected because it can be used to predict individual nutrient intakes for use as predictors in a disease model [56, 58].

Survey weighted logistic regression was used to test whether usual intake of total and percent added sugar intakes were associated with an increased odds of prediabetes relative to normoglycemia. The fasting subsample WTSAF2YR weight was applied to all analyses. Usual intake of added sugar was modeled as a continuous variable (g/day) and non-linear associations for added sugar as a percentage of total energy intake were examined (<10%, 10–15%, >15% kcal/day). A dichotomous indicator for prediabetes was constructed from HbA1c and FPG values. To aid in interpretation, estimated risks for prediabetes by total added sugar (g/day) were reported for mean and tertial intakes. Additionally, estimated risks for prediabetes by percent intakes of added sugar were reported as <10%, 10–15%, and >15% total energy from added sugar in kcals/day. Adjusted models included the following covariates: age in years, gender, race/ethnicity, BMI (kg/m<sup>2</sup>), total energy intake (kcal/day), engagement in physical activity, smoking status, education level, and family poverty to income ratio (PIR) (S1 Appendix in [S1 File](#)). An additional adjusted model that included additional dietary variables (dietary fiber, total fat, saturated fat, and total antioxidant capacity) was fitted to account for potential dietary effects that could confound the association between added sugar and prediabetes risk (S1 Appendix in [S1 File](#)). Interaction terms between added sugar and race/ethnicity were used to examine differences in the relationship between prediabetes risk and total and percent added sugar intakes by race/ethnicity for non-Hispanic White, non-Hispanic Black, Hispanic, Asian American and Other Race respondents. All tests were two-sided and a *p* value < .05 was considered statistically significant.

## Results

### Sample characteristics

A total of 5,306 adults with normoglycemia (41% of the sample) and prediabetes (59%) were included in the weighted sample and reported consuming 13.9% of their total daily calories from added sugar. There were no statistically significant differences in consumption of added sugar between groups (normoglycemia vs. prediabetes). [Table 1](#) shows the overall characteristics of adults  $\geq 20$  years and by normoglycemia and prediabetes status.

In the overall sample, the average age was 47 years and included more females (51.1%) than males (48.9%) and mostly non-Hispanic White adults (65.7%), followed by Hispanic including Mexican American and Latino (14.9%), non-Hispanic Black (10.8%), Asian American (4.8%), or Other Race (3.8%) adults. The majority of the sample had obesity (36.8%), reported engaging in moderate and/or vigorous physical activity (54.7%), reported being non-smokers (77.5%), had more than a high school degree (63.2%), and reported a family income that represented a PIR > 1.85 (67.8%). The average HbA1c was 5.4% and the average FPG was 101 mg/dL. Usual intakes for total calories were 2,067 kcal/day and usual intakes of total added sugar were 72 grams (290 kcal/day).

Comparing between participants (normoglycemia vs prediabetes), those with prediabetes were more likely to be older (51 years), to be male (54.2%), to identify as being of Hispanic including Mexican American (15.6%), Asian American (4.9%), or Other Race (4.3%), have overweight (34.9%) or obesity (43.7%), be less likely to engage in moderate and/or vigorous

Table 1. Overall characteristics of adults  $\geq 20$  years and by normoglycemia and prediabetes status, the NHANES<sup>a</sup> 2013–2018.

Characteristics	Overall, (SE <sup>b</sup> )	Normoglycemia, (SE)	Prediabetes (SE)	p value =
<b>Age (years)</b>		N = 2,154	N = 3,152	< .05
	47 (.38)	41 (.55)	51 (.38)	
<b>Gender</b>		N = 2,154	N = 3,152	< .05
Female	51.1% (.71)	57.8% (1.51)	45.8% (1.12)	
Male	48.9% (.71)	42.2% (1.51)	54.2% (1.12)	
<b>Race/ethnicity</b>		N = 2,154	N = 3,152	.03
Non-Hispanic White	65.7% (1.97)	66.8% (2.35)	64.8% (1.94)	
Non-Hispanic Black	10.8% (1.08)	11.3% (1.31)	10.3% (1.02)	
Hispanic (including Mexican American and Latino)	14.9% (1.49)	14.3% (1.65)	15.6% (1.50)	
Asian American	4.8% (.47)	4.6% (.46)	4.9% (.55)	
Other Race	3.8% (.45)	3.0% (.39)	4.3% (.64)	
<b>BMI status<sup>c</sup></b>		N = 2,136	N = 3,131	< .05
Underweight $\leq 18.49$ kg/m <sup>2</sup>	1.7% (.22)	2.6% (.37)	1.6% (.21)	
Normal 18.5–24.99 kg/m <sup>2</sup>	28.4% (.98)	38.6% (1.61)	20.3% (1.15)	
Overweight 25–29.99 kg/m <sup>2</sup>	33.1% (.79)	30.7% (1.28)	34.9% (1.10)	
Obese $\geq 30$ kg/m <sup>2</sup>	36.8% (1.04)	28.1% (1.46)	43.7% (1.42)	
<b>Moderate and/or vigorous physical activity<sup>d</sup></b>		N = 2,154	N = 3,152	< .05
No	45.3% (1.37)	39.1% (2.01)	50.1% (1.35)	
Yes	54.7% (1.37)	60.9% (2.01)	49.9% (1.35)	
<b>Smoking status<sup>e</sup></b>		N = 2,067	N = 3,029	.40
Smoker	22.5% (1.03)	23.4% (1.62)	21.8% (1.19)	
Non-smoker	77.5% (1.03)	76.6% (1.62)	78.2% (1.19)	
<b>Education<sup>f</sup></b>		N = 2,153	N = 3,150	< .05
< High school degree	12.9% (.95)	11.7% (1.31)	13.9% (.92)	
High school degree	23.9% (1.19)	20.9% (1.46)	26.2% (1.30)	
> High school degree	63.2% (1.78)	67.4% (2.36)	59.9% (1.66)	
<b>Family Poverty to Income Ratio (PIR)<sup>g</sup></b>		N = 1,978	N = 2,857	.49
< 1.3	21.5% (1.38)	22.5% (2.13)	20.7% (1.17)	
1.3–1.85	10.7% (.81)	10.5% (.94)	10.9% (.93)	
> 1.85	67.8% (1.75)	67.0% (2.51)	68.4% (1.60)	
<b>HbA1c (%)<sup>h</sup></b>		N = 2,150	N = 3,151	< .05
	5.4% (.01)	5.2% (.01)	5.6% (.01)	
<b>Fasting Plasma Glucose (mg/dL)<sup>i</sup></b>		N = 2,154	N = 3,151	< .05
	101mg/dL (.30)	93mg/dL (.27)	107 mg/dL (.24)	
<b>Percent intakes of total added sugar<sup>j</sup></b>		N = 2,154	N = 3,152	.62
% of participants with <10% calories from added sugars	31.1% (1.03)	30.9% (1.56)	31.3% (1.27)	
% of participants with 10–15% calories from added sugars	31.5% (.95)	32.5% (1.47)	30.6% (1.11)	
% of participants with >15% calories from added sugars	37.5% (1.20)	36.7% (1.84)	38.1% (1.44)	
<b>Usual intakes for total calories and total added sugar<sup>k</sup></b>		N = 2,154	N = 3,152	
Total calories (kcal/day)	2,067 (8.93)	2,046 (13.70)	2,084 (13.34)	.07
Added sugars (g <sup>l</sup> /day)	72 (.88)	71 (1.39)	73 (1.11)	.26
Added sugars (kcal/day)	290 (3.52)	285 (5.57)	293 (4.43)	.26

(Continued)



Table 1. (Continued)

Characteristics	Overall, (SE <sup>b</sup> )	Normoglycemia, (SE)	Prediabetes (SE)	<i>p</i> value =
Added sugar calories (%)	13.9% (.16)	13.9% (.27)	13.9% (.20)	.92

<sup>a</sup>NHANES = National Health and Nutrition Examination Survey

<sup>b</sup>SE = standard error

<sup>c</sup>BMI = body mass index and was based on standard weight status categories using CDC criteria for underweight, normal weight, overweight, obese.

<sup>d</sup>Physical activity was based on self-reported data of participant engagement in  $\geq 10$  minutes of moderate or vigorous recreational activity during a typical week (yes/no)

<sup>e</sup>Smoking status was based on self-reported data about the use of tobacco products within the last 5 days (yes/no). Smoker was defined as using products within the last 5 days. Non-smoker was defined as no use of tobacco products within the last 5 days.

<sup>f</sup>Education was based on self-reported data asking participants their highest grade or level of school completed/received. < High school includes less than high school degree or no high school diploma. High school includes being a graduate or having a GED or equivalent. > High school includes some college/ associate degree or greater.

<sup>g</sup>PIR = family poverty to income ratio. <1.3 indicates below PIR, 1.3–1.85 indicates at or above PIR, and > 1.85 indicates above PIR.

<sup>h</sup>HbA1c = hemoglobin a1c and was laboratory collected from NHANES during the medical examination center visits. Diagnostic criteria is based on the American Diabetes Association classification guidelines for prediabetes defined as HgbA1c of 5.7% - 6.4%.

<sup>i</sup>To convert mg/dL fasting plasma glucose to mmol/L, multiply mg/dL by 0.0555. To convert mmol/L fasting plasma glucose to mg/dL, multiply mmol/L by 18.02. Fasting plasma glucose of 70.0 mg/dL = 43.9 mmol/L.

<sup>j</sup>Percent intakes of total added sugar were based on a percent estimate of added sugar (g) converted into kcals and divided by total daily calories (kcals)

<sup>k</sup>usual intake was estimated using the National Cancer Institute Method for total calories and total added sugar and were based on at least 1 day of dietary recall information that contained a value for added sugar.

<sup>l</sup>g = grams

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activity (50.1%), identify as a non-smoker (78.2%), report having a high school (26.2%) or less than high school degree (13.9%) and report a family income that represented a PIR >1.85 (68.4%). Those with prediabetes had an average HbA1c of 5.6% and a FPG of 107 mg/dL compared to an average HbA1c of 5.2% and FPG of 93 mg/dL among adults with normoglycemia. Between the normoglycemia and prediabetes groups, total calories per day and added sugar intake was similar (2,084 vs 2,046 total kcal/day [ $p = .07$ ]; 71 vs. 73 g/day added sugar [ $p = .26$ ]; 285 vs. 293 kcal/day of added sugar [ $p = .26$ ]). Total energy intake from added sugar for both groups was 13.9% ( $p = .92$ ). Percent intakes of added sugar were also similar between groups (Table 1).

## Added sugar intake and prediabetes risk

**Total added sugar intakes.** Findings from both unadjusted and adjusted models (Table 2) indicated that total added sugar (g/day) intake did not significantly increase the odds of having prediabetes (unadjusted: OR: 1.01, 95% CI: .99–1.00,  $p = .26$ ; adjusted: OR: 1.00, 95% CI: .99–1.00,  $p = .91$ ). The addition of dietary variables to the model (fiber, total fat, saturated fat, and total antioxidant capacity) did not change this association (S1 Table in S1 File). Differences in the odds for having prediabetes were observed for some covariates in the adjusted model. For example, being older, being Hispanic, Asian American or Other Race, and having obesity was associated with a greater odds of having prediabetes, whereas being a non-smoker or having an education beyond a high school degree (relative to no high school degree) was associated with a lower odds of having prediabetes (Table 2).

Table 3 reports the estimated probability (i.e., risk) for prediabetes at mean (73 g/day) and tertial intakes (43 g/day, 64 g/day, 93 g/day) for total added sugar estimated from unadjusted and adjusted models. In both unadjusted and adjusted models, differences in the estimated risk for prediabetes and total added sugar intake were not statistically significant (unadjusted:  $p = .26$ ; adjusted:  $p = .91$ ). For example, in the unadjusted model, the estimated risk for

**Table 2. Unadjusted and adjusted odds of prediabetes for total added sugar (g<sup>a</sup>) in U.S. adults  $\geq 20$  years with normoglycemia and prediabetes, the NHANES<sup>b</sup> 2013–2018.**

		Estimate <sup>c</sup>	SE <sup>d</sup>	p value	OR <sup>e</sup>	95% CI <sup>f</sup>
Unadjusted (N = 5,306) <sup>g</sup>	Intercept	.155	.08	.07	-	-
	Total added sugar (g)	.001	.001	.26	1.01	.99–1.00
Adjusted (N = 4,617) <sup>h,i</sup>	Intercept	-2.78	.37	< .01	-	-
	Total added sugar (g)	.0002	.001	.91	1.00	.99–1.00
Age (years)		.04	.003	< .01	1.04	1.04–1.05
Gender	Female (Ref. <sup>j</sup> )	-	-	-	-	-
	Male	.647	.118	< .01	1.91	1.51–2.42
Race and ethnicity	Non-Hispanic White (Ref.)	-	-	-	-	-
	Non-Hispanic Black	.088	.105	.41	1.09	.89–1.35
	Hispanic (including Mexican American and Latino)	.364	.122	< .01	1.44	1.13–1.84
	Asian American	.779	.128	< .01	2.18	1.69–2.82
	Other Race	.737	.208	< .01	2.09	1.37–3.18
BMI <sup>k</sup>	Underweight $\leq 18.49$ kg/m <sup>2</sup> (Ref.)	-	-	-	-	-
	Normal 18.5–24.99 kg/m <sup>2</sup>	.004	.213	.99	1.00	.65–1.54
	Overweight 25–29.99 kg/m <sup>2</sup>	.617	.255	.02	1.85	1.11–3.10
	Obese $\geq 30$ kg/m <sup>2</sup>	1.14	.241	< .01	3.11	1.92–5.06
Total calorie intake (kcal <sup>l</sup> /day)		.00005	.0001	.67	1.00	1.00–1.00
Moderate and/or vigorous physical activity <sup>m</sup>	No (Ref.)	-	-	-	-	-
	Yes	-.174	.10	.09	.84	.69–1.03
Smoking status <sup>n</sup>	Smoker (Ref.)	-	-	-	-	-
	Non-smoker	-.034	.130	.8	.97	.74–1.26
Education <sup>o</sup>	< High school degree (Ref.)	-	-	-	-	-
	High school degree	.26	.150	.09	1.30	.96–1.76
	> High school degree	-.052	.151	.73	.95	.70–1.29
PIR <sup>p</sup>	<1.3 (Ref.)	-	-	-	-	-
	1.3–1.85	.124	.127	.33	1.13	.88–1.46
	>1.85	.0007	.137	.99	1.00	.76–1.32

<sup>a</sup>g = grams<sup>b</sup>NHANES = National Health and Nutrition Examination Survey<sup>c</sup>Estimate ( $\beta$  Coefficient) for usual intake of added sugar (g) represents a change in the odds of having prediabetes for every 1-gram increase in added sugar.<sup>d</sup>SE = standard error<sup>e</sup>OR = odds ratio<sup>f</sup>CI = confidence interval<sup>g</sup>Model fit- C statistic: .497<sup>h</sup>Model fit- C statistic: .733. Ns between unadjusted and adjusted models differ due to missing covariates included in the adjusted model.<sup>i</sup>Covariates included in the adjusted models are age, gender, race/ethnicity, BMI, total calorie intake (kcal/day), moderate and/or vigorous physical activity, smoking status, education, family income to poverty ratio (PIR).<sup>j</sup>Ref = reference category<sup>k</sup>BMI = body mass index and was based on standard weight status categories using CDC criteria for underweight, normal weight, overweight, obese.<sup>l</sup>kcal = kilocalories NHANES<sup>m</sup>Physical activity was based on self-reported data of participant engagement in  $\geq 10$  minutes of moderate or vigorous recreational activity during a typical week (yes/no)<sup>n</sup>Smoking status was based on self-reported data about the use of tobacco products within the last 5 days (yes/no). Smoker was defined as using products within the last 5 days. Non-smoker was defined as no use of tobacco products within the last 5 days.<sup>o</sup>Education was based on self-reported data asking participants their highest grade or level of school completed/received. < High school includes less than high school degree or no high school diploma. High school includes being a graduate or having a GED or equivalent. > High school includes some college/ associate degree or greater.<sup>p</sup>PIR = family poverty to income ratio. <1.3 indicates below PIR, 1.3–1.85 indicates at or above PIR, and > 1.85 indicates above PIR.<https://doi.org/10.1371/journal.pone.0286759.t002>



**Table 3. Estimated risk of prediabetes at mean and tertiles of total added sugar (g<sup>a</sup>) in U.S. adults ≥20 years, the NHANES<sup>b</sup> 2013–2018.**

	Total Added Sugar	Estimate <sup>c</sup>	SE <sup>d</sup>
<b>Unadjusted<sup>e</sup></b>	Mean (73g)	.558	.012
Prediabetes (N = 3,152)	1st Q <sup>f</sup> (43g)	.550	.014
	Median Q (64g)	.556	.012
	3rd Q (93g)	.564	.013
<b>Adjusted<sup>g,h</sup></b>	Mean (73g)	.607	.018
Prediabetes (N = 2,735)	1st Q (43g)	.606	.020
	Median Q (64g)	.606	.018
	3rd Q (93g)	.608	.020

<sup>a</sup>g = grams

<sup>b</sup>NHANES = National Health and Nutrition Examination Survey

<sup>c</sup>Estimates represent the risk probability for prediabetes based on mean and tertial intakes of total added sugar (g/day).

<sup>d</sup>SE = standard error

<sup>e</sup>Model fit- C statistic: .497 and p-value = .26

<sup>f</sup>Q = quartiles

<sup>g</sup>Model fit- C statistic: .733 and p-value = .91. Ns between unadjusted and adjusted models differ due to missing covariates included in the adjusted model.

<sup>h</sup>Adjusted for age, gender, race/ethnicity, BMI, total calorie intake (kcal/day), moderate and/or vigorous physical activity, smoking status, education, family poverty to income ratio (PIR).

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prediabetes at mean and tertial intakes for total added sugar ranged from 55.8% (mean) and from 55% to 55.6% to 56.4% (tertile). Estimated risk percentages were converted from the ‘estimates’ reported in Table 3 (e.g., .550 equates to 55%). Similarly, in the adjusted models, the estimated risk for prediabetes at mean and tertial intakes for total added sugar ranged from 60.7% (mean) and from 60.6% to 60.6% to 60.8% (tertile) indicating very little difference in estimated risk of prediabetes between varying amounts of total added sugar. This relationship pattern remained unchanged when including additional dietary variables in the model (S2 Table in S1 File).

### Percent intakes of added sugar

In both unadjusted and adjusted models (Table 4), consumption of different percent intakes of added sugar (<10%, 10–15%, >15%) did not significantly increase the odds of having prediabetes (unadjusted [<10%: (ref); 10–15%: OR: .93, 95% CI: .77–1.12,  $p = .44$ ; >15%: OR: 1.03, 95% CI: .82–1.28,  $p = .82$ ] and adjusted [<10%: (ref); 10–15%: OR: .82, 95% CI: .65–1.04,  $p = .09$ ; >15%: OR: .96, 95% CI: .74–1.24,  $p = .73$ ]). In the adjusted model, significant differences in the odds for prediabetes were noted for certain covariates including age, race/ethnicity, BMI, smoking status, and education (Table 4). Findings were similar to what was previously reported for the total added sugar adjusted model in Table 2.

The estimated risk of prediabetes by percent intakes of added sugar (<10%, 10–15%, >15%) was reported in unadjusted and adjusted models (Table 5). Similar to the findings for the total added sugar intake models (Table 3), differences in the estimated risk for prediabetes in the percent intake models were relatively small and not statistically significant (unadjusted:  $p = .51$ ; adjusted:  $p = .22$ ). For example, in the unadjusted model, the estimated risk for prediabetes by percent intakes ranged from 54.3% to 56.1% to 56.7% and in the adjusted model ranged from 57.7% to 61.4% to 62.5% (Table 5).

### Total and percent intake of added sugar by race and ethnicity

Results from the sensitivity analyses (Tables 6 and 7) indicated that the association between total and percent intakes of added sugar and risk for prediabetes did not differ by race/ethnicity (Type 3 tests for interaction of race/ethnicity by total added sugar: unadjusted model [ $p = .27$ ]; adjusted model [ $p = .33$ ] and percent intake of added sugar: unadjusted model [ $p = .21$ ]; adjusted model [ $p = .11$ ]). Irrespective of added sugar, it was observed that some racial/ethnic groups had higher odds for prediabetes. In Table 6, adjusted models indicated that the risk for prediabetes was high among those who identified as being Hispanic, Asian American, or Other Race with Asian Americans having the highest risk estimates (69% to 73%). Results were similar in Table 7 with adjusted risk estimates for Asian Americans between 71% to 76%.

### Discussion

This is the first known study to examine associations between usual intake of total added sugar and prediabetes risk in a large nationally representative sample of 5,306 U.S. adults  $\geq 20$  years.

**Table 4. Unadjusted and adjusted odds of prediabetes for percent intakes of total added sugar<sup>a</sup> in U.S. adults  $\geq 20$  years with normoglycemia and prediabetes, the NHANES<sup>b</sup> 2013–2018.**

		Estimate <sup>c</sup>	SE <sup>d</sup>	p value	OR <sup>e</sup>	95% CI <sup>f</sup>
Unadjusted (N = 5,306) <sup>g</sup>	Intercept	.246	.083	.57	-	-
	<10% (Ref. <sup>h</sup> )	-	-	-	-	-
	10–15%	-.072	.094	.44	.93	.77–1.12
	>15%	.025	.112	.82	1.03	.82–1.28
Adjusted (N = 4,617) <sup>ij</sup>	Intercept	-2.74	.378	.21	-	-
	<10% (Ref.)	-	-	-	-	-
	10–15%	-.197	.115	.09	.82	.65–1.04
	>15%	-.044	.129	.73	.96	.74–1.24
Age (yr)		.042	.003	< .01	1.04	1.04–1.05
Gender	Female (Ref.)	-	-	-	-	-
	Male	.637	.120	< .01	1.89	1.49–2.41
Race/ethnicity	Non-Hispanic White (Ref.)	-	-	-	-	-
	Non-Hispanic Black	.089	.104	.40	1.09	.89–1.35
	Hispanic (including Mexican American and Latino)	.373	.124	< .01	1.45	1.13–1.86
	Asian American	.762	.124	< .01	2.14	1.67–2.75
	Other Race	.736	.208	< .01	2.09	1.37–3.17
BMI <sup>k</sup>	Underweight $\leq 18.49$ kg/m <sup>2</sup> (Ref.)	-	-	-	-	-
	Normal 18.5–24.99 kg/m <sup>2</sup>	.006	.215	.98	1.01	.65–1.55
	Overweight 25–29.99 kg/m <sup>2</sup>	.615	.257	.02	1.85	1.10–3.10
	Obese $\geq 30$ kg/m <sup>2</sup>	1.14	.246	< .01	3.12	1.90–5.12
Total energy intake (kcal <sup>l</sup> /day)		.00006	.0001	.51	1.00	1.00–1.00
Moderate and/or vigorous physical activity <sup>m</sup>	No (Ref.)	-	-	-	-	-
	Yes	-.173	.099	.09	.84	.69–1.03
Smoking status <sup>n</sup>	Smoker (Ref.)	-	-	-	-	-
	Non-smoker	-.034	.131	.79	.97	.74–1.26
Education <sup>o</sup>	<High school degree (Ref.)	-	-	-	-	-
	High School Degree	.266	.149	.08	1.31	.97–1.76
	>High School Degree	-.041	.152	.79	.96	.71–1.30
PIR <sup>p</sup>	<1.3 (Ref.)	-	-	-	-	-
	1.3–1.85	.135	.128	.30	1.14	.89–1.48

(Continued)

Table 4. (Continued)

	Estimate <sup>c</sup>	SE <sup>d</sup>	p value	OR <sup>e</sup>	95% CI <sup>f</sup>
>1.85	-.002	.139	.99	1.00	.76–1.32

<sup>a</sup>Percent intakes of total added sugar were based on a percent estimate of usual intake of added sugar (g) converted into kcals and divided by total daily calories (kcals)

<sup>b</sup>NHANES = National Health and Nutrition Examination Survey

<sup>c</sup>Estimate (β Coefficient) for added sugar (g) intake represents a change in the odds of having prediabetes for every 1-gram increase in added sugar.

<sup>d</sup>SE = standard error

<sup>e</sup>OR = odds ratio

<sup>f</sup>CI = confidence interval

<sup>g</sup>Model fit- C statistic: .501

<sup>h</sup>Ref = reference category

<sup>i</sup>Model fit- C statistic: .733. N's between unadjusted and adjusted models differ due to missing covariates included in the adjusted model

<sup>j</sup>Covariates included in the adjusted models are age, gender, race/ethnicity, BMI, total calorie intake (kcal/day), moderate and/or vigorous physical activity, smoking status, education, family poverty to income ratio (PIR).

<sup>k</sup>BMI = body mass index and was based on standard weight status categories using CDC criteria for underweight, normal weight, overweight, obese.

<sup>l</sup>kcal = kilocalories NHANES

<sup>m</sup>Physical activity was based on self-reported data of participant engagement in ≥10 minutes of moderate or vigorous recreational activity during a typical week (yes/no)

<sup>n</sup>Smoking status was based on self-reported data about the use of tobacco products within the last 5 days (yes/no). Smoker was defined as using products within the last 5 days. Non-smoker was defined as no use of tobacco products within the last 5 days.

<sup>o</sup>Education was based on self-reported data asking participants their highest grade or level of school completed/received. < High school includes less than high school degree or no high school diploma. High school includes being a graduate or having a GED or equivalent. > High school includes some college/ associate degree or greater.

<sup>p</sup>PIR = family poverty to income ratio. <1.0 indicates below PIR, 1.0–2.9 indicates at or above PIR, and ≥ 3.0 indicates above PIR.

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In the study, added sugar accounted for 13.9% of the sample's total energy intake. Similarly, total energy intake from added sugar in adults with normoglycemia and prediabetes was 13.9%. The findings of this study suggest that even after controlling for total calorie intake,

Table 5. Estimated risk of prediabetes for percent intake of total added sugar<sup>a</sup> in U.S. adults ≥20 years, the NHANES<sup>b</sup> 2013–2018.

	% Added Sugar	Estimate <sup>c</sup>	SE <sup>d</sup>
<b>Unadjusted<sup>e</sup></b>	<10%		.561
	10–15%		.543
	>15%		.567
<b>Adjusted<sup>f,g</sup></b>	<10%		.625
	10–15%		.577
	>15%		.614

<sup>a</sup>Percent intakes of total added sugar were based on a percent estimate of usual intake of added sugar (g) converted into kcals and divided by total daily calories (kcals)

<sup>b</sup>NHANES = National Health and Nutrition Examination Survey

<sup>c</sup>Estimate represents the risk probability for prediabetes based on mean and quartile intakes of added sugar in grams per day.

<sup>d</sup>SE = standard error

<sup>e</sup>Model fit- C statistic: .501 and p-value = .51

<sup>f</sup>Model fit- C statistic: .733 and p-value = .22. Ns between unadjusted and adjusted models differ due to missing covariates included in the adjusted model.

<sup>g</sup>Adjusted for age, gender, race/ethnicity, BMI, total calorie intake (kcal/day), moderate and/or vigorous physical activity, smoking status, education, family poverty to income ratio (PIR).

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Table 6. Estimated risk of prediabetes at mean and tertials of total added sugar (g<sup>a</sup>) by race/ethnicity status for U.S. adults ≥20 years, the NHANES<sup>b</sup> 2013–2018.

	Unadjusted <sup>c</sup>			Adjusted <sup>d,e</sup>		
	Total Added Sugar	Estimate <sup>f</sup>	SE <sup>g</sup>	Total Added Sugar	Estimate	SE
Non-Hispanic White	Mean (72.45 g)	.55	.016	Mean (72.68 g)	.51	.026
	1st Q <sup>h</sup> (42.67 g)	.54	.019	1st Q <sup>h</sup> (42.67 g)	.51	.030
	Median Q (64.17 g)	.55	.017	Median Q (64.17 g)	.51	.027
	3rd Q (93.95 g)	.55	.017	3rd Q (93.95 g)	.51	.026
Non-Hispanic Black	Mean (72.45 g)	.54	.018	Mean (72.68 g)	.53	.027
	1st Q <sup>h</sup> (42.67 g)	.54	.023	1st Q <sup>h</sup> (42.67 g)	.52	.034
	Median Q (64.17 g)	.54	.019	Median Q (64.17 g)	.53	.028
	3rd Q (93.95 g)	.53	.020	3rd Q (93.95 g)	.54	.028
Hispanic (including Mexican American and Latino)	Mean (72.45 g)	.58	.017	Mean (72.68 g)	.60	.023
	1st Q <sup>h</sup> (42.67 g)	.56	.022	1st Q <sup>h</sup> (42.67 g)	.59	.028
	Median Q (64.17 g)	.58	.018	Median Q (64.17 g)	.60	.024
	3rd Q (93.95 g)	.60	.019	3rd Q (93.95 g)	.61	.025
Asian American <sup>i</sup>	Mean (72.45 g)	-	-	Mean (72.68 g)	.71	.027
	1st Q (42.67 g)	-	-	1st Q (42.67 g)	.69	.025
	Median Q (64.17 g)	-	-	Median Q (64.17 g)	.71	.025
	3rd Q (93.95 g)	-	-	3rd Q (93.95 g)	.73	.037
Other Race	Mean (72.45 g)	.64	.037	Mean (72.68 g)	.68	.040
	1st Q (42.67 g)	.60	.051	1st Q (42.67 g)	.66	.050
	Median Q (64.17 g)	.63	.039	Median Q (64.17 g)	.68	.040
	3rd Q (93.95 g)	.67	.04	3rd Q (93.95 g)	.70	.048

<sup>a</sup>g = grams

<sup>b</sup>NHANES = National Health and Nutrition Examination Survey

<sup>c</sup>Model fit- C statistic: .515 and p-value = .27. Total sample N = 5,306; prediabetes N = 3,152

<sup>d</sup>Model fit- C statistic: .734 and p-value = .33. Total sample N = 4,617; prediabetes N = 2,735. Ns between unadjusted and adjusted models differ due to missing covariates included in the adjusted model.

<sup>e</sup>Adjusted for age, gender, race/ethnicity, BMI, total calorie intake (kcal/day), moderate and/or vigorous physical activity, smoking status, education, family poverty to income ratio (PIR).

<sup>f</sup>Estimate represents the risk probability for prediabetes based on mean and tertial intakes of added sugar (g/day).

<sup>g</sup>SE = standard error

<sup>h</sup>Q = quartiles

<sup>i</sup>Estimates for unadjusted intakes not reported in SAS output file.

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BMI, and pertinent health behaviors/sociodemographic factors, all sources (i.e., total) of added sugar consumed as part of a usual diet, do not appear to significantly increase an individual's odds for having prediabetes. Average intakes for added sugar in this study exceeded current dietary guideline recommendations and were very close to average intake estimates reported for the total U.S. population (13.9% total energy intake/290 calories per day vs. 13% total energy intake/270 calories per day respectively) [16].

The main hypothesis of this study, that total added sugar consumption would be associated with and increase the risk of prediabetes, was not supported by the findings from this study. Nonetheless, the results are not in complete contrast to what has previously been reported in the literature. Evidence from both observational and experimental findings on this topic have been mixed with many studies suggesting that added sugar increases the risk for prediabetes [23, 28–30, 33–36] and fewer studies reporting no such relationship [61–67]. Yet, differences between study designs (observational vs experimental), characterization of prediabetes risk,

**Table 7. Estimated risk of prediabetes by percent intakes of total added sugar<sup>a</sup> consumed by race/ethnicity status for U.S. adults  $\geq 20$  years, the NHANES<sup>b</sup> 2013–2018.**

	% Added Sugar	Unadjusted <sup>c</sup>		Adjusted <sup>d,e</sup>	
		Estimate <sup>f</sup>	SE <sup>g</sup>	Estimate	SE
Non-Hispanic White	<10%	.56	.026	.56	.035
	10–15%	.53	.025	.48	.040
	>15%	.56	.025	.54	.034
Non-Hispanic Black	<10%	.55	.038	.56	.048
	10–15%	.55	.030	.55	.035
	>15%	.52	.027	.55	.036
Hispanic (including Mexican American and Latino)	<10%	.55	.029	.60	.032
	10–15%	.60	.031	.65	.041
	>15%	.59	.024	.62	.032
Asian American	<10%	.58	.027	.71	.030
	10–15%	.56	.038	.71	.040
	>15%	.61	.049	.76	.043
Other Race	<10%	.67	.087	.71	.071
	10–15%	.55	.056	.56	.082
	>15%	.68	.058	.73	.062

<sup>a</sup>Percent intakes of total added sugar were based on a percent estimate of usual intake of added sugar (g) converted into kcals and divided by total daily calories (kcals)

<sup>b</sup>NHANES = National Health and Nutrition Examination Survey

<sup>c</sup>Model fit- C statistic: .522 and p-value = .21. Total sample N = 5,306; prediabetes N = 3,152

<sup>d</sup>Model fit- C statistic: .335 and p-value = .11. Total sample N = 4,617; prediabetes N = 2,735. Ns between unadjusted and adjusted models differ due to missing covariates included in the adjusted model.

<sup>e</sup>Adjusted for age, gender, race/ethnicity, BMI, total calorie intake (kcal/day), moderate and/or vigorous physical activity, smoking status, education, family poverty to income ratio (PIR).

<sup>f</sup>Estimate represents the risk probability for prediabetes based on mean and quartile intakes of added sugar in grams per day.

<sup>g</sup>SE = standard error

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inclusion of representative minority groups, and operationalization of added sugar (i.e., proxies such as SSB or fructose-only beverages used to represent total added sugar intake) lend themselves to the inconsistent findings between many studies.

For example, experimental and observational studies have used a wide range of glycemic variables to assess prediabetes risk. In experimental studies, insulin sensitivity has been measured using the hyperinsulinemic clamp [24, 34, 63, 65, 68], the hepatic insulin sensitivity index [36], or a 75 g oral-glucose tolerance test (OGTT) [37] whereas insulin resistance has been measured via the homeostatic model assessment of insulin resistance (HOMA-IR) [62, 64, 66, 69]. In observational studies, HOMA-IR has commonly been used to assess insulin resistance [28–30, 33]. Interestingly, only a single, prospective cohort study has reported a significant association between added sugar and incident prediabetes measured via FPG and OGTT [33]. In contrast, prediabetes risk in this study was defined using HbA1c and FPG. Because OGTT was not collected in the 2017–2018 NHANES dataset, it was not used to identify prediabetes. It is possible that including all prediabetes measurements (HbA1c, FPG, and OGTT) may have resulted in a significant association between added sugar and prediabetes risk.

Sample characteristics have also varied widely between studies with experimental studies predominately using a homogenous sample of either male-only [24, 34–36, 63, 64] or female-only participants [62] whereas observational studies have mainly included heterogeneous

samples [28–30, 33]. Most of the studies failed to consider differences in added sugar intake by race/ethnicity status which limits the generalizability of past findings. In this study, a diverse and heterogeneous sample was included to test whether the associations between added sugar consumption and prediabetes differed by race/ethnicity. The findings of this study do not indicate prediabetes risk differs by race/ethnicity status for total or percent added sugar intakes. However, one notable finding from this study was that the highest risk estimates for prediabetes (irrespective of added sugar intake) was observed among Asian American adults. This is of interest since national estimates indicate that Asian American adults have a lower prevalence of prediabetes in the U.S. compared to other racial/ethnic groups (i.e., 37.3% compared to 39.2% for non-Hispanic Black, and 38.7% for non-Hispanic White adults) [2]. Research suggests Asian American adults often have higher rates of prediabetes at lower BMIs (underweight to obese class I) [3]. Participants in this study were predominately overweight or obesity; however, differences in BMI status by race/ethnicity were not estimated. Future studies should specifically include Asian Americans to better characterize their prediabetes risk.

Operationalization of added sugar has also varied widely between studies. For example, a plethora of observational studies have primarily relied on added sugar proxies (e.g., SSB sweetened with HFCS) to approximate total added sugar intake which has been shown to be positively correlated with risk for prediabetes and T2D [18–33]. Moreover, this relationship has been consistently observed in large prospective cohort studies in both the U.S. and Europe. Interestingly, studies have indicated that a dose relationship exists between SSB intake and T2D with > 1 to 2 servings per day (~355 mL or 12 ounces) attributed to a greater risk [18–21]. Notably, one study assessed 100% fruit juice and SSBs individually and combined as a single category (i.e., sugary beverages). Results indicated that  $\geq 0.5$  servings/day of sugary beverages, SSBs, and 100% fruit juice over 4 years was associated with a 16%, 9%, and 15% higher risk for T2D respectively [20]. Yet, a similar cohort study found that 100% fruit juice was not associated with T2D risk and in fact, greater intake (967 mL/week) was attributed to a decreased risk of T2D [19]. Given the clear distinction between SSBs that contain added sugars and 100% fruit juices that contain natural sugars [11], future studies should ensure that these beverages are clearly defined and categorized to ensure consistency in how added sugars are operationalized in the context of disease risk.

Other studies have used fructose to represent added sugar and have found that greater concentrations of fructose (15% to  $\geq 25\%$  of total calories) promote insulin resistance [34–36], increase fasting plasma glucose concentrations [37], and impair insulin sensitivity [35–37]. Yet, in the U.S., a typical ad libitum diet consists of different types (e.g., sucrose, glucose, fructose, HFCS) of added sugar that are consumed in both solid and liquid form (e.g., baked goods or beverages like sodas and fruit drinks) [11, 16, 70]. Aware of this knowledge, the objective of this study was to examine the relationship between all (i.e., total) added sugars (consumed as part of a usual diet) and risk for prediabetes among U.S. adults. Because this was a cross-sectional study, causal inferences could not be made to determine why total added sugar intake did not increase the risk for prediabetes in the study sample. With much of the literature pointing to SSBs as a driving factor for diabetes risk [28–33], it may be that liquid sources (e.g., SSBs) of added sugar compared to solid sources (e.g., baked goods, confectionaries) pose a greater risk for prediabetes. This was beyond this scope of this study; however, a few studies have found that added sugar consumed from liquids are responsible for impaired glucose homeostasis and insulin resistance in children (8–10 years) [71] and positively correlated with HOMA-IR in adults whereas similar correlations have not observed for solid food consumption [72]. Experimental research is needed to explore these differences in the context of prediabetes.



Lastly, it should be noted that the findings from this study are not in complete contrast to what has been previously reported in the literature. In a study by Lowndes et al. [66], added sugar represented ~18% of the sample's total energy intake and did not impair fasting glucose concentrations in adults without diabetes (pre- or type 2). In comparison, consumption of added sugar in this study was slightly lower than what was used in the study by Lowndes et al. It is possible that average intakes of ~14% to ~18% added sugar may not pose a significant risk for prediabetes in adults. However, experimental studies assessing varying intakes of total added sugar as part of an ad libitum diet are needed since Lowndes et al. supplemented sucrose to participants in liquid form (via unsweetened milk), which may have differing effects on risk for prediabetes [71, 72].

### Strengths and limitations

This study has some major strengths. This is the first known study to assess the associations between total and percent intakes of added sugar and risk for prediabetes in a nationally representative sample of U.S. adults. Differences by race and ethnicity status were also examined to improve the generalizability of the study results. Additionally, the NCI method was used to estimate usual individual intakes for added sugar for use in a disease model which helps account for between- and within-person variation in intake [56, 73].

This study also has limitations. First, the cross-sectional nature of this study did not allow for the assessment of causal or temporal inferences between added sugar and risk for prediabetes. Second, self-reported 24-hour dietary recalls were used to estimate usual intake of added sugars and total calories which may be subject to under- or over-reporting due to concerns of social desirability [74]. Optimal estimates for usual intake over a longer time period can be obtained using Food Frequency Questionnaires (FFQ) [75]. However, they were not utilized in this study due to their incompatibility with the NCI method to estimate usual dietary intake of added sugar in the context of a disease model [58]. Third, HbA1c is reported to have a lower sensitivity at cut-points of 5.7–6.4% and is associated with greater diagnostic inaccuracy in the presence of certain medical conditions that increase red blood cell turnover (e.g., sickle cell disease, pregnancy, erythropoietin therapy)<sup>1</sup> and are not reported in NHANES. Differences by race and ethnicity status have also been reported with HbA1c levels registering higher in non-Hispanic Black adults compared to non-Hispanic White adults who had similar fasting glucose levels [1]. It is possible some individuals were incorrectly classified as having prediabetes (or T2D); however, including both FPG and HbA1c likely improved identification of prediabetes among the study sample [76].

### Conclusions

This study found that added sugar averaged 13.9% of the sample's total energy intake and was the same for adults with normoglycemia and prediabetes. Total and percent intakes of added sugar did not increase the risk for prediabetes in this nationally representative study of U.S. adults  $\geq 20$  years, including no significant differences in risk by race/ethnicity status. As this topic continues to evolve, additional experimental studies are needed to determine if there are any direct effects from consuming total added sugar, as part of a usual diet, on prediabetes risk. As rates of prediabetes and T2D continue to rise, evidence-based research should determine what role added sugar plays in diabetes management and prevention to help advance the field of precision health and nutrition.

### Supporting information

**S1 File.**  
(DOCX)

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