ORIGINAL RESEARCH

CURRENT DEVELOPMENTS IN NUTRITION

Nutritional Epidemiology and Public Health

Associations of Added Sugar from All Sources and Sugar-Sweetened Beverages with Regional Fat Deposition in US Adolescents: NHANES 1999–2006

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ABSTRACT

Background: The relative distribution of upper- versus lower-body fat may be an important determinant of cardiometabolic disease risk in youths. Dietary components associated with adolescent regional body fat distribution require further investigation.

Objective: To evaluate associations of added sugar intake overall and from sugar-sweetened beverages (SSBs) with relative upper-body fat deposition in US adolescents.

Methods: This was a cross-sectional analysis of data from 6585 adolescents (aged 12–19 y) in the NHANES cycles 1999–2006. Trunk, leg, and total fat mass were assessed by DXA. Participants were grouped into categories of total and SSB added sugar intake as a percentage of total energy intake (TEI) in 5% increments. Stepwise multivariable linear regression was used to examine associations of added sugar intake with truncal-to-leg fat ratio (TLR) and truncal-to-total fat ratio (TTR).

Results: There were no associations of total added sugar intake with TLR or TTR. For SSB added sugar, compared with the lowest category of intake (<2% TEI), the highest category (>22% TEI) was associated with higher log-TLR [β (95% CI): >22% TEI versus <2% TEI: 0.05 (0.01, 0.09)] and TTR [1.30 (0.53, 2.07)] in the partially adjusted model with sex, age, race/ethnicity, income, physical activity, and smoking status as covariates (P-trend = 0.0001 for both). When BMI z-score and TEI were added as covariates, the magnitude of the associations were attenuated, but remained significant [log-TLR β (95% CI): 0.03 (0.005, 0.06), P-trend = 0.0018; TTR β (95% CI): 0.75 (0.27, 1.23), P-trend = 0.0004].

Conclusions: These findings support that added sugar from beverages is associated with higher upper-body adiposity, though the magnitude and clinical significance of the associations may be small, especially when adjusted for BMI and TEI. Additional studies are needed to elucidate the underlying biological mechanisms to explain these findings. *Curr Dev Nutr* 2019;3:nzz130.

Keywords: trunk fat, leg fat, soda, cardiometabolic disease, diabetes, body composition

Manuscript received July 22, 2019. Initial review completed October 24, 2019. Revision accepted November 7, 2019. Published online November 13, 2019.
Supported, in part, by the National Institute of Diabetes, Digestive, and Kidney Disease(NIDDK) grant/award numbers T32DK007734, P30DK111024, and K01DK102851, and the National Heart, Lung, and Blood Institute (NHLBI) grant/award number R01HL125442.
Author disclosures: CEC, JAW, JAA, TJH, KMVN, and MBV, no conflicts of interest.
Supplemental Tables 1–3 and Supplemental Figure 1 are available from the "Supplementary data" link in the online posting of the article and from the same link in the online table of contents at https://academic.oup.com/cdn/.

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Abbreviations used: CMD, cardiometabolic disease; FPED, Food Pyramid Equivalents Database; HFCS, high-fructose corn syrup; MEC, mobile examination center; MPED, MyPyramid Equivalents Database; MVPA, moderate and vigorous physical activity; NCHS, National Center for Health Statistics; PAL, physical activity level; PIR, poverty income ratio; SSB, sugar-sweetened beverage; TEI, total energy intake; TLR, truncal-to-leg fat ratio; TTR, truncal-to-total fat ratio.

Introduction

The prevalence of childhood obesity in the USA is a public health concern, in part due to associations with cardiometabolic disease (CMD) risk factors (1, 2). In particular, higher upper-body adiposity, i.e. truncal or abdominal fat, has been shown to be a strong risk factor for metabolic dysfunction independent of total body fat, whereas higher lower-body adiposity, i.e. leg or hip fat, may be protective (3, 4). Similarly, we recently found in US adolescents that a higher truncal-to-leg fat ratio (TLR) is associated with multiple CMD risk factors, including fasting insulin resistance and dyslipidemia, independent of BMI (5). One hypothesis to explain these findings is that impaired expansion of

peripheral subcutaneous fat increases susceptibility to abdominal and ectopic fat deposition, and the subsequent lipotoxic consequences, such as insulin resistance (6, 7).

Understanding if modifiable lifestyle factors influence body fat distribution may be important for reducing future CMD (8). Added sugar intake, especially in the form of sugar-sweetened beverages (SSBs), has been shown to be associated with abdominal visceral fat, but not subcutaneous fat, in observational studies in adults (9, 10) and youth (11, 12). This is also supported by a 6-mo intervention study in adults, which found that daily SSB consumption resulted in greater increases in abdominal visceral fat compared with milk, diet sodas, and water (13). Thus, evidence suggests that added sugar intake contributes to altered lipid partitioning among abdominal fat depots. However, data is lacking on the associations of added sugar with the ratio of upper- versus lower-body fat.

In this study, we aimed to examine associations of added sugar from all sources, and specifically from SSBs, with relative upper-body fat deposition in US adolescents. The primary outcome was truncal-to-leg fat ratio (TLR)measured by dual-energy X-ray absorptiometry (DXA), though we also examined truncal-to-total fat ratio (TTR). Our hypothesis was that higher intakes of added sugar would be associated with higher TLR and TTR, and that this association would be strongest for the intake of added sugars in SSBs.

Methods

NHANES is an ongoing, cross-sectional surveillance survey conducted by the National Center for Health Statistics (NCHS) within the CDC. It uses a multistage, probability sampling design to obtain a nationally representative sample of the US noninstitutionalized population and releases data in 2-y cycles. From 1999–2006 only, whole and regional body fat and lean mass were measured using DXA on NHANES participants aged 8 y or older. Thus, the initial eligible sample for this analysis was 8311 participants aged 12–19 y. Among this sample, participants were excluded for the following consecutive reasons: not having valid scanned or imputed DXA data (n = 261), not having 1 valid dietary recall day (n = 333), implausible total energy intake (TEI) (<500 TEI or >5000 TEI, n = 293); underweight BMI percentile (n = 181) or missing BMI percentile (n = 29); missing other covariates, i.e. household income status, self-reported physical activity, or self-reported smoking status (n = 629). This resulted in a final sample of 6585 adolescents. A CONSORT diagram is shown in **Supplemental Figure 1**. It should be noted that from 1999–2006, NHANES oversampled several subgroups, including non-Hispanic blacks, Mexican Americans, low-income whites, and adolescents aged 12–19 y. NHANES was approved by the NCHS Review Board, and all participants provided written informed consent.

Body composition and anthropometrics

Height in cm and weight in kg were measured using standardized protocols during the mobile examination center (MEC) visit (14). Age- and sex-adjusted BMI percentiles and z-scores were calculated using the 2000 CDC growth charts (15). Subjects were categorized as normal weight (5–84th percentile), overweight (85–94th percentile), or obese (≥95th percentile) (16). Body composition was measured by DXA during the MEC visit using a Hologic QDR-4500A fan-beam densitometer (Hologic, Inc.) and Hologic Discovery software version 12.1 (17). Soft tissue measures for fat and lean mass were obtained for the head, arms, legs, and trunk regions. Based on prior analyses showing that DXA overestimated lean mass and underestimated fat mass, values for lean mass were decreased by 5% by the NCHS and an equivalent weight was added to the fat mass (17, 18). Participants were not scanned if pregnant, had amputations other than toes or fingers, weighed >300 lbs, or were taller than 6'5" (195.6 cm). Some DXA scans did not result in 100% valid data; for example, due to nonremovable objects, obesity-related noise, and arm/leg overlap. This resulted in a decrease in valid DXA data with increasing age and BMI. Multiple imputation was performed by NCHS to account for this nonrandom nature of missing data (17). Among the sample of adolescents in this study, 5856 (88.9%) completed the scan and had 100% valid data, 317 (4.8%) completed the scan but ≥1 region was invalid and multiply imputed, and 412 (6.3%) did not complete the scan but had valid multiply imputed data. In each dataset, we calculated TLR as (trunk fat mass [g]/[right + left leg fat mass (g)] × 100), consistent with prior reports (5), and TTR as ([trunk fat (g)/total fat mass (g)] × 100).

Total and SSB added sugar

For 1999–2000 and 2001–2002, dietary intake in NHANES was assessed by 1 24-h dietary recall collected in-person during the household interview. Starting in 2002, an integrated dietary component administered by the USDA in partnership with NCHS, called What We Eat in America, was created and included a second 24-h dietary recall collected by telephone 3–10 d after the MEC visit (19). For consistency across cycles, the first 24-h recall only was used for the primary analysis; although a sensitivity analysis was also performed using 2-d mean intakes from a subset of the sample with a second 24-h recall (n = 3633 or 55% of the sample). The USDA's Food and Nutrient Database for Dietary Studies was used to convert dietary recall data into TEI per day. The USDA's MyPyramid Equivalents Database (MPED) versions 1.0 (for 1999–2002) and 2.0 (for 2003–2004), and the Food Pyramid Equivalents Database (FPED) (for 2005–2006) were used to determine added sugar intake. Details on the methodology used by the USDA to calculate the added sugar intake can be found elsewhere (20–22). Briefly, these databases are used to translate dietary intake data from national surveys, including NHANES, into food group equivalents relevant to dietary guidelines (23). This data is released as total intakes per person per day and as intakes per individual food item. The USDA defines added sugars as all caloric sweeteners that are added as ingredients in processed and prepared foods and beverages, including white sugar, brown sugar, raw sugar, corn syrup, corn syrup solids, high-fructose corn syrup (HFCS), malt syrup, maple syrup, pancake syrup, fructose sweetener, liquid fructose, honey, molasses, dextrose, and dextrin. Naturally occurring sugars, such as fructose in fruit or lactose in milk, are not included.

Added sugar from SSBs was calculated using individual food files and by summing per person per day their added sugar intake from sodas, fruit drinks and punches, sports drinks, energy drinks, sweetened tea or coffee drinks, and other SSBs. The food codes used to identify these drinks are summarized in **Supplemental Table 1**. Flavored milk, 100% fruit juice, beverages sweetened by the participant, and alcoholic beverages were not included, consistent with prior

TABLE 1 Characteristics of the sample of 6585 adolescents (aged 12–19 y) according to categories of total added sugar intake: NHANES 1999–2006

	Total added sugar category						
	<10% TEI	10–<15% TEI	15–<20% TEI	20– <25% TEI	25<30% TEI	≥30% TEI	*P*-trend
No. participants	1084 (17)	1151 (17)	1337 (19)	1142 (16)	837 (13)	1034 (18)	—
Median intake, % TEI	6.1%	12.7%	17.5%	22.3%	17.3%	36.0%	—
Male sex	569 (50)	609 (55)	745 (56)	626 (59)	479 (53)	599 (60)	0.033
Age, y	15.5 ± 0.1	15.2 ± 0.1	15.5 ± 0.1	15.4 ± 0.1	15.7 ± 0.1	15.7 ± 0.1	0.250
Race/ethnicity							
Non-Hispanic white	297 (62)	277 (60)	329 (59)	306 (63)	240 (66)	319 (68)	0.023
Mexican American	373 (12)	431 (13)	474 (12)	358 (11)	252 (9)	295 (8)	**0.001**
Non-Hispanic black	309 (11)	258 (14)	426 (16)	394 (16)	279 (14)	338 (13)	0.547
Other/multi-race	105 (15)	85 (13)	108 (13)	84 (11)	66 (11)	82 (12)	0.260
Family income							
PIR <130%	464 (34)	505 (29)	543 (31)	479 (28)	326 (31)	426 (32)	0.823
PIR 130–300%	401 (33)	411 (37)	486 (37)	402 (38)	324 (40)	283 (38)	0.103
PIR >300%	219 (32)	235 (34)	308 (32)	261 (34)	187 (29)	226 (30)	0.312
Current smoker	87 (10)	80 (9)	88 (9)	88 (9)	83 (13)	112 (15)	0.016
Activity, MVPA min/d	86.1 ± 5.8	77.3 ± 3.1	86.8 ± 5.5	87.3 ± 5.6	75.8 ± 4.9	82.1 ± 7.0	0.636
BMI *z*-score	0.76 ± 0.04	0.64 ± 0.05	0.51 ± 0.06	0.71 ± 0.05	0.62 ± 0.07	0.70 ± 0.06	0.783

Results are summarized as means ± SEs for continuous variables and counts and weighted percentages for categorical variables. *P* values calculated using the median value for each intake category in linear regression for continuous variables and logistic regression for categorical variables. **Bold** indicates significant linear trends at $P < 0.005$. MVPA, moderate and vigorous physical activity; PIR, poverty income ratio; TEI, total energy intake.

reports (24). In the MPED and FPED databases, added sugar is expressed in teaspoon equivalents, and this was converted to grams using the factor of 4.2 g/teaspoon, to kcal using the factor 4 kcal/g, and to a percentage of TEI by dividing by kcal/d. Participants were grouped into 6, approximately equal-sized categories of total added sugar intake, with the lowest level based on the current Dietary Guidelines for Americans recommendation to limit added sugar to <10% TEI: <10%, 10% to <15%, 15% to <20%, 20% to <25%, 25% to <30%, and ≥30% TEI. For SSB added sugar, participants were grouped into similar 5% incremental categories, but shifted down to mirror an overall shift in the distribution of SSB compared with total added sugar: <2%, 2% to <7%, 7% to <12%, 12% to <17%, 17% to <22%, and >22% TEI.

Covariates

Sociodemographic information was collected during the household interview for sex, racial/ethnic group (non-Hispanic white, Mexican American, non-Hispanic black, or other/mixed race), and age. The self-reported household poverty income ratio (PIR), a ratio of family income to poverty threshold, was used to measure income status and subjects were categorized as low-income (PIR <130%, which was based on the federal threshold for eligibility for Supplemental Nutrition Assistance Program benefits), middle income (PIR 130–350%), and high income (PIR >350%). Physical activity level (PAL) was measured as average minutes of moderate and vigorous physical activity (MVPA) per day, which was calculated based on the self-reported frequency and duration of individual activities per week. For **Table 1**, participants were categorized relative to the 2018 physical activity guidelines as inactive (<60 min MVPA per day) or active (≥60 min MVPA per day) (25), otherwise PAL was analyzed as a continuous covariate in MVPA/d. Smoking status was assessed during the MEC exam by the audio computer-assisted self-interview. Participants were dichotomized as smokers if they answered "yes" to the question "During the past 5 days, did you use cigarettes?"

Statistical analysis

All analyses were performed in SAS (SAS Institute Inc., version 9.4) and SUDAAN (RTI International; version 9.0.3), unless otherwise noted. Appropriate survey procedures and sample weights were used to adjust for the complex sampling design of NHANES. Analyses involving the multiply-imputed DXA data were performed 5 times in SUDAAN using "Proc Descript" or "Proc Regress", once on each multiply-imputed dataset, and estimates were combined using pooling methods according to NCHS (17). Characteristics of the sample were summarized as means and SEs for continuous variables and counts and weighted frequencies for categorical variables according to category of total or SSB added sugar intake. Linear trends in characteristics across categories of intake were tested by linear regression for continuous variables and logistic regression for dichotomized categorical variables using the median value for each intake category. Continuous variables were assessed for normality using histograms, and natural log-transformation was performed on TLR to correct for right-skewedness.

Stepwise multivariable-adjusted linear regression was used to estimate associations of total and SSB added sugar intake category with log-TLR and TTR. Covariates were adjusted sequentially as follows to understand their contribution to the model: model 1 was adjusted for age (y), sex, race/ethnicity, PIR, smoking status, and PAL; model 2 was adjusted for BMI *z*-score; and model 3 was adjusted for TEI. In this analysis, we considered the lowest category of intake the reference, and visualized the predicted marginal means and 95% CIs for log-TLR and TTR according to added sugar intake category using the *ggplot2* package in R statistical software (R Foundation for Statistical Computing; version 3.4.2) (26). Linear trends in TLR and TTR across intake category were tested using the median value for each category. Effect modification between added sugar intake and sex, race/ethnicity, and weight status was also tested by product interaction terms in the fully

TABLE 2 Characteristics of the sample of 6585 adolescents (aged 12–19 y) according to categories of sugar-sweetened beverage added sugar intake: NHANES 1999–2006

	Sugar-sweetened beverage added sugar category						
	<2% TEI	**2–< 7% TEI**	**7–<12% TEI**	**12–<17% TEI**	**17–<22%**	**≥22% TEI**	***P*-trend**
No. participants	1104 (21)	1108 (14)	1465 (21)	1197 (17)	742 (11)	969 (16)	—
Median intake, %TEI	0%	5.0%	9.4%	14.1%	19.5%	28.2%	—
Male sex	526 (45)	599 (56)	803 (58)	680 (59)	450 (64)	569 (57)	**0.002**
Age, y	15.4 ± 0.1	15.1 ± 0.1	15.4 ± 0.1	15.5 ± 0.1	15.7 ± 0.1	16.1 ± 0.1	**<0.001**
Race/ethnicity							
Non-Hispanic white	382 (70)	242 (53)	341 (58)	302 (63)	206 (61)	295 (68)	0.464
Mexican American	311 (9)	362 (13)	532 (13)	405 (11)	247 (11)	326 (9)	0.413
Non-Hispanic black	308 (10)	407 (19)	472 (15)	406 (16)	236 (15)	275 (11)	0.987
Other/multi-race	103 (12)	97 (15)	120 (14)	84 (10)	53 (13)	73 (12)	0.590
Family income							
PIR <130%	207 (27)	516 (37)	610 (28)	496 (32)	293 (29)	421 (35)	0.152
PIR 130–300%	422 (45)	384 (35)	534 (37)	447 (38)	274 (37)	345 (39)	0.145
PIR >300%	275 (38)	208 (28)	321 (35)	254 (29)	175 (34)	203 (26)	0.013
Current smoker	71 (8)	71 (7)	102 (10)	95 (10)	64 (10)	136 (18)	**<0.001**
Activity, MVPA min/d	81.9 ± 4.8	81.0 ± 4.2	84.9 ± 4.2	86.5 ± 4.6	79.2 ± 7.2	82.1 ± 8.0	0.999
BMI *z*-score	0.65 ± 0.05	0.52 ± 0.05	0.56 ± 0.04	0.72 ± 0.05	0.72 ± 0.06	0.80 ± 0.07	**0.004**

Results are summarized as means ± SEs for continuous variables and counts and weighted percentages for categorical variables. *P* values calculated using the median value for each intake category in linear regression for continuous variables and logistic regression for categorical variables. **Bold** indicates significant linear trends at $P < 0.005$. MVPA, moderate and vigorous physical activity; PIR, poverty income ratio; TEI, total energy intake.

adjusted linear trend models. Lastly, to determine if our results were consistent when 2 dietary recalls were collected, we performed a sensitivity analysis by running the same regression models as above based on 2-d averages for total and SSB added sugar intake in the subsample of participants ($n = 3633$) who completed a second dietary recall by phone.

When *P* values were reported, a more conservative $P < 0.005$ was considered significant (27); otherwise, point estimates and 95% CIs were used to summarize the results. Additionally, in the linear regression models of added sugar intake with log-TLR and TTR, a Bonferroni-correction was applied to correct for multiple testing on 2 adiposity outcomes (i.e., log-TLR and TTR), and $P < 0.0025$ (0.005/2 tests) was considered significant for the evaluation of linear trends and effect modification.

Results

Overall, the mean ± SEM for total added sugar intake was 20.3 ± 0.3% TEI and for SSB added sugar intake was 12.2 ± 0.3% TEI. Characteristics of the sample by category of total and SSB added sugar intake are in Table 1 and **Table 2**, respectively. A higher category of total added sugar intake was associated with a lower proportion of Mexican-American adolescents (*P*-trend <0.005). For SSB added sugar, a higher category of intake was associated with a higher proportion of boys and smokers, and higher mean age and BMI *z*-score (*P*-trend <0.005).

Spearman correlations for the relation between added sugar intake and the adiposity outcomes are detailed in **Table 3**. In multivariable-adjusted linear regression models, none of the interaction terms for effect modification by sex, race/ethnicity, or weight status were significant; therefore, overall estimates are presented. There were no significant associations of total added sugar intake with log-TLR or TTR in any of the stepwise models (**Table 4**). However, we did find associations of SSB added sugar with both outcomes (**Table 5**). In model 1, adjusted for age, sex, race/ethnicity, income group, smoking, and PAL, the β (95% CI) comparing the highest category (>22% TEI) to the lowest category of SSB intake (<2% TEI) for log-TLR was 0.05 (0.01, 0.09) and for TTR was 1.30 (0.53, 2.07) (*P*-trend = 0.0001 for both). The predicted marginal means and 95% CIs for TLR and

TABLE 3 Spearman correlations among total and sugar-sweetened beverage added sugar variables and adiposity variables in the sample of 6585 adolescents (aged 12–19 y): NHANES 1999–2006

	Total added sugar (% TEI)	**SSB added sugar (% TEI)**	**TLR**	**TTR**	**BMI *z*-score**
Total added sugar, % TEI	1.000	—	—	—	—
SSB added sugar, % TEI	0.636 ($P < 0.001$)	1.000	—	—	—
TLR	0.023 ($P = 0.060$)	0.116 ($P < 0.001$)	1.000	—	—
TTR	0.021 ($P = 0.095$)	0.116 ($P < 0.001$)	0.964 ($P < 0.001$)	1.000	—
BMI *z*-score	0.003 ($P = 0.834$)	−0.063 ($P < 0.001$)	−0.464 ($P < 0.001$)	−0.574 ($P < 0.001$)	1.000

All correlation coefficients were calculated using the first multiply-imputed DXA dataset only. SSB, sugar-sweetened beverage; TEI, total energy intake; TLR, truncal-to-leg fat ratio; TTR, truncal-to-total fat ratio.

TABLE 4 β-coefficients and 95% CIs for the association of total added sugar intake with log-TLR and TTR in the sample of 6585 adolescents (12–19 y): NHANES 1999–2006

	Total added sugar category					
Log-TLR:	10–≤15% vs. ≤10%	15–≤20% vs. ≤10%	20–≤25% vs. ≤10%	25–≤30% vs. ≤10%	≥30% vs. ≤10%	Linear trend
Model:[1]	β (95% CI)	β (95% CI)	β (95% CI)	β (95% CI)	β (95% CI)	*P* value
1	−0.02 (−0.05, 0.01)	−0.01 (−0.04, 0.02)	−0.01 (−0.04, 0.02)	0.01 (−0.03, 0.04)	0.005 (−0.03, 0.04)	0.258
2: + BMI z-score	−0.004 (−0.03, 0.02)	0.02 (−0.003, 0.04)	0.001 (−0.02, 0.03)	0.03 (0.001, 0.05)	0.01 (−0.01, 0.04)	0.077
3: + TEI, kcal/d	−0.001 (−0.03, 0.03)	0.02 (−0.001, 0.04)	0.003 (−0.02, 0.03)	0.03 (0.003, 0.06)	0.01 (−0.01, 0.04)	0.099
	Total added sugar category					
TTR:	10–≤15% vs. ≤10%	15–≤20% vs. ≤10%	20–≤25% vs. ≤10%	25–≤30% vs. ≤10%	≥30% vs. ≤10%	Linear trend
Model:[1]	β (95% CI)	β (95% CI)	β (95% CI)	β (95% CI)	β (95% CI)	*P* value
1	−0.54 (−1.15, 0.08)	−0.45 (−1.12, 0.22)	−0.17 (−0.84, 0.50)	0.011 (−0.65, 0.88)	0.14 (−0.56, 0.83)	0.194
2: + BMI z-score	−0.10 (−0.62, 0.43)	0.40 (−0.05, 0.85)	0.05 (−0.43, 0.52)	0.61 (0.12, 1.10)	0.36 (−0.16, 0.88)	0.032
3: + TEI, kcal/d	−0.02 (−0.55, 0.50)	0.45 (−0.01, 0.90)	0.10 (−0.37, 0.57)	0.66 (0.17, 1.14)	0.33 (−0.18, 0.84)	0.045

[1]Model 1 is adjusted for age (y), sex, race/ethnicity, household income group, physical activity (MVPA min/d), and smoking status. In model 2, age- and sex-adjusted BMI z-score was added to model 1 as a covariate. In model 3, TEI (kcal/d) was added to model 2 as a covariate. MVPA, moderate and vigorous physical activity; TEI, total energy intake; TLR, truncal-to-leg fat ratio; TTR, truncal-to-total fat ratio.

TTR across the 6 categories of total and SSB added sugar intake in partially adjusted model 1 are visualized in **Figure 1**. Note that for log-TLR, we performed back-transformations and geometric means are shown.

With the addition of BMI *z*-score in model 2, and TEI in model 3, the magnitude of these differences between the highest and lowest categories were attenuated, but the linear trends remained significant (model 3: *P*-trend = 0.0018 for TLR, and *P*-trend = 0.0004 for TTR, Table 5). The means and 95% CIs for TLR and TTR for each category of total and SSB added sugar and for each stepwise model are in **Supplemental Table 2**.

Results from the sensitivity analyses using mean intakes for total and SSB added sugar among the subsample of participants with 2 dietary recalls ($n = 3633$) are shown in **Supplemental Table 3**. This revealed that there were minor differences compared with the analyses using 1 dietary recall. First, the CIs were slightly wider in this analysis, which is likely due to the reduction in sample size. In addition, for the models with SSB added sugar intake as the independent variable, most of the linear trends were no longer significant at the Bonferroni-adjusted $P < 0.0025$, except for model 1 for TTR. Otherwise, the point estimates for the association of the highest compared with lowest categories of SSB added sugar intake with TLR and TTR were similar, if not larger in magnitude in the sensitivity analysis.

Discussion

The etiology of adipose expandability and body fat distribution is multifactorial, and the role of diet remains an active area of investigation. In this study, we examined whether added sugar intake from all sources and from SSBs specifically are determinants of relative upper-body fat deposition in a nationally representative sample of US adolescents. Overall, we observed that higher SSB added sugar intake (>22% TEI) was associated with higher relative trunk fat deposition, assessed as both TLR and TTF ratios. This association was strongest in partially adjusted models with age, sex, race/ethnicity, income, physical activity, and smoking status as covariates. In the additional models holding BMI z-score and TEI constant, the magnitude of the associations were reduced for both outcomes, by approximately half, but remained significant. In contrast, we did not find evidence of an association of added sugar from all sources with any adiposity outcome.

Our results are supported by other pediatric studies showing that liquid sources of added sugars compared with solid sources are more strongly associated with obesity-related outcomes (28, 29). The predominant explanation for this difference is that, compared with solid sources, liquid sources are associated with lower satiety and incomplete compensation at later meals, resulting in excess energy intake and weight gain (30). Because the magnitude of the associations we found were weakened when adjusting for BMI z-score and TEI, this would suggest that the associations we observed of SSB added sugar with trunk fat deposition was at least partially related to this mechanism.

Importantly, however, when we did adjust for body size and TEI, we still observed associations of SSB added sugar with upper-body fat distribution that, although small in magnitude, were partially independent of these covariates. The exact mechanisms for this finding are unclear and warrant further investigation but could relate to the higher

TABLE 5 β-coefficients and 95% CIs for the association of sugar-sweetened beverage added sugar intake with log-TLR and TTR in the sample of 6585 adolescents (aged12–19 y): NHANES 1999–2006

	SSB added sugar category					
Log-TLR:	2–≤7% vs. ≤2%	7–≤12% vs. ≤2%	12–≤17% vs. ≤2%	17–≤22% vs. ≤2%	≥22% vs. ≤2%	Linear trend
Model:[1]	β (95% CI)	β (95% CI)	β (95% CI)	β (95% CI)	β (95% CI)	*P* value
1	−0.03 (−0.07, 0.001)	−0.01 (−0.04, 0.02)	0.02 (−0.01, 0.05)	0.02 (−0.01, 0.06)	0.05 (0.01, 0.09)	**0.0001**
2: + BMI *z*-score	−0.02 (−0.05, 0.01)	0.003 (−0.02, 0.03)	0.01 (−0.02, 0.03)	0.02 (−0.01, 0.05)	0.03 (0.01, 0.06)	**0.0010**
3: + TEI (kcal/d)	−0.01 (−0.04, 0.01)	0.01 (−0.02, 0.03)	0.01 (−0.02, 0.04)	0.02 (−0.01, 0.05)	0.03 (0.005, 0.06)	**0.0018**
	SSB added sugar category					
TTR:	2–≤7% vs. ≤2%	7–≤12% vs. ≤2%	12–≤17% vs. ≤2%	17–≤22% vs. ≤2%	≥22% vs. ≤2%	Linear trend
Model:[1]	β (95% CI)	β (95% CI)	β (95% CI)	β (95% CI)	β (95% CI)	*P* value
1	−0.75 (−1.49, 0.01)	−0.32 (−0.94, 0.31)	0.46 (−0.23, 1.15)	0.65 (−0.03, 1.33)	1.30 (0.53, 2.07)	**0.0001**
2: + BMI *z*-score	−0.35 (−0.88, 0.12)	0.11 (−0.37, 0.60)	0.16 (−0.39, 0.70)	0.51 (−0.07, 1.07)	0.78 (0.30, 1.26)	**0.0002**
3: + TEI (kcal/d)	−0.22 (−0.74, 0.31)	0.22 (−0.36, 0.70)	0.24 (−0.30, 0.70)	0.54 (−0.02, 1.10)	0.75 (0.27, 1.23)	**0.0004**

[1]Model 1 is adjusted for age (y), sex, race/ethnicity, household income group, physical activity (MVPA min/d) and smoking status. In model 2, age- and sex-adjusted BMI *z*-score was added to model 1 as a covariate. In model 3, TEI (kcal/d) was added to model 2 as a covariate. **Bold** indicates if the *P*-trend is below the Bonferroni-corrected threshold ($P < 0.0025$). MVPA, moderate and vigorous physical activity; SSB, sugar-sweetened beverage; TEI, total energy intake; TLR, truncal-to-leg fat ratio; TTR, truncal-to-total fat ratio.

glycemic index of some SSBs compared with foods with added sugar, which may also contain other nutrients such as fat or fiber that reduce the glycemic index. The higher glycemic index of SSBs may promote trunk fat gain due to the lipogenic effects of an increased insulin response and/or impaired metabolic flexibility (31). This is supported by some adult intervention studies, which suggest that a low-glycemic index diet is associated with a lower insulin secretory response and greater loss in intra-abdominal fat, regardless of weight loss, compared with a high-glycemic index diet (32, 33). SSB intake has also been associated with higher concentrations of proinflammatory markers in observational studies of children (34), and in intervention studies in adults (35). This may be another mechanism to explain associations of SSBs with preferential trunk fat deposition, as low-grade inflammation is hypothesized to be a key determinant of impaired subcutaneous fat expansion and intra-abdominal fat susceptibility (36, 37).

In addition, SSBs are commonly sweetened with HFCS in the US, which consists of approximately equal parts fructose and glucose. Fructose in particular is able to bypass key regulatory steps during liver metabolism, and has been associated with lipogenic gene expression (38, 39), which could promote ectopic and intra-abdominal fat deposition (40, 41). However, because glucose is also present in HFCS, we cannot differentiate whether fructose alone or the combination of fructose and glucose may be responsible for these findings. Further, in this study, the DXA scans did not measure ectopic fat, such as in the liver, nor the specific type of abdominal fat deposition (i.e. visceral versus subcutaneous). More detailed phenotype assessments are needed in future pediatric research examining these diet-body fat distribution associations.

This study has both weaknesses and strengths that should be noted. Due to the cross-sectional nature of this study, we cannot assess directionality. We relied on self-reported dietary intake, which is prone to several biases, such as social desirability bias, especially among overweight and obese adolescents (42, 43). Recall bias may also be more common with foods, especially snacks, compared with beverages, and this might have led to more measurement error in our assessment of total added sugar (44, 45). In addition to not having more detailed body fat deposition assessments, as mentioned above, NHANES also did not assess genotype or pubertal stage, which both may independently influence body fat distribution. Lastly, although we used a more conservative *P* value to evaluate linear trends, we chose to report point estimates and 95% CIs for all other results; therefore, false positive results are possible and caution should be taken in interpreting the findings.

Strengths of our study included its large, nationally representative sample of adolescents in the USA. The sample was diverse in terms of race/ethnicity and income status, and included children with a range of BMI *z*-scores, which enhances generalizability. NHANES performs a combination of questionnaire-, physical examination-, and laboratory-based measurements, which allowed for the assessment of a comprehensive list of covariates. The availability of 2 dietary recalls among a subsample of participants starting in 2003 enabled us to perform sensitivity analyses to assess whether the results differed in comparison to the original analyses of 1 dietary recall, and this revealed only minor changes that were likely related to the reduction in sample size and subsequently statistical power. Lastly, the NHANES cycles in this study included accurate and reliable measurements of body composition by

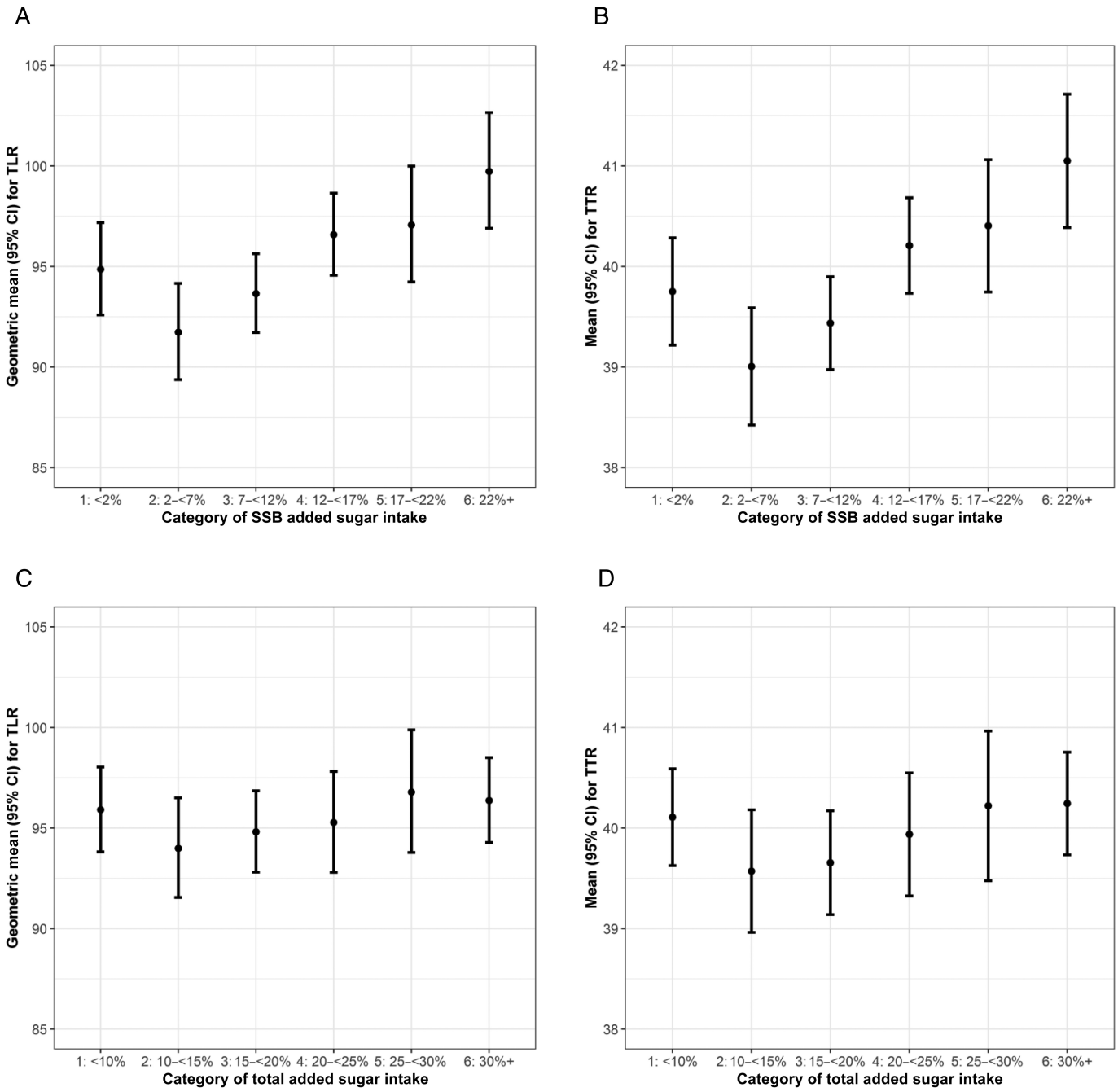

FIGURE 1 Means and 95% CIs of TLR and TTR according to categories of SSB and total added sugar intake in the sample of 6585 adolescents (aged 12–19 y), NHANES 1999–2006. Estimates are from the partially adjusted models with adjustment for age (y), sex, race/ethnicity, household income group, physical activity (MVPA min/d), and smoking status. (A) TLR and (B) TTR according to category of SSB added sugar intake; (C) TLR and (D) TTR according to category of total added sugar intake. For TLR, geometric means were calculated to account for log-transformation. Abbreviations: MVPA, moderate and vigorous physical activity; SSB, sugar-sweetened beverages; TLR, truncal-to-leg fat ratio; TTR, truncal-to-total fat ratio.

DXA, which is a gold standard for the evaluation of total and regional fat mass.

In conclusion, the findings of this study suggest that SSB added sugar intake is associated with higher relative upper-body fat deposition, expanding on prior studies of adolescents in NHANES that found associations of SSBs with waist circumference, HOMA-IR, and dyslipidemia (46). Together with evidence from adults that the long-term consumption of SSBs is associated with a higher risk of mortality, especially from cardiovascular disease, independent of BMI (47), evidence is mounting that SSBs may have effects on health beyond overall weight gain. How-

ever, it is important to emphasize that the effect sizes we found for the associations of SSB added sugar with TLR and TTR were relatively small, and driven by the highest category of intake; therefore, the clinical significance of our findings may be modest. Additional efforts are needed to understand the potential biological mechanisms that may explain a link between SSBs, body fat distribution, and metabolic dysfunction in youths.

Acknowledgments

The authors' responsibilities were as follows—CEC: designed and conducted the research, and JAW and MBV: provided oversight; CEC: wrote the manuscript, and JAW, JAA, TJH, KMVN, and MBV: reviewed the manuscript and assisted with revisions and interpretation; CEC and MBV: are responsible for the final content; and all authors read and approved the final manuscript.

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