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Sugar-sweetened beverage consumption is associated with visceral fat in children

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Abstract

Sugar-sweetened beverage (SSB) consumption has been associated with visceral fat partitioning in adults; however, the underlying mechanisms in childhood remain unclear and warrant exploration. This cross-sectional study aimed to investigate the association between SSB consumption and body fat in children aged 9–13 years and the potential modifying effect of children's sex and serum cortisol levels. A sample of 2665 Greek schoolchildren participated in the 'Healthy Growth Study', and anthropometric, body composition, dietary intake and serum cortisol data were assessed. SSB consumption was defined as low (<1 serving/d), medium (1–2 servings/d) or high (>2 servings/d). We used linear regression models to assess the association between SSB consumption and measures of adiposity and to assess effect modification; models were stratified by sex and tertiles of morning serum cortisol. A significant positive association was observed between high SSB consumption and visceral adipose tissue (VAT) ($\beta = 1{\cdot}4$, 95 % CI 0·4, 2·3, $P = 0{\cdot}01$) but not BMI or BMI *z*-score. When stratified by sex, the association was observed in boys ($\beta = 1{\cdot}8$, 95 % CI 0·3, 3·4, $P = 0{\cdot}02$) but not in girls. When stratified by cortisol levels, SSB consumption was associated with VAT in children with cortisol levels in the lowest tertile ($\beta = 2{\cdot}8$, 95 % CI 1·0, 4·6, $P < 0{\cdot}01$). These results indicate that increased SSB consumption is associated with visceral adiposity in schoolchildren and this association may be modified by sex and morning serum cortisol. To prevent VAT accumulation and concomitant disease risk, dietary interventions should target SSB consumption during childhood.

Key words: **Sugar-sweetened beverages: Visceral adipose tissue: Serum cortisol: Children**

Childhood obesity is a global epidemic affecting an estimated 124 million children worldwide[1]. Although it is well recognised that childhood obesity, as evaluated by BMI, increases the risk of developing CVD, hypertension and type 2 diabetes in adulthood; a growing body of research now indicates that abdominal obesity, particularly the accumulation of visceral adipose tissue (VAT), may be a stronger predictor of cardiovascular and metabolic disease risk than general BMI-defined obesity[2–6]. Furthermore, abdominal obesity can occur independently of BMI-defined obesity, meaning that akin to overweight and obese children; normal weight children with excess visceral adiposity are at a heighten risk of future morbidity and premature mortality[4–6].

Diet is an important lifestyle factor known to influence body fat distribution. In this context, evidence indicates that Mediterranean dietary patterns may be protective against the development of abdominal adiposity[7,8]. However, in recent decades, there has been a distinct shift away from traditional eating habits in Mediterranean regions and increasingly, children are adopting a more Western diet characterised by an increased consumption of refined sugars, saturated fats and processed foods[9]. Coinciding with this nutrition transition, children living in the Mediterranean regions of Southern Europe are now experiencing higher rates of abdominal obesity, even in the absence of an increased BMI[10–12]. As the accumulation of VAT begins in childhood and is an early predictor of future

Abbreviations: HPA, hypothalamic–pituitary–adrenal; SSB, sugar-sweetened beverage; VAT, visceral adipose tissue.

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morbidity[13], there is a need to identify modifiable dietary habits in children that could account for the preferential distribution of fat in visceral depots.

Sugar-sweetened beverages (SSBs) are typical of the Western diet and may play a role in visceral fat partitioning, as recent studies in adults[14–17] and adolescents[18,19] have reported a positive association between increased SSB consumption and VAT accumulation. To date, research regarding SSB consumption in children has typically explored associations with total adiposity; while there is now convincing evidence linking SSB consumption to weight gain and BMI-defined obesity[20,21], data on visceral adiposity remain scarce. Although a few studies in children have found SSB consumption to be positively associated with abdominal obesity[21–24], these studies are limited by their use of waist circumference, which is unable to distinguish VAT from subcutaneous adipose tissue. As VAT is a stronger correlate of chronic disease risk than subcutaneous adipose tissue[13], it is important to discern whether SSB consumption is specifically associated with VAT in children.

Furthermore, while the associations between SSB consumption and general adiposity can typically be explained by an increase in energy intake, the mechanisms explaining visceral fat partitioning are lesser known. One possible mechanism may involve the stress hormone cortisol, a glucocorticoid secreted as a function of the hypothalamic–pituitary–adrenal (HPA) axis. Under basal conditions, cortisol secretion typically follows a diurnal rhythm; however, in response to psychological or physiological stressors, the HPA axis becomes hyperactive and cortisol secretion is increased[25]. Dysregulation of the HPA axis and subsequent elevations in basal cortisol has been implicated in the aetiology of visceral obesity[25,26], and recent evidence suggests diets high in sugar may exacerbate this relationship, with work in overweight adolescents finding morning serum cortisol and high sugar intake interact to predict VAT accumulation[27]. As SSBs are a major source of sugar among children[28], it is possible that their consumption may increase VAT accumulation through mechanisms of HPA dysregulation. To date, only one study has explored the interrelationship between SSBs, cortisol and VAT. As such, the cross-sectional study by Shearrer *et al.*[18] found SSB consumption to be independently associated with cortisol and VAT in minority youth, but no interaction effects of SSB consumption and cortisol on VAT were observed. However, the study by Shearrer *et al.*[18] was limited by its small sample of overweight/obese minority youth and warrants repeating in a larger sample with a wider range of weight status. Therefore, in our study, we sought to assess the association between SSB consumption and body fat and whether sex and serum cortisol levels modified these associations in children.

Methods

Participants and design

The Healthy Growth Study was a large-scale, cross-sectional epidemiological study conducted from 2007 to 2009. The Healthy Growth Study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving human subjects were approved by the Ethics Committee of Harokopio University of Athens. The Greek Ministry of National Education also approved the study's protocol. The study sample comprised 2665 schoolchildren aged 9–13 years old, attending the fifth and sixth grades of primary schools located in municipalities within Attica, Aitoloakarnania, Thessaloniki and Iraklio. The sampling of schools was random, multi-stage and stratified by parents' educational level and total population of students attending schools within these municipalities. Specifically, the municipalities in the prefectures under study were divided into three groups on the basis of average educational level of their adult population (25–65 years old) that was estimated from data provided by the National Statistical Service of Greece (2001 census). Consequently, municipalities, proportional to the size of their population of children aged 9–13 years old, were randomly selected from each socio-economic level. Finally, a number of schools were randomly selected from each municipality, proportional to the population of schoolchildren registered in the fifth and sixth grades, according to data obtained from the Greek Ministry of Education. Written informed consent was obtained from all parents before data were collected. All participating children underwent a physical examination by an experienced paediatrician and children's health status was assessed using a standardised checklist (see online Supplementary material 1). Additionally, information regarding children's medical history was collected from their parents via a standardised questionnaire (see online Supplementary material 2). Further details describing the sampling procedure of the Healthy Growth Study are provided elsewhere[29].

Anthropometric and visceral fat mass data

Weight was measured to the nearest 0·1 kg using a SECA model 770 digital scale (SECA) and height was measured to the nearest 0·1 cm using a stadiometer (Leicester Height Measure; Invicta Plastics Ltd). BMI was calculated using the equation weight (kg) divided by height squared (m^2), and children were categorised as underweight, normal weight, overweight and obese in accordance with the International Obesity Task Force cut-off points[30]. The WHO 2007 Growth Reference macro package was used to calculate children's BMI-for-age *z*-score[31]. Bioelectrical impedance analysis was used to determine abdominal VAT (VIScan AB-140; Tanita Corporation). In this simple, non-invasive method, a weak electrical current is passed between the regions near the umbilicus and spinal cord at the umbilicus level and the voltage generated in the lateral abdomen is recorded. Because the equipotential line that passes through visceral fat appears on the lateral abdominal surface, the amount of visceral fat can be estimated by measurement of the voltage generated at this location using a regression equation determined by computed tomography[32]. Although imaging techniques, such as computed tomography and magnetic resonance imaging, are considered to be the gold standard for measuring VAT, these methods are highly expensive and involve radiation exposure[33]. The bioelectrical impedance analysis method is therefore favourable for a sample of this size and age, and VAT estimated by bioelectrical impedance analysis has previously been shown to be highly correlated with VAT determined by computed tomography[32]. In the 4 h prior to

measurement, children were instructed to abstain from consuming food or liquid and from any intensive exercise. Children were also instructed not to wear any metallic object during measurement. Total VAT was read straight from the instrument in a rating scale of 1–59 units, reported to the nearest 0·5 increment.

Sugar-sweetened beverage consumption and dietary intake data

Data regarding dietary intake were collected for two consecutive weekdays and one weekend day via the 24 h recall method. Dietary intake recalls were analysed using the Nutritionist V diet analysis software (version 2.1, 1991; First Databank) which was extensively amended to include traditional Greek recipes and nutritional information of processed foods provided by independent research institutes, food companies and fast food chains. Mean values from the three 24 h recalls were used and daily energy intake was expressed as kJ. SSBs were defined as any beverage containing added sugar, namely sugar-sweetened soft drink and sugar-sweetened fruit juice, and consumption was measured in g/d. To align with prior research[18], grams were converted to fluid ounces and one serving of SSBs was defined as 8 oz (or 226·8 g). The WHO strongly recommends both children and adults limit the consumption of added sugars to less than twelve teaspoons (about 50 g) per d and suggests that a further reduction to less than six teaspoons (about 25 g) per d provides additional health benefits[34]. As an 8 oz serving of SSBs typically contains approximately 25 g of added sugar, the children were classified into three SSB consumption categories, that is, low SSB consumption (<1 serving/d), medium SSB consumption (≥1 to <2 servings/d) and high SSB consumption (≥2 servings/d), the levels modelling this 25 g increase in daily added sugar intake.

Serum cortisol data

Blood samples were obtained in the morning between 08.30 and 10.30 hours following a 12-h overnight fast. Morning serum cortisol was measured by electrochemiluminescence immunoassay on the Roche Cobas e 411 analyzer (Roche Diagnostics SA). The lower and upper detection limits were 0·05 and 63·4 μg/dl, respectively.

Socio-demographic, physical activity and biological maturation data

Data on the level of parental education were collected from the parents (preferably from the mother) during face-to-face interviews. Maternal and paternal years of education were each stratified into three categories, that is, less than 9 years, which corresponds to having a junior high school degree; 9–12 years, which corresponds to having a high school degree; and more than 12 years, which corresponds to having a college, university or post-graduate education. Children's physical activity was assessed via step count using a waist-mounted pedometer (Yamax SW-200 Digiwalker; Yamax Corporation), which they were instructed to wear for 1 week. Tanner stage, an index of biological maturation, was determined by female paediatricians, who thoroughly inspected breast development in girls and genital development in both girls and boys.

Statistical analysis

Continuous variables were expressed as mean values and standard deviations, and categorical variables were reported as frequencies and percentages. Student's t test and χ^2 analyses were performed to evaluate differences in descriptive variables between boys and girls. Multivariate linear regression models were developed to assess the relationship between SSB consumption and VAT, BMI and BMI z-scores for the total sample. Both unadjusted models and models adjusted for sex, Tanner stage, daily energy intake, total daily steps and parental education status are presented. To explore effect modification, we first stratified all regression models by sex to understand whether the associations between SSB consumption and outcome variables are influenced by sex. We then fitted an interaction term between SSB and sex in all regression models for VAT, BMI and BMI z-scores and reported these interactions if they were statistically significant.

To adjust for the possible confounding effects of cortisol, serum cortisol level (μg/dl) was added as a continuous variable in all regression models. Serum cortisol levels were then recoded into tertiles based on its distribution within the total sample, and children were categorised as having low, medium or high cortisol levels if they were in the first, second or third tertile, respectively. We then conducted strata-specific analysis by these serum cortisol tertiles to assess the association of SSB consumption and VAT, BMI and BMI z-scores with adjustment for all possible variables. The results from the multiple linear regression models are presented as β-coefficients and 95 % CI. All statistical analyses were conducted using Stata (version 15.1, StataCorp) and the level of significance was set at $P < 0·05$.

Results

The sample was composed of 2665 children (50·5 % boys) attending the fifth and sixth grades of primary school. Ages ranged from 9–13 years, with a mean age of 11·2 (SD 0·7) years (Table 1). Of the total sample, 3·1 % of children were underweight, 55·1 % were normal weight, 30·3 % were overweight and 11·5 % were obese. Significant sex differences were found in regard to adiposity, with boys having a higher BMI, BMI z-score and visceral fat rating than girls. In addition, girls were found to have significantly lower cortisol levels and were more likely to be in Tanner stages 3–5 compared with boys. Regarding energy intake and expenditure, boys consumed more energy per d and were more physically active than girls. No significant sex differences were found in regard to socio-economic characteristics (maternal and paternal education).

The majority of children (81·9 %) were categorised as having low SSB consumption, although boys were more likely than girls to be medium (62·7 *v.* 37·3 %) and high (61·2 *v.* 38·8 %) consumers of SSBs ($P < 0·01$; Table 1).

High SSB consumption was significantly associated with VAT but not with BMI or BMI z-scores (Table 2). High SSB consumers had a visceral fat rating 1·3 units higher than low consumers (95 % CI 0·3, 2·3, $P = 0·01$) and adjusting for covariates strengthened this relationship ($\beta = 1·4$, 95 % CI 0·4, 2·3, $P = 0·01$). In this model, sex, daily energy intake and physical activity were significantly associated with VAT ($P < 0·01$) as well as Tanner stages 2

Table 1. Descriptive characteristics of children by sex
(Mean values and standard deviations; numbers and percentages)

	Total (*n* 2665)				Girls (*n* 1318)				Boys (*n* 1347)				
	Mean	SD	*n*	%	Mean	SD	*n*	%	Mean	SD	*n*	%	*P*
SSB consumption													
Low			2095	81·9			1095	86·3			1000	77·6	<0·01†
Medium			346	13·5			129	10·2			217	16·9	
High			116	4·5			45	3·6			71	5·5	
Cortisol (μg/dl)‡	11·9	5·5			11·6	5·6			12·3	5·4			<0·01*
Age (years)	11·2	0·7			11·2	0·7			11·2	0·7			0·95*
Tanner stage													
1			827	32·3			277	21·0			550	44·2	<0·01†
2			1072	41·8			522	39·6			550	44·2	
3			469	18·3			348	26·4			121	9·7	
4			160	6·3			138	10·5			22	1·8	
5			34	1·3			33	2·5			1	0·1	
Lifestyle parameters													
Daily energy intake (kJ)	7479·0	2317·8			7052·3	2104·0			7903·5	2440·2			<0·01*
Daily steps	13 249·5	5226·5			11 789·8	4316·8			14 700·2	563·8			<0·01*
Maternal education													
Low (<9 years)			573	22·2			306	23·9			267	20·6	0·13†
Medium (9–12 years)			1010	39·2			488	38·1			522	40·3	
High (>12 years)			994	38·6			487	38·0			507	39·1	
Paternal education													
Low (<9 years)			688	26·4			348	26·9			340	26·0	0·82†
Medium (9–12 years)			997	38·3			489	37·8			508	38·8	
High (>12 years)			920	35·3			458	35·4			462	35·3	
Anthropometric measures													
Weight (kg)	45·3	11·1			45·2	11·0			45·5	11·2			0·50*
Height (cm)	148·7	7·9			149·2	8·3			148·3	7·4			<0·01*
BMI (km/m^2)	20·3	3·8			20·1	3·7			20·5	4·0			0·01*
BMI *z*-score	0·95	1·2			0·8	1·2			1·1	1·2			<0·01*
Visceral fat (rating)	4·9	3·4			4·0	2·3			5·9	4·0			<0·01*
Weight status													
Underweight			82	3·1			49	3·8			33	2·5	<0·01†
Normal weight			1438	55·1			743	57·3			695	52·9	
Overweight			790	30·3			382	29·5			408	31·0	
Obese			301	11·5			122	9·4			179	13·6	

SSB, sugar-sweetened beverage.
* Derived from Student's *t* test.
† Derived from χ^2 test.
‡ Cortisol values are presented in conventional units (μg/dl). To convert values to SI units (nmol/l), multiply by 27·6.

and 3, and maternal education >12 years ($P < 0·05$). Sex was significantly associated with measures of adiposity in each model, with girls having significantly lower VAT, BMI and BMI *z*-scores compared with boys ($P < 0·01$, results not shown). Therefore, to assess for potential effect modification, models were stratified by sex (Table 2). While no significant associations were found between SSB consumption and measures of adiposity in girls, high SSB consumption in boys was significantly associated with VAT, but not BMI or BMI *z*-scores, in the adjusted model ($\beta = 1·8$, 95 % CI 0·3, 3·4, $P = 0·02$). In this model, the following covariates were significant: daily energy intake ($P < 0·01$), physical activity ($P < 0·01$), maternal education >12 years and paternal education 9–12 years ($P < 0·05$).

After inclusion of cortisol in the models (Table 3), high SSB consumption remained significantly associated with VAT in the adjusted model ($\beta = 1·3$, 95 % CI 0·3, 2·3, $P = 0·01$), as did sex ($P < 0·01$), Tanner stage 3 ($P < 0·01$), daily energy intake ($P < 0·01$), physical activity ($P < 0·01$) and maternal education >12 years ($P < 0·05$). Although cortisol was not significantly associated with measures of general adiposity (BMI and BMI *z*-scores), an inverse association was found between cortisol and visceral adiposity, with every 1 μg/dl increase in cortisol predicting a –0·04 reduction in VAT (95 % CI –0·1, –0·0, $P = 0·01$). Converted to SI units, every 1 nmol/l increase in cortisol is associated a –0·001 reduction in VAT (95 % CI –0·003, –0·0003, $P = 0·01$; SI units are not presented in Table 3). The effects for the sex stratification remained the same after inclusion of cortisol as a covariate in the adjusted models (Table 3).

When the association between SSB consumption and measures of adiposity was stratified by cortisol levels (Table 4), it was found that high compared with low SSB consumption was associated with a greater VAT in children with low cortisol levels ($\beta = 2·8$, 95 % CI 1·0, 4·6, $P < 0·01$). For children with medium or high cortisol levels, no associations were found between SSB consumption and measures of adiposity.

Table 2. Associations of sugar-sweetened beverage (SSB) consumption and measures of adiposity (β-Coefficients and 95 % confidence intervals)

	Visceral fat						BMI						BMI *z*-score					
	Unadjusted			Adjusted*			Unadjusted			Adjusted*			Unadjusted			Adjusted*		
	β	95 % CI	*P*	β	95 % CI	*P*	β	95 % CI	*P*	β	95 % CI	*P*	β	95 % CI	*P*	β	95 % CI	*P*
Total																		
SSB low	Reference category			Reference category			Reference category			Reference category			Reference category			Reference category		
SSB medium	0·5	−0·1, 1·0	0·10	0·3	−0·2, 0·9	0·23	0·2	−0·3, 0·6	0·52	0·3	−0·2, 0·7	0·25	−0·01	−0·2, 0·1	0·92	0·03	−0·1, 0·2	0·69
SSB high	1·3	0·3, 2·3	0·01	1·4	0·4, 2·3	0·01	0·4	−0·4, 1·1	0·32	0·4	−0·3, 1·2	0·23	−0·04	−0·3, 0·2	0·75	0·02	−0·2, 0·2	0·88
Boys																		
SSB Low	Reference category			Reference category			Reference category			Reference category			Reference category			Reference category		
SSB medium	−0·00	−0·8, 0·8	1·00	0·4	−0·5, 1·2	0·40	0·2	−0·4, 0·8	0·51	0·5	−0·2, 1·1	0·14	−0·1	−0·2, 0·1	0·61	0·1	−0·1, 0·3	0·47
SSB high	1·0	−0·5, 2·4	0·21	1·8	0·3, 3·4	0·02	0·7	−0·3, 1·6	0·18	0·8	−0·2, 1·8	0·10	−0·00	−0·3, 0·3	0·99	0·1	−0·2, 0·4	0·47
Girls																		
SSB low	Reference category			Reference category			Reference category			Reference category			Reference category			Reference category		
SSB medium	0·3	−0·3, 1·0	0·27	0·3	−0·3, 0·9	0·36	−0·1	−0·8, 0·6	0·84	0·01	−0·6, 0·7	0·98	−0·1	−0·3, 0·2	0·54	−0·02	−0·2, 0·2	0·85
SSB high	0·8	−0·3, 2·0	0·16	1·0	−0·2, 2·1	0·10	−0·2	−1·3, 0·9	0·71	−0·1	−1·1, 1·0	0·90	−0·2	−0·5, 0·2	0·26	−0·1	−0·5, 0·2	0·51

* Adjusted for sex (total sample only), Tanner stage, total daily energy intake, parental education and total steps per d.

Table 3. Association between sugar-sweetened beverage (SSB) consumption, cortisol and measures of adiposity (β-Coefficients and 95 % confidence intervals)

	Visceral fat						BMI						BMI *z*-score					
	Unadjusted			Adjusted*			Unadjusted			Adjusted*			Unadjusted			Adjusted*		
	β	95 % CI	*P*	β	95 % CI	*P*	β	95 % CI	*P*	β	95 % CI	*P*	β	95 % CI	*P*	β	95 % CI	*P*
Total																		
SSB low	Reference category			Reference category			Reference category			Reference category			Reference category			Reference category		
SSB medium	0·5	−0·1, 1·1	0·07	0·4	−0·2, 0·9	0·21	0·1	−0·4, 0·6	0·67	0·2	−0·3, 0·6	0·50	−0·01	−0·2, 0·1	0·89	0·0	−0·1, 0·1	0·98
SSB high	1·2	0·2, 2·2	0·02	1·3	0·3, 2·3	0·01	0·4	−0·4, 1·2	0·29	0·4	−0·3, 1·2	0·29	−0·02	−0·3, 0·2	0·85	−0·01	−0·2, 0·2	0·98
Cortisol (μg/dl)†	−0·01	−0·0, 0·0	0·59	−0·04	−0·1, −0·0	0·01	−0·02	−0·0, 0·0	0·28	−0·03	−0·1, 0·0	0·06	−0·00	−0·0, 0·0	0·48	−0·01	−0·0, 0·0	0·11
Boys																		
SSB low	Reference category			Reference category			Reference category			Reference category			Reference category			Reference category		
SSB medium	0·04	−0·8, 0·9	0·93	0·4	−0·5, 1·3	0·39	0·3	−0·3, 0·9	0·36	0·4	−0·2, 0·1	0·17	−0·01	−0·2, 0·2	0·94	0·1	−0·1, 0·3	0·50
SSB high	0·8	−0·8, 2·3	0·33	1·6	−0·1, 3·3	0·05	0·6	−0·4, 1·6	0·24	0·7	−0·3, 1·7	0·15	−0·02	−0·3, 0·3	0·91	0·1	−0·2, 0·4	0·53
Cortisol (μg/dl)†	−0·02	−0·1, 0·0	0·52	−0·1	−0·1, 0·0	0·11	−0·02	−0·1, 0·0	0·42	−0·02	−0·1, 0·0	0·28	−0·01	−0·0, 0·0	0·32	−0·01	−0·0, 0·0	0·32
Girls																		
SSB low	Reference category			Reference category			Reference category			Reference category			Reference category			Reference category		
SSB medium	0·4	−0·3, 1·0	0·29	0·3	−0·3, 1·0	0·33	−0·4	−1·1, 0·4	0·33	−0·3	−0·9, 0·4	0·46	−0·1	−0·4, 0·1	0·20	−0·1	−0·3, 0·1	0·40
SSB high	0·9	−0·3, 2·0	0·13	1·0	−0·1, 2·2	0·07	−0·1	−1·3, 1·1	0·86	−0·1	−1·2, 1·1	0·91	−0·2	−0·6, 0·2	0·31	−0·1	−0·5, 0·2	0·47
Cortisol (μg/dl)†	−0·02	−0·1, 0·0	0·19	−0·03	−0·1, −0·0	0·04	−0·1	−0·1, 0·0	0·30	−0·03	−0·1, 0·0	0·12	−0·00	−0·0, 0·0	0·51	−0·01	−0·0, 0·0	0·21

* Adjusted for sex (total sample only), Tanner stage, total daily energy intake, paternal education and total steps per d.
† Cortisol values are presented in conventional units (μg/dl). SI units (nmol/l) are not presented.

Table 4. Association between sugar-sweetened beverage (SSB) consumption and measures of adiposity, stratified by serum cortisol levels (β-Coefficients and 95 % confidence intervals)

	Visceral fat								
	Low cortisol			Medium cortisol			High cortisol		
	β	95 % CI	*P*	β	95 % CI	*P*	β	95 % CI	*P*
Unadjusted									
SSB low		Reference category			Reference category			Reference category	
SSB medium	0·02	−1·0, 1·0	0·97	0·9	−0·2, 2·0	0·12	0·7	−0·2, 1·7	0·13
SSB high	2·8	1·0, 4·6	<0·01	1·0	−0·6, 2·7	0·22	−0·4	−2·3, 1·6	0·72
Adjusted*									
SSB low		Reference category			Reference category			Reference category	
SSB medium	0·01	−1·0, 1·0	0·98	0·7	−0·4, 1·8	0·20	0·4	−0·5, 1·3	0·36
SSB high	2·8	1·0, 4·6	<0·01	1·0	−0·6, 2·6	0·21	0·1	−1·8, 2·0	0·94
	BMI								
	Low cortisol			Medium cortisol			High cortisol		
Unadjusted									
SSB low		Reference category			Reference category			Reference category	
SSB medium	−0·5	−1·3, 0·3	0·20	0·5	−0·3, 1·4	0·23	0·4	−0·4, 1·1	0·37
SSB high	1·1	−0·4, 2·5	0·14	−0·2	−1·5, 1·0	0·70	0·6	−0·7, 1·9	0·34
Adjusted*									
SSB low		Reference category			Reference category			Reference category	
SSB medium	−0·5	−1·2, 0·4	0·27	0·6	−0·3, 1·4	0·17	0·4	−0·4, 1·1	0·35
SSB high	1·3	−0·2, 2·8	0·08	−0·1	−1·3, 1·1	0·91	0·3	−0·9, 1·6	0·60
	BMI *z*-score								
	Low cortisol			Medium cortisol			High cortisol		
Unadjusted									
SSB low		Reference category			Reference category			Reference category	
SSB medium	−0·2	−0·5, 0·0	0·08	0·2	−0·1, 0·4	0·29	0·1	−0·2, 0·3	0·63
SSB high	0·2	−0·2, 0·6	0·38	−0·3	−0·7, 0·1	0·12	0·1	−0·3, 0·5	0·56
Adjusted*									
SSB low		Reference category			Reference category			Reference category	
SSB medium	−0·2	−0·4, 0·1	0·12	0·2	−0·1, 0·4	0·27	0·1	−0·2, 0·3	0·65
SSB high	0·3	−0·2, 0·7	0·23	−0·2	−0·6, 0·1	0·22	0·1	−0·3, 0·5	0·72

* Adjusted for sex, Tanner stage, total daily energy intake, parental education and total steps per d.

Discussion

Our findings suggest an association between high SSB consumption and visceral, but not general, adiposity, and this association was found to be stronger in boys. Furthermore, we aimed to investigate HPA dysregulation as a potential mechanism accounting for the association between SSBs and fat partitioning in visceral adipose depots. The results from our stratified analysis found high SSB consumption was only associated with VAT in children with low morning cortisol levels.

To date, much of the focus has been on the association between SSBs and general adiposity in children[20,21], but we found no association between SSBs and BMI or BMI *z*-scores. Although the majority of the literature supports a positive association, much of this research was conducted in US children with reportedly high SSB intakes[20,21]. One other study in Greek schoolchildren also found a positive association between SSB consumption and BMI[35]; however, SSB consumption in their sample was similar to that reported in US children and was much higher than what was observed in the present study. It is therefore possible that consumption patterns are not high enough in our sample to have observable effects on general adiposity. Additionally, fewer than 20 % of children in our sample consumed more than one serving of SSBs per d, and so our analysis may have lacked sufficient power to detect a significant association in medium or high SSB consumers. Moreover, it has been argued that studies should not adjust for energy intake in their analyses, as energy is likely to mediate the association between SSBs and adiposity[36]. However, even without adjustment for energy intake, we found no association between SSBs and general adiposity.

Nevertheless, SSB consumption patterns in our sample were sufficient to detect an association between SSB consumption and visceral adiposity, with our results showing that those consuming ≥2 servings of SSBs per d had a significantly greater visceral fat rating than those consuming <1 serving per d, even after adjustment for energy intake. Previous work investigating the relationship between SSBs and visceral adiposity has shown that increased SSB consumption is positively associated with VAT accumulation in adults[14–17] and adolescents[18,19]; however, the present study is the first to extend these findings to children. Moreover, our results are consistent with several studies demonstrating a positive association between SSB consumption and waist circumference in school-aged children[21–24], and further support WHO recommendations to reduce added sugar intake to below 50 g/d[34].

Sex-stratified analyses revealed that the association between SSB consumption and VAT was stronger in boys. However, when an interaction term was included in the regression models, the results were not statistically significant and so additional studies are needed to replicate our findings. Nevertheless, one other study has examined sex differences in the relationship between

SSBs and abdominal obesity in children[22]. In line with our findings, Collison *et al.*[22] reported SSB consumption was associated with a higher waist circumference in Saudi school boys but not in girls. There are several possible interpretations to explain these sex differences. Firstly, it is well established that men accumulate more visceral fat than females, who typically store more fat in subcutaneous depots, particularly in their hips and thighs[37]. Moreover, in a review of evidence in children, Staiano & Katzmarzyk[13] confirmed that sexual dimorphism in fat patterning may also be evident in children, as was demonstrated in our study, whereby boys had an average visceral fat rating 1·9 units higher than girls. Although the mechanisms responsible for these sex differences in body fat distribution are not well understood in children[13], the aforementioned differences may explain why the association between SSB consumption and VAT was more pronounced in boys. Secondly, in both our sample and the sample of Saudi schoolchildren, boys were greater consumers of SSBs than girls. While this is to be expected, as males typically consume greater intakes of SSBs than females globally[38], it is possible that consumption patterns in girls were not high enough to detect a significant association and/or stratified analyses may have lacked sufficient power. Furthermore, it is important to note that the majority of girls in our sample were at later stages of pubertal maturation than were boys and this could also play a part in the sex differences observed.

The positive association between SSB consumption and VAT remained robust, even after adjustment for morning serum cortisol levels. Moreover, we found a weak negative association between morning serum cortisol and VAT accumulation. Literature on the relationship between morning cortisol and abdominal adiposity in youth is limited. Although some studies have shown morning serum cortisol to be positively associated with visceral adiposity[27,39,40], these studies have only included overweight and obese subjects. Two studies inclusive of normal weight children assessed morning salivary cortisol[41,42], a strong correlate of serum cortisol[43]. Both studies were conducted in samples of Western children and neither found an association between cortisol and abdominal adiposity[41,42]. Disparities between our results and those previous may be explained by differences in the characteristics of study participants as well as differences in cortisol sampling procedures, as some studies used salivary cortisol and the time at which samples were collected varied. Furthermore, in the present study, associations between cortisol and VAT were adjusted for lifestyle factors such as energy intake and physical activity, while similar adjustments were only made in one of the previous studies[27]. Although our findings are novel in children, low morning serum cortisol levels have been observed in adults with abdominal obesity and are thought to be a consequence of increased peripheral cortisol clearance, facilitated by increased VAT[44]. However, whether this explains the negative association we observed in children is yet to be tested.

Only one other study has previously assessed the interaction between cortisol and SSB consumption on visceral adiposity. In a small sample of overweight and obese adolescents, Shearrer *et al.*[18] found no interactive effect between morning salivary cortisol and SSBs on VAT. Although our findings are similar for children with medium and high morning cortisol levels, where no associations were observed when stratified for these cortisol levels, we did find an association between high SSB consumption and visceral fat in children with low levels of morning cortisol. The reason for this effect is unclear; however, low morning cortisol in children may be a marker of allostatic load resulting from repeated or chronic exposure to stress[45]. Under conditions of chronic stress, individuals are more likely to consume foods high in sugar[46] and evidence suggests they may also be more vulnerable to diet-related abdominal obesity[47]. Taken together, it is possible that chronic stress may be accounting for the association between high SSB consumption and VAT in children with low morning cortisol levels. However, as we do not have data pertaining to children's perceived stress, this interpretation is speculative and the possibility that morning serum cortisol is a stronger determinant of VAT than high SSB intake should also be considered as an explanation for the lack of association between SSBs and VAT in children with cortisol levels in the two highest tertiles. Further research is warranted to explain how low morning cortisol levels, as opposed to high, may moderate the association between SSBs and visceral adiposity.

A major strength of the present study was the large representative sample of primary school-aged children. Furthermore, the sample included children covering a wide range of BMI and was sufficiently sized to allow for strata-specific analyses. However, several limitations should be considered when interpreting our findings. Firstly, given the cross-sectional nature of the present study, we are unable to determine causality. Secondly, children's diets were assessed using a subjective method and self-reports of dietary intake are often susceptible to error, particularly under-reporting of energy intake from fats and sugars[48]. In addition, dietary intake was only assessed for three consecutive days, which may not accurately reflect children's long-term habitual intake. Nevertheless, dietary recalls remain widely used in epidemiological studies and are a validated tool for measuring dietary intake in children of this age[48]. Lastly, morning serum cortisol was only assessed once for each child. Given that cortisol secretion follows a diurnal pattern, a single measure may be imperfect as a marker of HPA axis activity, and by nature of the design, we are unable to ascertain abnormalities in individual secretory patterns. Although the use of a single cortisol measure is most practical for a sample of this size, multiple measures throughout the day would have provided a more accurate assessment of HPA dysregulation.

In summary, in this cross-sectional study, high SSB consumption was associated with visceral adiposity in young children and boys were at an elevated risk. Morning serum cortisol may moderate the association between SSB consumption and VAT; however, additional studies are needed to replicate our findings and more precise measures of HPA dysregulation should be explored. As visceral adiposity is a strong predictor of future disease risk, it is important that SSB consumption is reduced during childhood and public health policy needs to continue to prioritise the reduction of sugar intake across all populations.

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The authors declare that there are no conflicts of interest.

Supplementary material

For supplementary materials referred to in this article, please visit https://doi.org/10.1017/S0007114520003256

References

1. Abarca-Gómez L, Abdeen Z, Hamid Z, *et al.* (2017) Worldwide trends in body-mass index, underweight, overweight, and obesity from 1975 to 2016: a pooled analysis of 2416 population-based measurement studies in 128·9 million children, adolescents, and adults. *Lancet* **390**, 2627–2642.
2. Kelishadi R, Mirmoghtadaee P, Najafi H, *et al.* (2015) Systematic review on the association of abdominal obesity in children and adolescents with cardio-metabolic risk factors. *J Res Med Sci* **20**, 294–307.
3. Revenga-Frauca J, González-Gil E, Bueno-Lozano G, *et al.* (2009) Abdominal fat and metabolic risk in obese children and adolescents. *J Physiol Biochem* **65**, 415–420.
4. Suliga E (2009) Visceral adipose tissue in children and adolescents: a review. *Nutr Res Rev* **22**, 137–147.
5. Mokha JS, Srinivasan SR, DasMahapatra P, *et al.* (2010) Utility of waist-to-height ratio in assessing the status of central obesity and related cardiometabolic risk profile among normal weight and overweight/obese children: the Bogalusa Heart Study. *BMC Pediatr* **10**, 73.
6. Khoury M, Manlhiot C & McCrindle BW (2013) Role of the waist/height ratio in the cardiometabolic risk assessment of children classified by body mass index. *J Am Coll Cardiol* **62**, 742–751.
7. Bacopoulou F, Landis G, Rentoumis A, *et al.* (2017) Mediterranean diet decreases adolescent waist circumference. *Eur J Clin Invest* **47**, 447–455.
8. Romaguera D, Norat T, Mouw T, *et al.* (2009) Adherence to the Mediterranean diet is associated with lower abdominal adiposity in European men and women. *J Nutr* **139**, 1728–1737.
9. Grosso G & Galvano F (2016) Mediterranean diet adherence in children and adolescents in southern European countries. *NFS J* **3**, 13–19.
10. Schröder H, Ribas L, Koebnick C, *et al.* (2014) Prevalence of abdominal obesity in Spanish children and adolescents. Do we need waist circumference measurements in pediatric practice? *PLOS ONE* **9**, e87549–e87549.
11. Hassapidou M, Tzotzas T, Makri E, *et al.* (2017) Prevalence, geographic variation of abdominal obesity in 7-, 9-year-old children in Greece; World Health Organization Childhood Obesity Surveillance Initiative 2010. *BMC Public Health* **17**, 126.
12. Albuquerque D, Nóbrega C, Samouda H, *et al.* (2012) Assessment of obesity and abdominal obesity among Portuguese children. *Acta Med Port* **25**, 169–173.
13. Staiano AE & Katzmarzyk PT (2012) Ethnic and sex differences in body fat and visceral and subcutaneous adiposity in children and adolescents. *Int J Obes* **36**, 1261–1269.
14. Odegaard AO, Choh AC, Czerwinski SA, *et al.* (2012) Sugar-sweetened and diet beverages in relation to visceral adipose tissue. *Obesity* **20**, 689–691.
15. Ma J, Sloan M, Fox CS, *et al.* (2014) Sugar-sweetened beverage consumption is associated with abdominal fat partitioning in healthy adults. *J Nutr* **144**, 1283–1290.
16. Ma J, McKeown FN, Hwang SS-J, *et al.* (2016) Sugar-sweetened beverage consumption is associated with change of visceral adipose tissue over 6 years of follow-up. *Circulation* **133**, 370–377.
17. Maersk M, Belza A, Stodkilde-Jorgensen H, *et al.* (2012) Sucrose-sweetened beverages increase fat storage in the liver, muscle, and visceral fat depot: a 6-mo randomized intervention study. *Am J Clin Nutr* **95**, 283–289.
18. Shearrer G, Daniels M, Toledo-Corral C, *et al.* (2016) Associations among sugar sweetened beverage intake, visceral fat, and cortisol awakening response in minority youth. *Physiol Behav* **167**, 188–193.
19. Mollard RC, Sénéchal M, MacIntosh AC, *et al.* (2014) Dietary determinants of hepatic steatosis and visceral adiposity in overweight and obese youth at risk of type 2 diabetes. *Am J Clin Nutr* **99**, 804–812.
20. Bleich SN & Vercammen KA (2018) The negative impact of sugar-sweetened beverages on children's health: an update of the literature. *BMC Obes* **5**, 6.
21. Frantsve-Hawley J, Bader JD, Welsh JA, *et al.* (2017) A systematic review of the association between consumption of sugar-containing beverages and excess weight gain among children under age 12. *J Public Health Dent* **77**, S43–S66.
22. Collison KS, Zaidi MZ, Subhani SN, *et al.* (2010) Sugar-sweetened carbonated beverage consumption correlates with BMI, waist circumference, and poor dietary choices in school children. *BMC Public Health* **10**, 234.
23. Mirmiran P, Yuzbashian E, Asghari G, *et al.* (2015) Consumption of sugar sweetened beverage is associated with incidence of metabolic syndrome in Tehranian children, adolescents. *Nutr Metab (Lond)* **12**, 25.
24. Bigornia SJ, LaValley MP, Noel SE, *et al.* (2014) Sugar-sweetened beverage consumption and central and total adiposity in older children: a prospective study accounting for dietary reporting errors. *Public Health Nutr* **18**, 1155–1163.
25. Björntorp P (2001) Do stress reactions cause abdominal obesity and comorbidities? *Obes Rev* **2**, 73–86.
26. Anagnostis P, Athyros VG, Tziomalos K, *et al.* (2009) The pathogenetic role of cortisol in the metabolic syndrome: a hypothesis. *Endocrinology* **150**, 3433–3433.
27. Gyllenhammer LE, Weigensberg MJ, Spruijt-Metz D, *et al.* (2014) Modifying influence of dietary sugar in the relationship between cortisol and visceral adipose tissue in minority youth. *Obesity* **22**, 474–481.
28. Pawellek I, Grote V, Theurich M, *et al.* (2017) Factors associated with sugar intake and sugar sources in European children from 1 to 8 years of age. *Eur J Clin Nutr* **71**, 25–32.
29. Moschonis G, Tanagra S, Vandorou A, *et al.* (2010) Social, economic and demographic correlates of overweight and obesity

in primary-school children: preliminary data from the Healthy Growth Study. *Public Health Nutr* **13**, 1693–1700.
30. Cole TJ, Bellizzi MC, Flegal KM, *et al.* (2000) Establishing a standard definition for child overweight and obesity worldwide: international survey. *BMJ* **320**, 1240–1243.
31. de Onis M, Onyango AW, Borghi E, *et al.* (2007) Development of a WHO growth reference for school-aged children and adolescents. *Bull World Health Organ* **85**, 660–667.
32. Ryo M, Maeda K, Onda T, *et al.* (2005) A new simple method for the measurement of visceral fat accumulation by bioelectrical impedance. *Diabetes Care* **28**, 451–453.
33. Shuster A, Patlas M, Pinthus JH, *et al.* (2012) The clinical importance of visceral adiposity: a critical review of methods for visceral adipose tissue analysis. *Br J Radiol* **85**, 1–10.
34. World Health Organization (2015) *Guideline: Sugars Inake for Adults and Children*. Geneva: World Health Organization.
35. Papandreou D, Andreou E, Heraclides A, *et al.* (2013) Is beverage intake related to overweight and obesity in school children? *Hippokratia* **17**, 42–46.
36. Hu FB (2013) Resolved: there is sufficient scientific evidence that decreasing sugar-sweetened beverage consumption will reduce the prevalence of obesity and obesity-related diseases. *Obes Rev* **14**, 606–619.
37. Wells JCK (2007) Sexual dimorphism of body composition. *Best Pract Res Clin Endocrinol Metab* **21**, 415–430.
38. Singh G, Micha R, Khatibzadeh S, *et al.* (2019) Global, regional, and national consumption of sugar-sweetened beverages, fruit juices, and milk: a systematic assessment of beverage intake in 187 countries. *PLOS ONE* **10**, e0124845.
39. Weigensberg MJ, Toledo-Corral CM & Goran MI (2008) Association between the metabolic syndrome and serum cortisol in overweight Latino youth. *J Clin Endocrinol Metab* **93**, 1372–1378.
40. Barat P, Gayard-Cros M, Andrew R, *et al.* (2007) Truncal distribution of fat mass, metabolic profile, hypothalamic-pituitary adrenal axis activity in prepubertal obese children. *J Pediatr* **150**, 535–539.e531.
41. Hill EE, Eisenmann JC, Gentile D, *et al.* (2011) The association between morning cortisol and adiposity in children varies by weight status. *J Pediatr Endocrinol Metab* **24**, 709–713.
42. Hill EE, Eisenmann JC, Holmes ME, *et al.* (2010) Morning cortisol is not associated with truncal fatness or resting blood pressure in children: cross-sectional and 1–2 year follow-up analyses. *J Pediatr Endocrinol Metab* **23**, 1031–1037.
43. Dorn L, Lucke J, Loucks T, *et al.* (2007) Salivary cortisol reflects serum cortisol: analysis of circadian profiles. *Ann Clin Biochem* **44**, 281–284.
44. Björntorp P (1991) Metabolic implications of body fat distribution. *Diabetes Care* **14**, 1132–1143.
45. Badanes LS, Watamura SE & Hankin BL (2011) Hypocortisolism as a potential marker of allostatic load in children: associations with family risk and internalizing disorders. *Dev Psychopathol* **23**, 881–896.
46. Torres SJ & Nowson CA (2007) Relationship between stress, eating behavior, and obesity. *Nutrition* **23**, 887–894.
47. Aschbacher K, Kornfeld S, Picard M, *et al.* (2014) Chronic stress increases vulnerability to diet-related abdominal fat, oxidative stress, and metabolic risk. *Psychoneuroendocrinology* **46**, 14–22.
48. Foster E & Bradley J (2018) Methodological considerations and future insights for 24-hour dietary recall assessment in children. *Nutr Res* **51**, 1–11.

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