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ORIGINAL CONTRIBUTION

Assessment of oxidative balance score with hypertension and arterial stiffness in children and adolescents: NHANES 2001–2018

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Abstract

Objective To investigate the complex relationship between oxidative balance score (OBS), hypertension (HTN) and arterial stiffness in children and adolescents utilizing data gathered from the National Health and Nutrition Examination Survey (NHANES).

Study design Through utilizing NHANES data (2001–2018), OBS, comprising dietary and lifestyle components, was calculated and categorized into tertiles. The correlation between OBS and HTN was explored employing weighted multivariate logistic regression. Stratified analyses were further performed to evaluate the associations across different subgroups.

Results A total of 11,754 children and adolescents were ultimately enrolled in analyses. High OBS tertiles demonstrated a consistent negative association with HTN across models. Compared with the lowest OBS tertile, the risk of HTN in the highest OBS tertile was decreased by 37% (95% CI 0.44–0.90, p = 0.011). After dividing OBS into dietary OBS and lifestyle OBS, Lifestyle OBS exhibited a significant inverse association with HTN, while dietary OBS showed no significant correlation. Stratified analyses notably revealed the protective impacts of OBS on the risk of HTN in males. Restricted cubic spline analysis confirmed a nonlinear association between OBS and HTN. Moreover, the elevated OBS was significantly associated with decreased ePWV, indicating a potential link between arterial stiffness and OBS.

Conclusion In summary, the risk of HTN was inversely correlated with high OBS. Adopting a wholesome lifestyle enriched with antioxidants to boost OBS may help shield children from HTN risk.

Keywords Hypertension · Oxidative balance score · Oxidative stress · Arterial stiffness · Children and adolescents

Introduction

Hypertension (HTN) is a highly prevalent widespread disease globally and also the most pervasive and modifiable risk factor for decreasing cardiovascular morbidity and mortality [1]. There has been a reported rise in the occurrence of elevated blood pressure (BP) and hypertension in children and adolescents in the past three decades [2, 3]. The actual prevalence of clinical HTN in children and adolescents is around 4%. In comparison, the incidence of elevated BP is different from as low as 3.4% up to 15.7%, with greater incidences in overweight or obese children and adolescents [4–6]. Essential hypertension is increasingly becoming the most common type of hypertension observed in children and adolescents. Evidence suggests that high BP in childhood can contribute to essential HTN in adults and cardiovascular events in later life [7–9]. Therefore, the development of prophylactic and therapeutic strategies for childhood HTN, including lifestyle and diet modification and medicines, may become imperative.

Although artery damage is a result of hypertension, artery stiffness is also thought to be a causative component since it precedes and predicts the development of hypertension [10, 11]. Therefore, to facilitate the prevention of disease and decrease the course of cardiovascular disease (CVD), it is crucial to recognize and assess children and adolescents who are at higher risk of hypertension and increased arterial stiffness. The carotid-femoral pulse wave velocity (cf-PWV) is considered the most accurate indicator of arterial

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stiffness [12]. Previous study has certificated that estimated-pulse wave velocity (ePWV) exhibits comparable predictive power to cf-PWV, and it can indicate cardiovascular events independent of established cardiovascular indicators in patients with HTN [13]. In our investigation, ePWV was used to measure arterial stiffness in children and adolescents.

Abundant evidence suggests that oxidative stress, characterized as an imbalance between oxidant formation and antioxidant protective mechanisms, is thought to perform a major role in the pathogenesis of HTN [14]. Numerous animal models of hypertension have provided thorough validation of a relationship between oxidative stress and hypertension. Oxidative stress could promote endothelial dysfunction, vascular dysfunction, myocardial fibrosis, renal damage, and blood pressure increase [15–17]. However, unlike in animal models, there is now conflicting evidence regarding how oxidative stress affects human health. The complicated interplay of various pro- and anti-oxidant parameters with external factors and endogenous enzymatic pathways may be the cause of the discrepancies observed in clinical investigations. Oxidative stress is influenced by a range of exogenous factors, such as the environment, dietary patterns, physical activity, and pharmaceuticals. Reformulating one's lifestyle and diet to reduce oxidative stress during childhood may represent a viable approach to mitigating hypertension. Therefore, the oxidative balance score (OBS), which is made up of pro- and anti-oxidant elements from diet and lifestyle choices, could comprehensively reflect individuals' global oxidative stress burden [18]. Higher OBS values reflect higher antioxidant exposures.

Prior research revealed an adverse relationship between greater OBS and the risk of cancers [19], chronic kidney disease [20], non-alcoholic fatty liver disease [21], diabetes [22], ischaemic heart disease [23], hypertension in adults [24], all-cause, and cardiovascular mortality [25]. In addition, Clinical studies have demonstrated decreased biomarkers of antioxidant status in hypertension [26, 27]. To our knowledge, no study has been done on the correlation between OBS, HTN and arterial stiffness in children and adolescents. Increasing body mass index and obesity are correlated with increased hypertension prevalence in children and adolescents [28]. Additionally, research has revealed a correlation between obesity and oxidative stress in adipose tissue. When considering essential hypertension in children and adolescents, obesity is also a contributing factor to elevated blood pressure, which is also linked to oxidative stress [29]. Clinical observations suggest that arterial stiffness is more pronounced in children and adolescents who are obese [30]. Therefore, OBS may be an independent predictor of hypertension and subsequent arterial stiffness in children and adolescents, and a healthy lifestyle and diet that promotes OBS may act as a defense against the prevalence of hypertension in children and adolescents.

Our study examined the potential association between OBS and hypertension and arterial stiffness in children and adolescents utilizing data gathered from the National Health and Nutrition Examination Survey (NHANES) from 2001 to 2018, intending to control hypertension better through dietary and lifestyle guidance.

Materials and methods

Study design and population

This cross-sectional study pooled data from nine 2-year survey cycles of the NHANES spanning from 2001 to 2018. Written informed consent was obtained from all participants, and the protocol received approval from the Ethics Review Board of the National Center for Health Statistics.

In this study, a total of 11,754 survey participants aged 17 years and younger, with complete data on OBS and covariates (as described in the covariates section) in NHANES 2001–2018 were included in the final analysis. A flowchart detailing the inclusion and exclusion process is presented in Fig. 1. Initially, we enrolled 91,351 participants from NHANES cycles spanning 2001–2002 through 2017–2018. Subsequently, 69,675 participants with an age exceeding 18 years were excluded. Among the remaining 21,676 teenagers, 8366 participants with missing records of covariates and a diagnosis of hypertension, 1400 participants with fewer than 16 items for the 20 components of OBS, and 156 participants with diabetes were also excluded. Ultimately, a total of 11,754 teenagers were enrolled for further analysis.

Exposure variable

The calculation of the OBS drew upon a prior study [31]. OBS was categorized into dietary OBS with 16 components and lifestyle OBS with 4 components, including 15 antioxidants and 5 prooxidants. Dietary OBS components comprised dietary fiber, riboflavin, carotene, calcium, zinc, copper, magnesium, selenium, niacin, vitamin C, vitamin B6, vitamin B12, vitamin E, total fat, total folate, and iron. Lifestyle OBS consisted of body mass index (BMI), alcohol consumption, physical activity and smoking. Among these 20 factors, BMI, smoking, alcohol consumption, iron, and total fat were designated as pro-oxidants while the rest were categorized as antioxidants. The dietary data was obtained from a 24-h dietary recall, which was conducted in person by proficient dietary interviewers across diverse age groups, aiming to depict comprehensive dietary patterns within the US population. Physical activity data was derived from a physical activity questionnaire collected at home by interviewers utilizing the Computer Assisted Personal Interview system. Briefly,

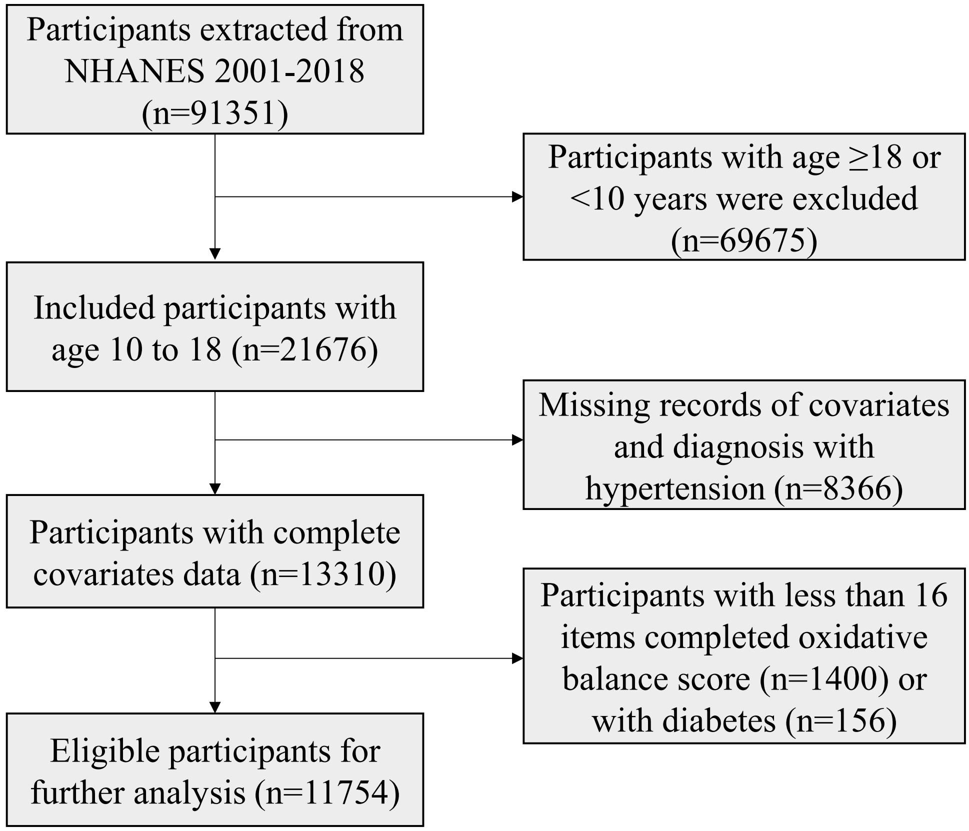

Fig. 1 Flowchart of study participants

physical activity was quantified as metabolic equivalent (MET) score × weekly frequency × duration of each physical activity [32]. BMI equaled weight in kilograms divided by height in meters squared. Alcohol consumption was estimated based on the mean number of alcoholic drinks consumed per day in the past year, encompassing all types of alcoholic beverages. Cotinine, the main metabolite of nicotine, existing in serum, urine, or saliva, could serve as an indicator of active smoking due to its long half-life in blood compared to nicotine. Cotinine also functioned as an indicator of exposure to environmental tobacco smoke or passive smoking. Therefore, plasma cotinine was selected for quantitative exposure assessment studies. The specific definitions are as follows: tobacco exposure was considered positive if a participant reported the presence of at least 1 smoker in the home or had a serum cotinine level greater than 0.05 ug/L. Active smoking was defined as answering yes to the question "During the past 5 days, including today, did you smoke cigarettes, pipes, cigars, little cigars or cigarillos, water pipes, hookahs, or e-cigarettes?" or having a serum cotinine level greater than 10 ug/L [33]. Passive smoking was defined as exposure to tobacco smoke without directly smoking, indicated by a serum cotinine level greater than 0.05 ug/L but less than or equal to 10 ug/L [33, 34].

The overall OBS was computed by aggregating scores for each variable, where an elevated OBS indicated greater exposure to antioxidants. Table s1 contains the classifications and scores corresponding to each OBS component. In our study, individuals with 16 or more complete data out of 20 OBS components were included. In cases where OBS components were missing, a score of 0 was imputed for the absent component, whether it pertained to antioxidants or prooxidants.

Composite Dietary Antioxidant Index (CDAI), an index on the basis of a combination of different dietary antioxidants, including selenium, zinc, manganese, vitamin A, vitamin C, and vitamin E [35], was used to estimate an individual's overall antioxidant capacity.

Dietary Approaches to Stop Hypertension (DASH) score is derived from nine components (protein, fiber, magnesium, calcium, potassium, total fat, saturated fat, cholesterol, and sodium) and is generated by the sum of all the nutrient target intakes (ranging from 0 points to 9) [36]. Higher scores indicate greater adherence to the DASH dietary pattern.

Study outcome

The primary outcomes of interest consist of hypertension and arterial stiffness. Blood pressure measurements were conducted by trained medical personnel using a mercury sphygmomanometer equipped with a cuff of appropriate size. Participants underwent three consecutive measurements following a 5-min rest period. Measurements were performed in a seated position, with the right arm utilized unless special circumstances dictated otherwise. The mean of the three blood pressure readings was computed and employed for subsequent analysis. Hypertension was defined as a mean systolic blood pressure or a mean diastolic blood pressure greater than 95% for age, sex, and height, or self-reported use of antihypertensive medications or receiving a physician's diagnosis of hypertension [37]. We have referred to this outcome as "hypertension" throughout for convenience, recognizing that a true diagnosis of pediatric hypertension requires multiple readings at several time points. Arterial stiffness was presented with ePWV. According to the equation derived from the Reference Values for Arterial Stiffness Collaboration, ePWV was determined based on age and mean blood pressure (MBP) [13, 38]: $9.587 - 0.402 \times \text{age} + 4.560 \times 10^{-3} \times \text{age}^2 - 2.621 \times 10^{-5} \times \text{age}^2 \times \text{MBP} + 3.176 \times 10^{-3} \times \text{age} \times \text{MBP} - 1.832 \times 10^{-2} \times \text{MBP}$.

Covariates

In this study, several variables previously reported or hypothesized to be related to OBS or hypertension were considered as covariates, including demographic covariates and dietary data. Demographic covariates obtained through self-reported questionnaires included age, sex (female or male), race or ethnicity (Hispanic, Mexican American, non-Hispanic Black, non-Hispanic White, or other races), educational level (less than fifth grade, ninth to eleventh grade, high school and high school above) and income-to-poverty ratio (< 1.3, 1.3–3.5, > 3.5). The income-to-poverty ratio was defined as the ratio of family income to poverty guidelines. Total energy intake was calculated and taken into account as a covariate.

Statistical analysis

In adherence to the NHANES protocol of statistics analyses, the sampling scheme, subsample weights, and data clustering were taken into account in our analyses [39]. The dietary day one sample weight (WTDRD1) was employed to ensure accurate estimates reflecting the civilian non-institutionalized US general population. For continuous variables, mean and standard error (mean (SE)) were calculated, while unweighted frequencies (weighted proportion) were represented for categorical variables. As no established cut-off value for OBS to diagnose hypertension existed, all enrolled individuals were categorized into three groups based on the OBS tertile according to previous research [40, 41]. To analyze differences in variables between various OBS groups (tertiles), the Kruskal–Wallis test and Rao-Scott chi-squared test were performed. Odds ratios (OR) and 95% confidential intervals (CI) were assessed to evaluate the association between different tertiles of OBS and hypertension in children and adolescents by using multivariable logistic regression models. The first tertile served as the reference group. Three logistic regression models were employed for the analyses. Model 1 adjusted for age and sex. Model 2 was further adjusted for race/ethnicity, income-to-poverty ratio, and education level. Model 3 additionally adjusted for total energy intake and BMI. We stratified the analyses by age, sex, ethnicity, BMI, and income-to-poverty ratio to further examine the effects of total OBS in different subgroups by model 3. Furthermore, OBS was divided into dietary OBS and lifestyle OBS to independently examine their association with hypertension in children and adolescents. Moreover, restricted cubic spline (RCS) analysis was conducted to discern the relationship between OBS and hypertension in children and adolescents.

All statistical analyses were carried out utilizing R version 4.2.2. Statistical significance was determined based on a two-sided P value < 0.05.

Results

Baseline participants characteristics

In this present study, 11,754 subjects were finally enrolled in the analyses, consisting of 5856 females and 5898 males. The baseline characteristics of the study subjects, grouped by OBS tertiles (tertile 1: $4 \leq \text{OBS} \leq 15$, n = 4254; tertile 2: $15 < \text{OBS} \leq 22$, n = 3854, tertile 3: $22 < \text{OBS} \leq 36$, n = 3646) are presented in Table 1. Compared to the lowest tertile of the OBS, participants in the highest tertile of the OBS were more likely to be older, male, have higher family income, more educated, have higher level of physical activity, have lower BMI, have lower level of tobacco exposure, and have higher total energy intake.

Association between OBS and hypertension in children and adolescents

As presented in Table 2, we examined the association between OBS and hypertension in children and adolescents on four models constructed through weighted logistic regression analysis, including the crude model, Model 1, Model 2, and Model 3. The second and third tertiles of the OBS were all more negatively related to the risk of hypertension compared with the lowest tertile of the OBS (all $p < 0.05$), demonstrating relative stability across models. Compared with the lowest OBS tertile, the risks of HTN in the second and third OBS tertiles were decreased by 42%(95%

Table 1 The baseline participants characteristics by tertiles of the OBS: National Health and Nutrition Examination Survey 2001–2018

Characteristic	Total n = 11,754	T1, [4, 15] n = 4254	T2, (15, 22] n = 3854	T3, (22, 36] n = 3646	*P* value
Age, year, Mean (SE)	13.5 (0.03)	13.5 (0.05)	13.4 (0.06)	13.7 (0.07)	0.01
Sex, n (%)					< 0.0001
Female	5856 (50.13)	1948 (46.00)	1954 (50.40)	1954 (53.75)	
Male	5898 (49.87)	2306 (54.00)	1900 (49.60)	1692 (46.25)	
Race/ethnicity, n (%)					< 0.0001
Hispanic	882 (6.24)	269 (5.87)	290 (5.99)	323 (6.83)	
Mexican American	3117 (13.50)	988 (12.59)	1063 (13.97)	1066 (13.88)	
Non-Hispanic Black	3351 (14.18)	1574 (20.10)	996 (12.77)	781 (9.97)	
Non-Hispanic White	3348 (58.25)	1088 (53.83)	1131 (58.54)	1129 (62.14)	
Other, including multiracial	1056 (7.84)	335 (7.61)	374 (8.73)	347 (7.17)	
Income-to-poverty ratio, n (%)					< 0.0001
< 1.3	4321 (27.50)	1723 (34.59)	1373 (27.72)	1225 (24.96)	
1.3–3.5	4172 (36.29)	1547 (39.66)	1376 (38.19)	1249 (36.98)	
≥ 3.5	2542 (31.08)	730 (25.75)	866 (34.09)	946 (38.06)	
Education level, n (%)					0.02
< 5th Grade	1711 (15.56)	586 (15.69)	645 (17.41)	480 (13.64)	
5th-9th Grade	7598 (63.16)	2800 (63.67)	2465 (63.04)	2333 (62.82)	
High school	2427 (21.14)	860 (20.49)	740 (19.49)	827 (23.38)	
High school above	16 (0.13)	7 (0.15)	4 (0.07)	5 (0.17)	
BMI, kg/m^2, Mean (SE)	22.41 ± 0.10	23.37 ± 0.17	22.49 ± 0.16	21.41 ± 0.11	< 0.0001
Cotinine, ug/L, Mean (SE)	6.95 ± 0.65	10.44 ± 1.36	6.34 ± 0.84	4.43 ± 0.90	< 0.001
Physical activity, MET-minutes/week,Median (IQR)	1212.1 (240.0,3480.0)	760.0 (148.0,2880.0)	1240.0 (264.1,3360.0)	1688.4 (372.1,3840.0)	< 0.0001
Total energy intake, kcal, Mean (SE)	2119.15 ± 14.88	1579.01 ± 13.50	2055.16 ± 18.37	2691.84 ± 26.56	< 0.0001
Tobacco exposure					< 0.0001
No	5582 (50.11)	1521 (41.64)	1913 (58.30)	2148 (66.05)	
Active smoking	521 (4.96)	252 (7.66)	169 (5.55)	100 (3.58)	
Passive smoking	4503 (34.73)	1994 (50.70)	1399 (36.15)	1110 (30.37)	
Hypertension, n (%)					0.002
No	11,251 (96.07)	4020 (94.65)	3708 (96.70)	3523 (96.78)	
Yes	503 (3.93)	234 (5.35)	146 (3.30)	123 (3.22)	

CI 0.39–0.87, $p = 0.008$) and 37% (95% CI 0.44–0.90, $p = 0.011$). The same trend also was detected in the sensitivity analysis (p for trend < 0.05).

Association between dietary OBS or lifestyle OBS and hypertension in children and adolescents

To further examine the relationship between OBS and hypertension, OBS was subdivided into dietary OBS and lifestyle OBS. Table 2 presented the findings of multivariate logistic regression analysis assessing the association between dietary OBS, lifestyle OBS and hypertension in children and adolescents. For dietary OBS, in the crude model and model 1, the second or third tertiles of dietary OBS were associated with a reduced risk of hypertension ($p < 0.05$). As adjustments increased, no statistically significant association was observed between dietary OBS and HTN in model 2 and 3 ($p > 0.05$). For lifestyle OBS, higher levels of lifestyle OBS were significantly associated with a lower risk of HTN, especially the highest lifestyle OBS group, which showed a very strong negative relationship across four models Only the second lifestyle OBS group showed a change in the relationship in model 3, with the OR increasing to 0.75, but the *P*-value became 0.127, indicating that the relationship was no longer statistically significant. The trend test showed a statistically significant downward trend (p for trend < 0.05).

Table 2 Weighted logistic regression models showing the association between Total/Dietary/Lifestyle OBS and hypertension in children and adolescents

OBS	T1	T2 (OR 95% CI)	*P* value	T3 (OR 95% CI)	*P* value	*P* for trend
OBS						
Crude model	Ref	0.60 (0.42, 0.87)	0.007	0.59 (0.42, 0.82)	0.002	0.002
Model 1	Ref	0.59 (0.41, 0.85)	0.006	0.58 (0.42, 0.82)	0.002	0.002
Model 2	Ref	0.59 (0.40, 0.87)	0.008	0.60 (0.44, 0.83)	0.002	0.003
Model 3	Ref	0.58 (0.39, 0.87)	0.008	0.63 (0.44, 0.90)	0.008	0.011
Dietary OBS						
Crude model	Ref	0.68 (0.48, 0.97)	0.035	0.74 (0.54, 0.98)	0.041	0.046
Model 1	Ref	0.69 (0.47, 0.98)	0.038	0.73 (0.54, 0.99)	0.047	0.050
Model 2	Ref	0.70 (0.46, 1.01)	0.066	0.75 (0.54, 1.01)	0.060	0.053
Model 3	Ref	0.69 (0.45, 1.02)	0.072	0.72 (0.50, 1.04)	0.082	0.060
Lifestyle OBS						
Crude model	Ref	0.55 (0.39, 0.79)	0.001	0.30 (0.19, 0.45)	< 0.0001	< 0.0001
Model 1	Ref	0.55 (0.39, 0.79)	0.001	0.32 (0.21, 0.49)	< 0.0001	< 0.0001
Model 2	Ref	0.57 (0.39, 0.82)	0.003	0.31 (0.20, 0.50)	< 0.0001	< 0.0001
Model 3	Ref	0.75 (0.52, 1.09)	0.127	0.46 (0.28, 0.75)	0.002	0.005

Crude Model: Unadjusted model. Model 1: Adjusted for age, sex. Model 2: Additionally adjusted for race/ethnicity, educational level, and income-to-poverty ratio. Model 3: Additionally adjusted for total energy intake and BMI. The specific range for the tertiles: The OBS tertiles is consistent with Table 1; Dietary OBS: T1 [2, 11] T2 (11, 18]; T3 (18, 29]; Lifestyle OBS: T1 [0, 4]; T2 (4, 5]; T3 (5, 7]

Association between OBS and hypertension in children and adolescents during different subgroups

Further stratified analysis was employed to evaluate the association between OBS and hypertension in different subgroups. As depicted in Fig. 2, a significant protective role of evaluated OBS on the risk of hypertension in males was observed (*p* for trend < 0.001, *p* for interaction = 0.037). In participants with a BMI under 25 and age below 14, the higher OBS might reduce the risk of hypertension. Besides, we further analyzed CDAI, a dietary indice indicating the anti-inflammatory potential of diets. Consistent with the results of hypertension and dietary OBS, no significant association between CDAI and hypertension was found (Table s2). The association between DASH score and hypertension was also assessed, showing a DASH dietary palyed a protective role in hypertension in children and adolescents (Table s3).

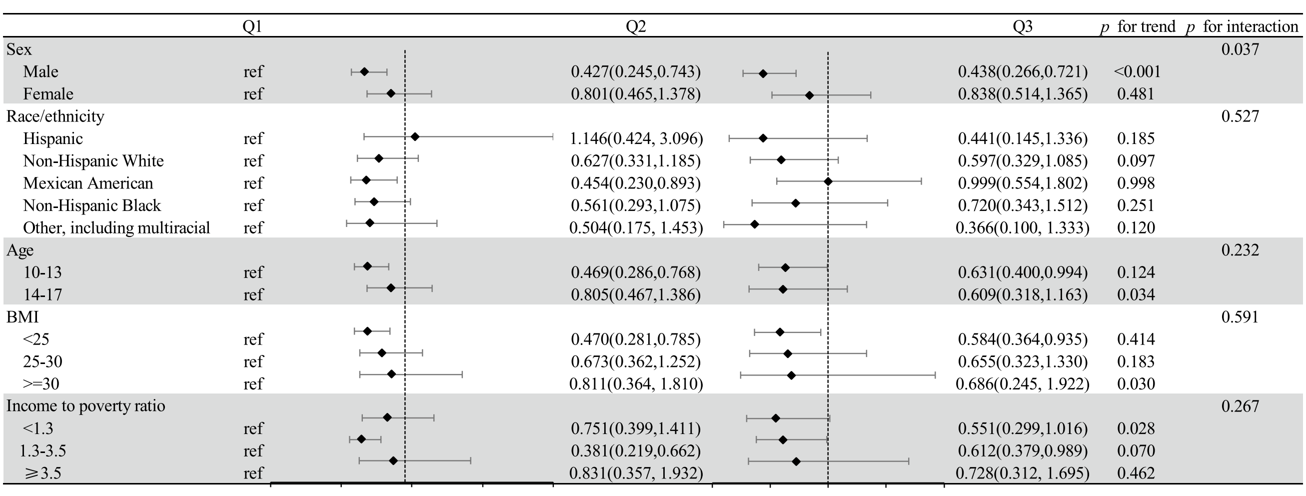

Fig. 2 Subgroup analyses for the association between OBS and hypertension in children and adolescents

Restricted cubic spline regression analysis

Figure 3 shows the results of a restricted cubic spline analysis, revealing a significant non-linear relationship between OBS, dietary OBS, and hypertension in children and adolescents after adjusting for covariates (*p* for nonlinearity = 0.017, 0.030, respectively).

Association between OBS and arterial stiffness

Table 3 showed the regression coefficient (β) depicting the correlation between OBS and arterial stiffness. OBS, particularly lifestyle OBS, exhibited a negative association with ePWV in both unadjusted and adjusted models. After full adjustment for covariates (Model 3), each 1-unit increase in lifestyle OBS was associated with a 0.012 m/s decrease in ePWV levels ($p < 0.0001$).

Table 3 Beta between ePWV by OBS tertiles in the NHANES 2001–2018

Variables	Beta (95% CI)	*p* value
OBS		
Crude model	– 0.002 (– 0.003, – 0.001)	< 0.001
Model 1	– 0.001 (– 0.002, 0.0001)	0.019
Model 2	– 0.001 (– 0.002, 0.0001)	0.035
Model 3	– 0.001 (– 0.002, – 0.001)	0.002
Dietary OBS		
Crude model	– 0.001 (– 0.001, 0.0001)	0.266
Model 1	0 (– 0.001, 0.0001)	0.441
Model 2	0 (– 0.001, 0.001)	0.565
Model 3	– 0.001 (– 0.002, 0.0001)	0.184
Lifestyle OBS		
Crude model	– 0.025 (– 0.029, – 0.020)	< 0.0001
Model 1	– 0.013 (– 0.017, – 0.009)	< 0.0001
Model 2	– 0.012 (– 0.017, – 0.009)	< 0.0001
Model 3	– 0.012 (– 0.017, – 0.008)	< 0.0001

Crude Model: Unadjusted model. Model 1: Adjusted for age, sex. Model 2: Additionally adjusted for race/ethnicity, educational level, and income to poverty ratio. Model 3: Additionally adjusted for total energy intake and BMI

Discussion

For the first time, this cross-sectional study examined the correlation between OBS and hypertension as well as arterial stiffness in children and adolescents based on NHANES (from 2001 to 2018). Our study highlighted that OBS, particularly lifestyle OBS, had a negative correlation with hypertension and arterial stiffness in children and adolescents. The relationship between lifestyle OBS and hypertension and arterial stiffness remained even after covariates were adjusted. The results of our study align with prior epidemiological research that demonstrates a notable correlation between oxidative stress and hypertension [24, 42].

There exist variations in the construction of published OBSs in terms of the type and quantity of components, as well as the scoring assigned to each component. A comprehensive review has outlined that the quantity of OBS elements can range from 3 to 20, encompassing both anti-oxidants and pro-oxidants. The primary mechanisms of antioxidants involve the scavenging of free radicals via the transfer of hydrogen atoms or single electrons to reactive species, the restriction of the activity or synthesis of pro-oxidant enzymes that are responsible for producing reactive species; the ability to bind to metal ions that promote reactive species, and the stimulation of antioxidant enzymes. Pro-oxidants play the opposing roles [18]. In our study, the OBS was composed of 7 anti-oxidants and 5 pro-oxidants which involved multiple oxidative stress mechanisms.

To date, a cross-sectional study of 317 HTN adults revealed that OBS was inversely associated with hypertension in the US [42]. Later in 2022, Similar research showed

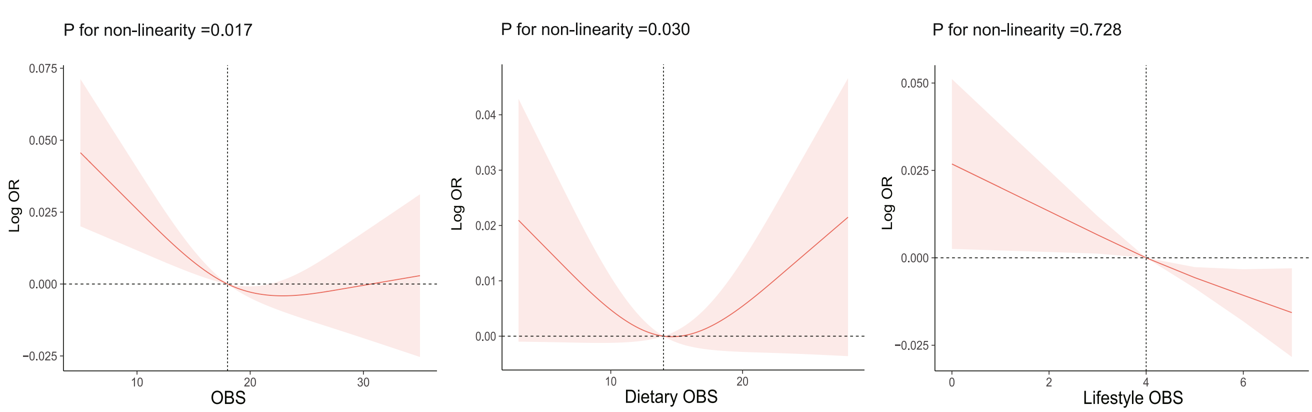

Fig. 3 The restricted cubic spline of OBS, dietary/lifestyle OBS and the incidence of hypertension in children and adolescents

that middle-aged and elderly people with high OBS were at lower risk of new-onset HTN in a large, community-based, prospective Korean cohort [24]. While previous research on the correlation between OBS and hypertension remains limited, our findings align with the aforementioned studies. Our study was the first to prove that OBS, especially lifestyle OBS, remains a protective factor for hypertension in children and adolescents.

Concerning lifestyle OBS, physical activity was the only antioxidant, as multiple studies have demonstrated that acute exercise could temporarily increase oxidative stress and anti-oxidant activity; chronic exercise training could enhance the anti-oxidant levels, resulting in a decrease in the production of oxidative stress in children; and these responses are influenced by various factors, including the phase of training, intensity, volume, health state, type of exercise and so on [43]. Limited evidence from prospective observational studies has validated the beneficial impact of physical activity in children and adolescents with essential HTN, with partially early vascular ageing reversion, accompanied by significant decreases in BP and BMI [44]. Thus, the World Health Organization advised participating in moderate-to-vigorous exercise for a minimum of one hour every day during childhood [45], regardless of health status, to balance the redox state and reduce the risk of HTN. BMI was a vital pro-oxidant in lifestyle OBS. Obesity, as measured by BMI, was strongly linked to HTN, and its impact on the development of HTN becomes more significant as time moves on [46]. Prior studies indicated that nearly 60% of American children and adolescents with hypertension were overweight or obese. Moreover, the population attributable risk (%) for hypertension due to overweight or obesity in children and adolescents reached a maximum of 42.7% [47]. Obesity in children and adolescents has been found to have a direct relationship with endothelial dysfunction, inflammation, and oxidative stress. Therapeutic approaches, such as implementing changes in lifestyle and diet during early childhood obesity, are becoming important due to their established impact on inflammatory and oxidative stress [48]. Smoking has been linked to arterial stiffness in adults and endothelial dysfunction in children [49]. Passive tobacco exposure in children was associated with increased risk of cardiovascular diseases in adulthood [50]. While some studies in children indicate an association between passive tobacco exposure and hypertension [51], others have not [52]. The difference was caused by nonstandard definitions of smoking and significant heterogeneity in study design. Chronic alcohol consumption was associated with hypertension in a dose-dependent, linear manner, and is independent of BMI, smoking status, and levels of physical activity [53]. The average quantity of alcohol consumption has a more important role in the risk of hypertension than the frequency of drinking [54]. Basic research has established an association between alcohol-induced hypertension and oxidative stress [55].

The results of our study indicate that there is no significant relationship between dietary OBS and HTN after fully adjust; thus, the impact of dietary OBS on predicting the risk of HTN is still unclear. The result of anti-oxidant supplements in managing HTN has not been convincing. A randomized primary prevention trial failed to identify any positive impact of low-dose anti-oxidant supplements on the 6.5-year incidence of HTN [56]. However, other promising findings exist about the relationship between an antioxidant-rich diet and HTN. In this study, we observed an inverse association between higher Dietary Approaches to Stop Hypertension (DASH) scores and the prevalence of HTN in children and adolescents. Specifically, our results showed that participants in the highest tertile of DASH scores had a significantly lower prevalence of hypertension compared to the reference group ($p = 0.047$ in the crude model and 0.015 in Model 3). DASH dietary patterns were distinguished by a high consumption of fruits, vegetables, and low-fat products, as well as low fat, sugar and sodium intake. In youth, many types of research, including cross-sectional, nonintervention, and intervention cohort studies, have shown that following a DASH-style dietary pattern is linked to decreased BP [57–59]. A diet rich in high potassium and low sodium, as well as high magnesium and calcium can reduce water sodium retention [60], improve endothelial function and regulate vascular smooth muscle relaxation [61], thereby lowering blood pressure. Additionally, the DASH diet is abundant in dietary fiber, polyphenols, vitamin C, and vitamin E, which act as antioxidants to help reduce inflammation and oxidative stress, mitigate arterial stiffness and atherosclerosis, and consequently lower blood pressure [62, 63]. Furthermore, limiting saturated fats and refined sugars contributes to reducing insulin resistance, lowering dyslipidemia, and improving arterial elasticity [64, 65], all of which are closely related to hypertension. Moreover, the DASH diet, focusing on an overall healthy dietary pattern rather than isolated nutrients, may contribute to its beneficial effects, reinforcing our findings that dietary habits play a crucial role in cardiovascular health even in a younger population. The Children's Dietary Inflammatory Index (C-DII), representing the inflammatory potential of diet, showed a correlation with inflammation and oxidative stress biomarkers [66]. Cross-sectional research revealed a positive correlation between C-DII and elevated systolic blood pressure (SBP), as well as a negative correlation with reduced diastolic blood pressure (DBP) among obese adolescents [67]. Furthermore, a negative linear association between composite dietary antioxidant index (CDAI) and hypertension was found in general adults [68]. Our study attempted to investigate the association between antioxidant diets and HTN in children and adolescents using CDAI, and the findings revealed a lack of correlations between HTN and oxidative stress diet. Several reasons may account for the inconsistent results of oxidative stress dietary. First, the intricate interaction between pro- and anti-oxidant variables was not taken into account. Second, there were measurement errors and inaccuracies in dietary assessments. Third, the observational cross-sectional study could just reveal limited alterations in dietary fiber, trace elements, and vitamins within the diet, suggesting the necessity for further validation through specialized dietary intervention studies.

There were interactions between sex and OBS. Similar to previous studies, sex significantly affected the correlations between OBS and HTN [24]. This result suggested that the physiological mechanism of oxidative stress may differ between the sexes. Inferences from the subgroup analysis, boys were found to have a more pronounced protective effect against hypertension due to elevated OBS.

Adolescent arterial stiffness may represent a novel risk factor for hypertension in young adults [69]. Arterial stiffness is presently a compelling theoretical justification for commencing antihypertensive therapy in pediatric and young adult populations [70]. In our study, the elevated OBS was significantly associated with decreased ePWV, indicating that children and adolescents with higher antioxidant levels had less arterial stiffness. ePWV may be a promising early predictor for arterial stiffness in children and adolescents, allowing pediatricians and other medical practitioners to supervise adolescents to adopt a healthy lifestyle rich in antioxidants, before serious target organ damage occurs.

This study has several limitations. Firstly, the assessment of dietary patterns was susceptible to measurement errors and inaccuracies, particularly with self-reported data such as 24-h dietary recalls. Secondly, memory and selection bias were unavoidable in cross-sectional studies. Thirdly, all the components of OBS were assigned equal weights, disregarding the varying pro- or anti-oxidant potencies of each component. The potential for this equal-weighting approach to fail to faithfully represent the true biological contributions of the OBS components exists. Additionally, dietary OBS focused on the contribution of dietary nutrients to the body's redox balance. Although some micronutrients were counted, detailed macronutrient information was lacking, especially the proportions of saturated fat, monounsaturated fat, and polyunsaturated fat, the ratio of omega-6 to omega-3, and the content of free sugar. Different types of fat have different effects on cardiovascular health through multiple mechanisms such as regulating blood lipids, inflammation, and immune function, not just limited to oxidative stress. Furthermore, variables related to lifestyle were generally easier to quantify than dietary variables, creating a potential imbalance in data quality. Finally, it is challenging to prove causation due to the cross-sectional nature of our study. Nevertheless, in spite of these limitations, we regard as reliable and instructive our findings of the negative correlations between OBS and the prevalence of HTN and arterial stiffness in a large-scale cross-sectional investigation encompassing children and adolescents. Prospective studies are required to further validate the predictive value of OBS in HTN so as to increase the applicability of our findings.

Conclusion

This cross-sectional study indicates that OBS, particularly lifestyle OBS, is inversely correlated with the prevalence of HTN and arterial stiffness among children and adolescents. This study suggests that an antioxidant-rich lifestyle may help shield children from HTN risk.

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Author contributions Conceived and designed research, Che Wang and Rujie Zheng; analyzed data, Che Wang and Rujie Zheng; interpreted results of analysis, Che Wang; prepared figures, Rujie Zheng; drafted manuscript, Che Wang; edited and revised manuscript, Xiaoyu Du, Wenjuan Song, Xiaotong Sun and Zhihao Liu; approved final version of manuscript, Chengzhi Lu.

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Data availability Data are available on the NHANES website (https://www.cdc.gov/nchs/nhanes/index.htm), and the analytic codes will be made available pending email request to the corresponding author.

Declarations

Conflict of interest The authors declare no conflict of interest.

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