

Evaluation of Various Obesity Indicators as Predictors of Elevated Blood Pressure in Chinese Adolescents

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Abstract

Background This study aims to assess the relationship between various obesity indicators and elevated blood pressure (BP) among Chinese adolescents, identifying which indicators can predict the risk of elevated BP.

Methods From October 2023 to January 2024, a questionnaire survey and medical examination were conducted on 10,609 adolescents aged 12–17 years in Shiyao City, China, using convenience sampling. Conventional obesity indicators were measured including body mass index (BMI), ponderal index (PI), waist circumference (WC), waist-to-hip ratio (WHR), conicity index (CI). Additionally, novel obesity indicators such as waist-to-height ratio (WHtR), body shape index (ABSI), body roundness index (BRI), abdominal volume index (AVI), a new hip index (HI), and body adiposity index (BAI), were also calculated. To assess the effectiveness of these obesity indicators in predicting elevated BP, receiver operating characteristic (ROC) curves were used. Multivariate logistic regression was employed to examine the relationship between these obesity indicators and the risk of elevated BP.

Results The overall detection rate of elevated BP among adolescents was 22%, with rates of 20.1% in boys and 24.2% in girls. ROC curve analysis demonstrated statistically significant areas under the curve for predicting elevated BP using Z-scores of the following obesity indicators: BMI, WC, WHtR, WHR, AVI, HI, CI, PI, ABSI, and BAI. The optimal cut-off values for these indicators were: BMI: 0.153, WC: 0.121, WHtR: 0.069, WHR: 0.387, AVI: 0.058, HI: 0.444, CI: 0.444, PI: 0.419, ABSI: 0.282, and BAI: 0.301. Multivariate logistic regression identified HI Z-scores, BAI Z-scores, and WHtR Z-scores as significant predictors of elevated BP risk in adolescents. Specifically, participants with HI Z-scores ≥ 0.444 had a 0.22-fold higher risk of elevated BP. Similarly, those with BAI Z-scores ≥ 0.301 , WHtR Z-scores ≥ 0.069 exhibited 0.28, 0.33 times greater risk, respectively, compared to individuals with lower values.

Conclusion BMI, WC, WHtR, WHR, AVI, HI, CI, PI, ABSI, and BAI were statistically associated with elevated blood pressure in adolescents, but their predictive power was limited. Higher Z-scores of HI, BAI, and WHtR were identified as independent risk factors for elevated BP in this population.

Introduction

Hypertension is a prevalent chronic disease, and its incidence continues to rise annually. Hypertension-related cardiovascular disease imposes a significant health burden on the Chinese population [1–2]. Recent research indicates that shifts in dietary patterns, eating behaviors, physical activity, and development are contributing to an increasing incidence and prevalence of hypertension among younger individuals. Addressing hypertension has emerged as a critical challenge in adolescent health. Studies in Europe indicate that the prevalence of hypertension among adolescents reaches 29% in high-stress academic environments [3]. The American Heart Association reports that approximately 15% of adolescents in the United States exhibit abnormal blood pressure (BP) [4]. A global survey of adolescents aged 19 and younger found a hypertension prevalence of 9.7% [5]. In Iran, the prevalence of hypertension among adolescents stands at 8.98% [6]. Adolescent hypertension typically develops more

gradually than adult hypertension, often with subtle early symptoms [7]. Untreated elevated BP during adolescence can progress to hypertension in adulthood, raising the risk of cardiovascular and cerebrovascular diseases [8]. Risk factors for hypertension include genetic predispositions and unhealthy lifestyle choices. Previous research has identified overweight and obesity as significant risk factors for hypertension [9]. As China's economy and living standards improve, the rates of overweight and obesity among adolescents have increased in recent years. Overweight has emerged as a major public health issue that adversely affects the physical and mental health of adolescents, leading to complications such as cardiovascular diseases, diabetes, and psychological disorders [10]. Body mass index (BMI) and WC are conventional anthropometric indicators commonly used to predict hypertension. Recently, researchers have introduced novel obesity evaluation indicators, including abdominal volume index (AVI) [11], a new hip index (HI) [12], a body shape index (ABSI) [13], body adiposity index (BAI) [14], waist-to-height ratio (WHtR) [15], and body roundness index (BRI) [16].

Numerous studies have investigated the relationship between obesity and hypertension in adolescents. Ma et al. identified the WHtR (WHtR) as the most effective indicator for predicting hypertension prevalence in children and adolescents [17]. Calderon-Garcia et al. found that higher levels of the BRI and ABSI were linked to an increased risk of adolescent hypertension. They noted that ABSI demonstrated significantly lower predictive ability for hypertension compared to BRI, BMI, WC, and WHtR [18]. Another study concluded that WC had the strongest predictive capacity for adolescent hypertension, while the conicity index (CI) showed the weakest effectiveness [19].

Currently, the relationship between various obesity indicators and adolescent hypertension remains contentious, and research on the association of novel obesity indicators with elevated BP in this population is limited. Thus, there is an urgent need to identify simple and effective obesity indicators for predicting elevated BP in adolescents. This study aims to explore the connections between both conventional and novel obesity indicators and elevated BP in adolescents, with the goal of identifying those that more accurately predict elevated BP. This research will provide valuable insights for the prevention and management of elevated BP among adolescents.

Methods

Design and Participants

A cross-sectional survey was conducted in 13 schools in Shiyan City, China, using convenience sampling to select participants. Data collection took place from October 2023 to January 2024. Inclusion criteria for subjects were as follows: (1) aged 12 to 17 years; (2) self-aware and capable of independently completing questionnaires and answering questions accurately; (3) participants and their guardians understood the research's content, purpose, and significance, and provided signed informed consent. Exclusion criteria included participants who withdrew from the study. All participants had the opportunity to ask questions during the survey process. A total of 10,629 adolescents were invited to participate, and after excluding those with missing data, the final analysis included 10,622 participants.

Data collection

Questionnaire interview

The questionnaire included items on demographic characteristics (e.g., gender, age, ethnicity, personality), lifestyle behaviors (e.g., sedentary time, screen time), and assessments of sleep quality and psychological distress.

Sedentary time was recorded as the daily hours spent sitting at school or at home. Following a previous study [20], participants were asked to estimate their average daily screen time across several activities, including viewing television and/or DVDs, using a computer or laptop, engaging with smartphones and tablets, and playing video games. The total screen time was calculated by summing these hours.

Subjective sleep quality over the past month was measured using the Pittsburgh Sleep Quality Index (PSQI), developed by Buysse et al [21]. This index comprises 19 self-rated items categorized into seven components: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleep medication, and daytime dysfunction. Each component is scored on a 4-point Likert scale (0–3), with total scores ranging from 0 to 21. A higher total score indicates poorer sleep quality, with a cut-off score of 7 signifying the worst sleep quality. The Chinese version of the PSQI has demonstrated good internal consistency and test-retest reliability [22], achieving a Cronbach's alpha of 0.74 in this study.

Psychological distress over the past four weeks was assessed using the Kessler Psychological Distress Scale (K10). The Chinese version of the K10 has shown strong reliability and validity [23]. This scale consists of 10 items measuring anxiety and depressive symptoms, with each item scored from one (1 = none of the time) to five (5 = all of the time). A higher total score reflects a greater risk of mental illness [24]. In this study, the K10 achieved a Cronbach's alpha of 0.92.

Anthropometric measurements

Body morphometric indicators, including height, weight, neck circumference, chest circumference, waist circumference, and hip circumference, as well as BP measurements (systolic blood pressure (SBP) and diastolic blood pressure (DBP)), were collected by trained medical researchers. Following China's "Technical Standards for Physical Examination of Students" (GB/T26343-2010), height and weight were measured using an ultrasonic device (Meilen MSG003SC), with participants in light clothing and barefoot. Neck, chest, waist, and hip circumferences were measured using a flexible measuring tape (ER301). BP was measured with a calibrated Omron HEM-1020 automatic electronic sphygmomanometer.

Participants were instructed to avoid strenuous exercise for one hour prior to BP measurement and to rest for five minutes before the assessment. The sphygmomanometer was positioned at heart level to

measure the brachial artery. Measurements were taken twice with a 1–2 minute interval, and the average of these two readings was recorded. If the SBP or DBP measurements differed by more than 5 mm Hg, a third measurement was performed, and the average of all three readings was calculated. BP measurements were performed during school hours within two standardized time windows (8:00–11:00 a.m. and 2:30–5:30 p.m.) to accommodate school schedules. While exact individual measurement times were not recorded, all assessments occurred within these periods to ensure temporal consistency across participants.

Definition of elevated BP

Elevated BP was defined in accordance with the national reference standard issued by the National Health Commission of China: *Reference for Screening Elevated Blood Pressure in Children and Adolescents Aged 7–18 Years* (WS/T 610–2018). According to this guideline, adolescents are classified as having elevated BP if their SBP and/or DBP is equal to or greater than the 95th percentile for the same sex, age, and height [25].

Calculation of obesity indicators

The WHR was calculated by dividing WC (cm) by hip circumference (cm), and the WHtR was obtained by dividing WC (cm) by height (cm). BMI was derived by dividing weight (kg) by height squared (m²), and PI was computed as weight (kg) divided by height cubed (m³). The remaining anthropometric indicators (CI, ABSI, BRI, AVI, HI, BAI) were calculated using the following formulas:

$$CI (m^{1/2} kg^{-1/2}) = WC (m) / [0.109 \times (\text{weight (kg)} / \text{height (m)})^{1/2}] [26].$$

$$ABSI (kg^{-2/3} m^{11/6}) = WC (m) / [BMI (kg/m^2)^{2/3} \times \text{height (m)}^{1/2}] [13].$$

$$BRI = 364.2 - 365.5 \times \{1 - [(WC (m) / 2 \pi) / (0.5 \times \text{height (m)})^2]^{1/2}\} [16].$$

$$AVI (cm^2) = [2 \times WC (cm)^2 + 0.7 (WC - \text{hip circumference}) (cm)^2] / 1000 [11].$$

$$HI (cm) = \text{hip circumference (cm)} \times [\text{height (cm)} / 166 (cm)]^{0.310} \times [(\text{weight (kg)} / 73 (kg))^{-0.482}] [12].$$

$$BAI = \text{hip circumference (cm)} / \text{height (m)}^{1.5} [14].$$

As the units vary among different adiposity indicators, the indicators including BMI, WC, WHtR, WHR, BAI, AVI, HI, CI, PI, ABSI, BRI and BAI were converted into age- and sex-specific s.d.scores (Z-scores), to make the effect estimates for different adiposity indicators comparable[27].

$$Z - \text{scores} = \frac{\text{Observed value} - \text{age} - \text{and sex} - \text{specific mean}}{\text{Age} - \text{and sex} - \text{specific s. d.}}$$

Quality control

All investigators received standardized training and successfully passed competency assessments prior to data collection. Measuring instruments were calibrated following strict operational protocols. Before formal data collection, the study's purpose and significance were clearly explained to all participants. Anthropometric measurements were conducted according to standardized procedures to ensure consistency across survey sites. To maintain data quality, two trained researchers were present in each classroom to provide real-time guidance and address any participant questions. Furthermore, a random sample of completed questionnaires was reviewed for quality assurance, and all data were entered using a double-entry method combined with logical verification to ensure accuracy and completeness.

Statistical analysis

Statistical analysis and plotting were conducted using SPSS 17.0 (SPSS Inc., Chicago, IL, USA) and R 4.2.2 software. Continuous variables were reported as means with standard deviations (SD), and comparisons between groups were made using t-tests. Categorical variables were expressed as percentages, with the χ^2 test used for group comparisons. Cut-off values for each obesity indicator were determined using receiver operating characteristic (ROC) curves, quantified by the area under the ROC curve (AUC). The optimal cut-off point for each indicator was established using Youden's index (sensitivity + specificity - 1).

In line with previous research, variance inflation factor (VIF) was used to assess multicollinearity. A VIF value of ≥ 10 indicates the presence of multicollinearity [28]. Multivariate logistic regression was conducted to analyze the association between obesity indicators and elevated BP among adolescents, treating elevated BP status as the dependent variable (No = 0, Yes = 1). Odds ratios (ORs) were presented with 95% confidence intervals (CIs). A two-tailed p-value of < 0.05 was considered statistically significant.

Results

Characteristics of the participants

The basic characteristics of the study participants are summarized in Table 1. Data from 10,609 adolescents were analyzed, with a mean age of 13.83 years (SD: 1.40). Statistically significant differences were observed between adolescents with elevated BP and those without in several factors, including gender, screen time, school period, gender, traits of character, father's smoking status, and extracurricular exercise time ($P < 0.05$). The overall detection rate of elevated BP was 22.0% (2,335/10,609), with rates of 20.1% (1,131/5,635) among boys and 24.2% (1,204/4,974) among girls.

Table 1
Sample characteristics of study population [n (%)]

Variables	Total (n = 10609)	Elevated BP (n = 2335)	Normotension (n = 8274)	t/χ^2	P
Age (years) (mean $\pm$ SD)	13.83 $\pm$ 1.40	13.89 $\pm$ 1.36	13.82 $\pm$ 1.41	-2.057	0.040
Screen Time (h) (mean $\pm$ SD)	6.08 $\pm$ 2.63	5.97 $\pm$ 2.79	6.11 $\pm$ 2.59	2.341	0.019
Sedentary time(h)(mean $\pm$ SD)	10.16 $\pm$ 2.45	10.08 $\pm$ 2.55	10.18 $\pm$ 2.42	1.824	0.068
School period				5.093	0.024
Junior high school	8313 (78.4)	1790 (76.7)	6523 (78.8)		
Senior high school	2296 (21.6)	545 (23.3)	1751 (21.2)		
Gender				26.315	< 0.001
Male	5635 (53.1)	1131 (48.4)	4504 (54.4)		
Female	4974 (46.9)	1204 (51.6)	3770 (45.6)		
Ethnicity				1.144	0.285
Han	10472(98.7)	2310 (98.9)	8162 (98.6)		
Other	137 (1.3)	25 (1.1)	112 (1.4)		
Academic performance				1.889	0.169
Better	2646 (25.0)	557 (23.9)	2089 (25.2)		
Normal	7963 (75.0)	1778 (76.1)	6185 (74.8)		
Traits of character				8.289	0.016
Introversion	1374 (12.9)	314 (13.4)	1060 (12.8)		
Neutral	6478 (61.1)	1468 (62.9)	5010 (60.6)		
Extroversion	2757 (26.0)	553 (23.7)	2204 (26.6)		
Father's smoking status				5.534	0.019
Yes	4194 (39.5)	874 (37.4)	3320 (40.1)		
No	6415 (60.5)	1461 (62.6)	4954 (59.9)		
The Table 5 should be placed in the results section.					

Variables	Total (n = 10609)	Elevated BP (n = 2335)	Normotension (n = 8274)	t/χ^2	P
Extracurricular exercise time (min)				11.065	0.011
0	373 (3.5)	70 (3.1)	303 (3.7)		
< 30	4200 (39.6)	984 (42.1)	3216 (38.9)		
30–60	4552 (42.9)	984 (42.1)	3568 (43.1)		
> 60	1484 (14.0)	297 (12.7)	1187 (14.3)		
Dietary preferences				5.691	0.058
Saltish	3082 (29.0)	635 (27.2)	2447 (29.6)		
Normal	6580 (62.0)	1496 (64.1)	5084 (61.4)		
Light taste	947 (9.0)	204 (8.7)	743 (9.0)		
Sleep quality				0.004	0.947
Good	6349 (59.8)	1396 (59.8)	4953 (59.9)		
Poor	4260 (40.2)	939 (40.2)	3321 (40.1)		
Mental health				0.001	0.982
Good	7317 (69.0)	1610 (69.0)	5707 (69.0)		
Poor	3292 (31.0)	725 (31.0)	2567 (31.0)		
The Table 5 should be placed in the results section.					

Measurement results of obesity indicators in adolescents by BP Group

The Z-scores of WC, BMI, WHR, WHtR, AVI, CI, HI, ABSI, PI, and BAI were significantly higher in adolescents with elevated BP compared to those with normal BP ($P < 0.05$) (Table 2).

Table 2

Comparison of Z-scores for sphysiological indicators between adolescents with elevated BP and those with normal BP ($\bar{x} \pm s$)

Indexes	Total (n = 10609)	Elevated BP (n = 2335)	Normal BP (n = 8274)	t	P
BMI Z-scores	0.00 ± 1.00	0.14 ± 1.04	-0.04 ± 0.98	-7.55	< 0.001
WC Z-scores	-0.00 ± 1.00	0.21 ± 1.06	-0.06 ± 0.97	-11.75	< 0.001
WHtR Z-scores	0.00 ± 0.85	0.18 ± 0.92	-0.05 ± 0.82	-11.70	< 0.001
WHR Z-scores	0.00 ± 1.00	0.11 ± 0.98	-0.03 ± 1.00	-5.84	< 0.001
AVI Z-scores	0.00 ± 1.00	0.21 ± 1.07	-0.06 ± 0.97	-11.68	< 0.001
HI Z-scores	0.00 ± 1.00	0.14 ± 1.10	-0.04 ± 0.96	-7.45	< 0.001
CI Z-scores	-0.00 ± 1.00	0.17 ± 1.08	-0.05 ± 0.97	-9.48	< 0.001
PI Z-scores	0.00 ± 1.00	0.14 ± 1.05	-0.04 ± 0.98	-7.45	< 0.001
ABSI Z-scores	-0.00 ± 1.00	0.14 ± 1.09	-0.04 ± 0.97	-7.91	< 0.001
BRI Z-scores	0.00 ± 1.00	-0.01 ± 1.00	0.01 ± 0.99	0.02	0.981
BAI Z-scores	0.00 ± 1.00	0.23 ± 1.06	-0.06 ± 0.97	-12.50	< 0.001
Note: SBP: systolic blood pressure, DBP: diastolic blood pressure, BMI: body mass index, WC: waist circumference, WHtR: waist-to-height ratio, WHR: waist-to-hip ratio, AVI: abdominal volume index, HI: a new hip index, CI: conicity index, PI: ponderal index, ABSI: a body shape index, BRI: body roundness index, BAI: body adiposity index.					

Performance of obesity indicators to predict elevated BP

Table 3 presents the ROC curve analysis of Z-scores for all obesity indicators used to predict elevated BP in adolescents, along with the corresponding optimal cut-off points. Among these indicators, the BAI Z-scores exhibited the highest AUC, followed by Z-scores of WHtR, WC, AVI, CI, BMI, PI, ABSI, WHR, HI, and BRI. The optimal cut-off values for BMI, WC, WHtR, WHR, AVI, HI, CI, PI, ABSI, and BAI Z-scores were 0.153, 0.121, 0.069, 0.387, 0.058, 0.444, 0.444, 0.419, 0.282, and 0.301, respectively (see Table 3, Fig. 1).

Table 3

ROC curve analysis of obesity indicators Z-scores as predictors of elevated BP in adolescents

Indexes	AUC	95CI%	P	Cut-off value	Sensitivity	Specificity	Youden index
BMI Z-scores	0.550	0.536 ~ 0.563	< 0.001	0.153	0.496	0.585	0.081
WC Z-scores	0.577	0.564 ~ 0.590	< 0.001	0.121	0.480	0.636	0.116
WHtR Z-scores	0.578	0.565 ~ 0.591	< 0.001	0.069	0.461	0.673	0.134
WHR Z-scores	0.547	0.533 ~ 0.560	< 0.001	0.387	0.692	0.387	0.079
AVI Z-scores	0.577	0.563 ~ 0.590	< 0.001	0.058	0.484	0.638	0.121
HI Z-scores	0.540	0.526 ~ 0.554	< 0.001	0.444	0.319	0.754	0.073
CI Z-scores	0.560	0.546 ~ 0.573	< 0.001	0.444	0.332	0.760	0.092
PI Z-scores	0.548	0.535 ~ 0.562	< 0.001	0.419	0.376	0.702	0.077
ABSI Z-scores	0.547	0.534 ~ 0.561	< 0.001	0.282	0.376	0.704	0.080
BAI Z-scores	0.579	0.566 ~ 0.593	< 0.001	0.301	0.451	0.672	0.123
BRI Z-scores	0.499	0.486 ~ 0.513	0.936	0.239	0.686	0.325	0.011

Note: BMI: body mass index, WC: waist circumference, WHtR: waist-to-height ratio, WHR: waist-to-hip ratio, AVI: abdominal volume index, HI: a new hip index, CI: conicity index, PI: ponderal index, ABSI: a body shape index, BAI: body adiposity index, BRI: body roundness index.

Comparison of the proportion of participants with elevated BP across different obesity indicator categories

Based on the cut-off values for both novel and conventional obesity indicators, each obesity indicator Z-scores was dichotomized, and the proportions of adolescents with normal and elevated BP were compared across these categories. Significant differences in the proportions between elevated and normal BP groups were observed for WHtR Z-scores, AVI Z-scores, HI Z-scores, ABSI Z-scores, and BAI Z-scores ($P < 0.001$) (Fig. 2). In contrast, no statistically significant difference was found for the BRI Z-scores categories ($P > 0.05$). Additionally, WC Z-scores, WHR Z-scores, CI Z-scores, PI Z-scores, and BMI

Z-scores categories also showed significant differences in proportions between elevated and normal BP groups ($P < 0.05$) (Fig. 3).

The relationship between different obesity indicators and elevated BP in adolescents

The multicollinearity test revealed that the VIF values for WC Z-scores and AVI Z-scores exceeded 10; therefore, these indicators were excluded from the regression model (Table 4). In model 1 (unadjusted), participants with BAI Z-scores of ≥ 0.301 , and WHtR Z-scores of ≥ 0.069 had significantly higher odds of elevated BP. Model 2, adjusted for screen time, school period, gender, personality, father's smoking status, extracurricular exercise time, and age. After adjustment, elevated BP risk remained significantly higher among participants with WHtR Z-scores ≥ 0.069 (OR = 1.33, 95% CI: 1.14–1.54), HI Z-scores ≥ 0.444 (OR = 1.22, 95% CI: 1.07–1.39), BAI Z-scores ≥ 0.301 (OR = 1.28, 95% CI: 1.11–1.41) (Table 5).

Table 4
Collinearity test of independent variables

Variables	β	SE	t	P	VIF
WC Z-scores	-0.057	0.037	-1.560	0.119	20.151
BMI Z-scores	0.014	0.012	1.167	0.243	2.336
WHtR Z-scores	0.045	0.015	3.118	0.002	3.072
ABSI Z-scores	-0.001	0.017	-0.032	0.975	4.033
AVI Z-scores	0.068	0.036	1.877	0.061	19.762
HI Z-scores	0.021	0.013	1.661	0.097	1.922
BAI Z-scores	0.034	0.012	2.882	0.004	1.991
WHR Z-scores	-0.003	0.012	-0.257	0.798	1.770
PI Z-scores	0.023	0.013	1.704	0.088	2.429
CI Z-scores	0.022	0.019	1.176	0.239	4.394
School period	0.019	0.016	1.216	0.224	2.674
Traits of character	-0.015	0.007	-2.296	0.022	1.018
Gender	0.041	0.008	5.075	0.000	1.032
Father's smoking status	0.020	0.008	2.422	0.015	1.003
Screen time	-0.007	0.002	-4.141	0.000	1.096
Extracurricular exercise time	-0.001	0.006	-0.099	0.921	1.124
age	0.004	0.005	0.864	0.388	2.538

Note: WC: waist circumference, BMI: body mass index, WHtR: waist-to-height ratio, ABSI: a body shape index, AVI: abdominal volume index, HI: a new hip index, BAI: body adiposity index, WHR: waist-to-hip ratio, PI: ponderal index, CI: conicity index.

Table 5
Multivariate Logistic regression analysis of the relationship between obesity indicators Z-scores and elevated BP

Variables	Model 1		Model 2	
	OR (95%CI)	P value	OR (95%CI)	P value
BMI Z-scores				
< 0.153	Reference		Reference	
≥ 0.153	1.10 (0.95 ~ 1.26)	0.203	1.10 (0.96 ~ 1.28)	0.146
WHtR Z-scores				
< 0.069	Reference		Reference	
≥ 0.069	1.34 (1.16 ~ 1.54)	< 0.001	1.33 (1.14 ~ 1.54)	< 0.001
ABSI Z-scores				
< 0.282	Reference		Reference	
≥ 0.282	1.03 (0.84 ~ 1.26)	0.778	1.01 (0.82 ~ 1.24)	0.096
HI Z-scores				
< 0.444	Reference		Reference	
≥ 0.444	1.13 (0.98 ~ 1.30)	0.090	1.22 (1.07 ~ 1.39)	0.040
BAI Z-scores				
< 0.301	Reference		Reference	
≥ 0.301	1.20 (1.05 ~ 1.37)	0.007	1.28 (1.11 ~ 1.41)	0.004
WHR Z-scores				
< 0.387	Reference		Reference	
≥ 0.387	0.98 (0.86 ~ 1.11)	0.716	1.13 (0.97 ~ 1.32)	0.109
PI Z-scores				
< 0.419	Reference		Reference	
≥ 0.419	1.15 (0.99 ~ 1.34)	0.067	1.14 (0.91 ~ 1.41)	0.252
CI Z-scores				

Note: Model 1 was not adjusted for confounding factors, whereas Model 2 was adjusted for screen time, school period, gender, personality, father's smoking status, extracurricular exercise time, and age. WC: waist circumference, BMI: body mass index, WHtR: waist-to-height ratio, ABSI: a body shape index, AVI: abdominal volume index, HI: a new hip index, BAI: body adiposity index, WHR: waist-to-hip ratio, PI: ponderal index, CI: conicity index.

Variables	Model 1		Model 2	
	OR (95%CI)	P value	OR (95%CI)	P value
< 0.444	Reference		Reference	
≥ 0.444	1.12(0.90 ~ 1.39)	0.308	1.11 (0.92 ~ 1.33)	0.271
Note: Model 1 was not adjusted for confounding factors, whereas Model 2 was adjusted for screen time, school period, gender, personality, father's smoking status, extracurricular exercise time, and age. WC: waist circumference, BMI: body mass index, WHtR: waist-to-height ratio, ABSI: a body shape index, AVI: abdominal volume index, HI: a new hip index, BAI: body adiposity index, WHR: waist-to-hip ratio, PI: ponderal index, CI: conicity index.				

Discussion

The overall detection rate of elevated BP among adolescents in this study was higher than the 9.0% reported for Korean adolescents aged 10–18 years [29] and 10.6% for Mexican adolescents aged 11–15 years [30], but lower than the 25.1% found in Indian adolescents aged 13 and older [31]. This variation suggests significant regional differences in the detection rate of elevated BP, potentially influenced by cultural, dietary, and economic factors, which merits further investigation.

Our study found significant gender differences in the prevalence of elevated blood pressure, which may result from biological factors, such as hormonal profiles and patterns of fat distribution, as well as behavioral and psychosocial factors, including physical activity habits, dietary behaviors, and stress responses [32–34]. Future research should incorporate gender-stratified analyses to explore the underlying physiological and behavioral mechanisms linking obesity to elevated blood pressure in both boys and girls. Identifying modifiable, gender-specific risk factors through such focused investigations could provide valuable insights for developing tailored hypertension prevention strategies. Designing gender-sensitive interventions that take into account differences in physiology, health behaviors, and responsiveness to health information may significantly enhance the effectiveness and equity of efforts aimed at reducing hypertension risk among adolescents.

This study is the first to assess the predictive value of both traditional and novel obesity indicators for elevated BP in Chinese adolescents. Obesity, characterized by excessive fat accumulation, is a significant predictor of elevated BP in this population [35]. Through ROC curve analysis, we identified optimal cut-off values for conventional obesity indicators (BMI, WC, WHR, CI) and novel indicators (WHtR, AVI, HI, ABSI, BAI) for predicting elevated BP risk.

WHtR, BAI, and HI are all indicators of central or abdominal obesity. WHtR reflects the distribution of fat, particularly around the waist, and is considered a practical and sensitive predictor of cardiometabolic risk. In our study, a higher WHtR was significantly associated with elevated BP in adolescents, aligning with findings from previous study [36]. BAI, which incorporates hip circumference and height, offers a relatively objective estimate of body fat percentage. Our results showed that elevated BAI was also

associated with elevated BP, consistent with the findings of Dong et al. [37]. HI, a relatively novel index that standardizes hip circumference based on height and weight, has previously been linked to a U-shaped relationship with mortality [12]. In our analysis, adolescents with higher HI Z-scores had an increased risk of elevated BP, suggesting that excessive hip adiposity, even when adjusted for body size, may contribute to early blood pressure dysregulation.

The mechanism by which central obesity contributes to elevated blood pressure is multifactorial, with chronic low-grade inflammation being one of the key pathways. Previous studies have linked obesity to a chronic low-grade inflammatory state driven by various inflammatory factors [38]. Beyond energy storage, adipose tissue secretes adipokines such as leptin, adiponectin, and cytokines like TNF- α and IL-6. In normal physiology, adipose tissue maintains a balanced secretion pattern, regulating functions like endothelial health and immunity. However, in obesity, lipid accumulation can lead to adipocyte hypertrophy, decreasing adiponectin levels and increasing inflammatory cytokine production [39]. This chronic inflammation can result in endothelial damage, hemodynamic changes, and myocardial remodeling, promoting atherosclerosis and elevating BP [40].

In addition, visceral adipose tissue in central obesity is particularly metabolically active, producing higher levels of pro-inflammatory cytokines and adipokines that reduce nitric oxide bioavailability [41]. The resulting endothelial dysfunction further elevates BP. Heightened sympathetic nervous system activity in obesity promotes lipolysis, releasing more free fatty acids from adipose tissue, contributing to metabolic disorders that raise BP [42]. These metabolic abnormalities can also lead to insulin resistance, enhanced renal sodium reabsorption, and fluid retention, collectively increasing BP levels [43–44]. Furthermore, excess body fat may also mediate increased peripheral vascular resistance and other functional impairments, including high leptin and low adiponectin levels, as well as elevated RAAS hormones [45]. Collectively, these adipose tissue dysfunctions may result in endothelial dysfunction, vascular hypertrophy, and impaired sodium pressure regulation through RAAS and the sympathetic nervous system, ultimately causing elevated BP [46].

Our study has several limitations. First, as a cross-sectional design, it cannot establish causal relationships between obesity-related anthropometric indicators and elevated BP among adolescents. Longitudinal data are needed to track changes in obesity and BP over time, assess the stability and predictive power of these indicators, and identify critical periods for intervention. We plan to conduct multi-center longitudinal cohort studies involving diverse populations to evaluate the practical value of obesity indicators in early prediction and prevention of elevated BP risk. Second, BP measurements were conducted during regular school hours, with timing dependent on school class schedules. However, the lack of individually recorded measurement times may have introduced intra-individual variability due to unaccounted circadian influences, potentially affecting the accuracy of BP classification. Third, the use of a convenience sampling strategy may limit the generalizability of our findings. Participants were recruited from selected schools based on accessibility rather than random sampling, which may result in a sample that does not fully reflect the broader adolescent population in terms of demographic or geographic characteristics. Therefore, caution is warranted when applying these results to other

populations. Future research should consider employing probability-based sampling to enhance both internal and external validity. Fourth, the study did not include detailed lifestyle assessments—such as comprehensive dietary intake or objectively measured physical activity—which may have resulted in residual confounding. The omission of more detailed lifestyle data could have influenced the observed associations between obesity indicators and elevated BP. Future studies should incorporate more rigorous lifestyle measures, such as validated food frequency questionnaires and wearable activity trackers, to better account for these potential confounders. Fifth, the cut-off values for obesity-related Z-score indicators identified in this study were derived from a large adolescent sample in Shiyao City, China. While these thresholds are appropriate for populations with similar demographic, ethnic, and socio-economic characteristics, they may not be universally applicable. Given the potential variability in genetic background and socio-economic context across regions, the generalizability of these thresholds is limited. We recommend that future research validate and, if necessary, recalibrate these cut-off values in more diverse adolescent populations, particularly in multi-ethnic or geographically distinct settings.

Conclusions

This study found that BMI, WC, WHtR, WHR, AVI, HI, CI, PI, ABSI, and BAI were all statistically associated with elevated blood pressure in adolescents. However, their AUC values were generally low, indicating limited predictive power. After adjustment for confounders, higher Z-scores of HI, BAI, and WHtR remained significantly associated with elevated BP, suggesting their value as independent predictors.

Abbreviations

95%CI 95% Confidence interval

VIF Variance inflation factor

ROC Receiver operating characteristics curve

AUC Area under the curve

SE Standard Error

BP Blood pressure

SBP Systolic blood pressure

DBP Diastolic blood pressure

BMI Body mass index

WC Waist circumference

WHtR Waist-to-height ratio

WHR Waist-to-hip ratio

AVI Abdominal volume index

HI a new hip index

CI Conicity index

PI Ponderal index

ABSI A body shape index

BRI Body roundness index

BAI Body adiposity index

Declarations

Ethics approval and consent to participate

The study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Humanities Research Ethics Committee of the Hubei University of Medicine (Approval No. 2023-RE-027), and written informed consent was obtained from all participants prior to the study.

Consent for publication

Not applicable.

Data availability

The datasets used during the current study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare no competing interests.

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Authors' contributions

WX analyzed, interpreted the data, and drafted the manuscript. LZ and XL designed the study framework and contributed to editing the manuscript. CZ, XM, and HY conceived the idea for the writing. JC (Jun Chen), JC (Jishun Chen), DL, ZL and EX participated in the statistical analysis. HX, WW reviewed and revised the manuscript. All authors have read and agreed to the published version of the manuscript.

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Figures

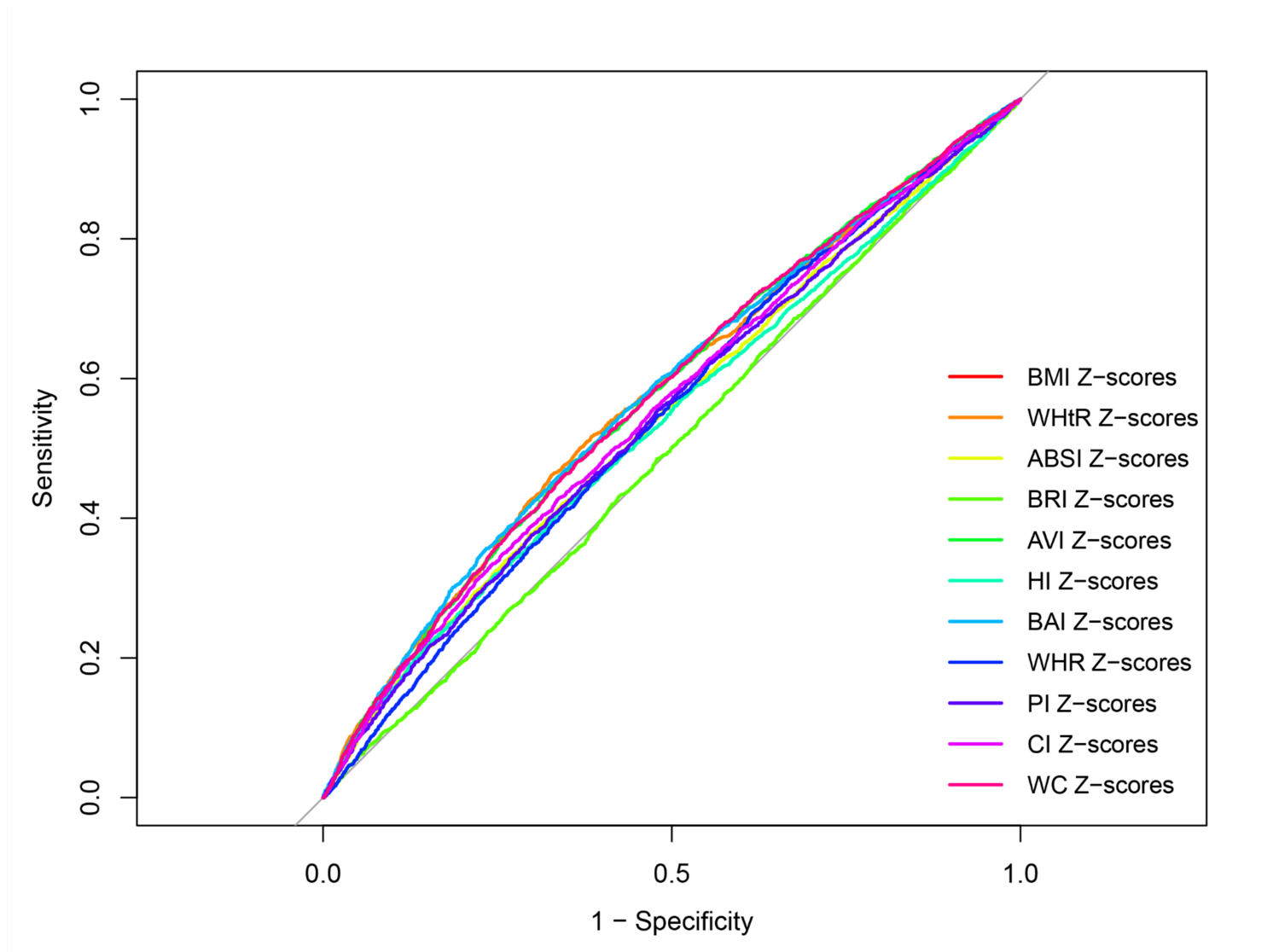


Figure 1

ROC curve analysis of obesity indicators Z-scores for predicting elevated BP in adolescents

Note: BMI: body mass index, WC: waist circumference, WHtR: waist-to-height ratio, WHR: waist-to-hip ratio, AVI: abdominal volume index, HI: a new hip index, CI: conicity index, PI: ponderal index, ABSI: a body shape index, BRI: body roundness index, BAI: body adiposity index.

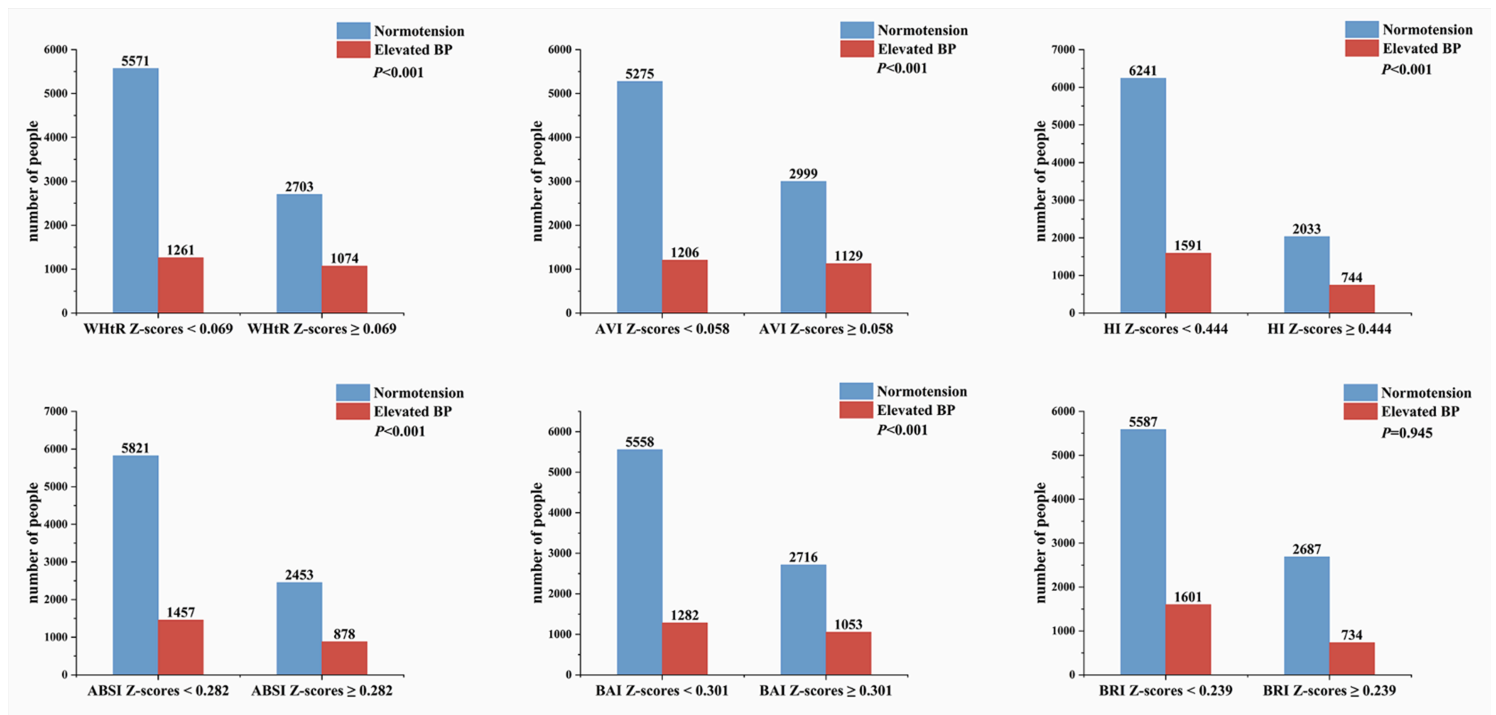


Figure 2

Proportion of participant with elevated BP and normal BP across categories of novel obesity indicators Z-scores

Note: WHtR: waist-to-height ratio, AVI: abdominal volume index, HI: a new hip index, ABSI: a body shape index, BAI: body adiposity index, BRI: body roundness index.

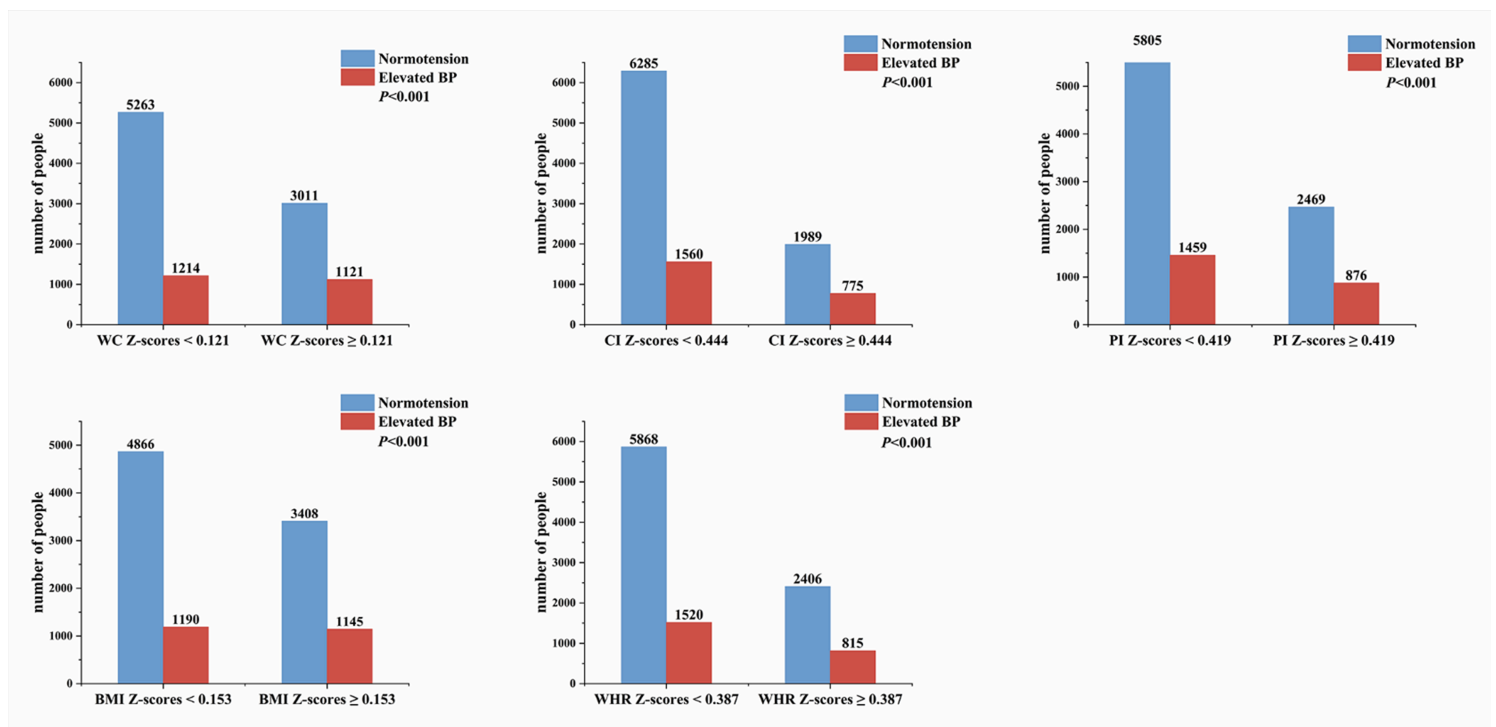


Figure 3

Proportion of participant with elevated BP and normal BP across categories of conventional obesity indicators Z-scores

Note: WC: waist circumference, CI: conicity index, PI: ponderal index, WHR: waist-to-hip ratio, BMI: body mass index.