International Journal of Obesity www.nature.com/ijo

ARTICLE

Check for updates

Pediatrics

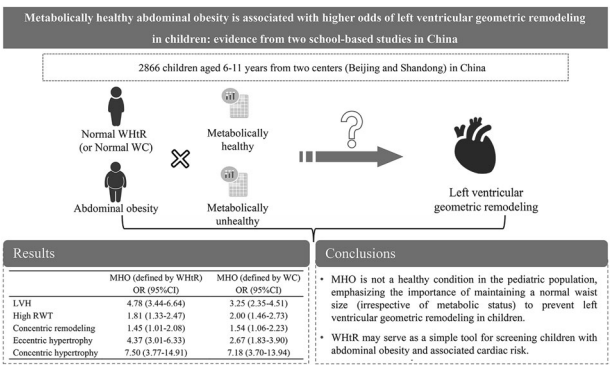
Metabolically healthy abdominal obesity is associated with higher odds of left ventricular geometric remodeling in children: Evidence from two school-based studies in China

Lili Yang[1], Menglong Li[2], Huan Wang[3], Min Zhao[4], Costan G. Magnussen[5,6,7,8], Yifei Hu[2]✉ and Bo Xi[1]✉

OBJECTIVES: The association between metabolically healthy abdominal obesity (MHO) and subclinical cardiovascular outcomes in the general pediatric population remains largely unexplored. We aimed to investigate the relationship of MHO with left ventricular geometric (LVG) remodeling in Chinese children.
METHODS: Data were obtained from two school-based cross-sectional studies in China, involving 2866 children aged 6–11 years. Abdominal obesity was defined using waist-to-height ratio (WHtR) or waist circumference references. The metabolically healthy phenotype was defined by the absence of four cardiovascular risk factors: elevated blood pressure, elevated triglycerides, elevated fasting blood glucose, and decreased high-density lipoprotein cholesterol. LVG was categorized into four patterns (normal geometry, concentric remodeling, eccentric hypertrophy, and concentric hypertrophy) based on two indices including left ventricular mass index and relative wall thickness.
RESULTS: Using WHtR to define abdominal obesity, 543 (18.9%) children were classified as MHO. In the multivariable logistic regression models, compared with children with metabolically healthy normal WHtR, the adjusted odds ratios (95% confidence intervals) of children with MHO were 4.78 (3.44–6.64) for left ventricular hypertrophy, 1.81 (1.33–2.47) for high relative wall thickness, 1.45 (1.01–2.08) for concentric remodeling, 4.37 (3.01–6.33) for eccentric hypertrophy, and 7.50 (3.77–14.91) for concentric hypertrophy. In contrast, children with metabolically unhealthy normal WHtR did not exhibit increased odds of any type of LVG remodeling. Similar results were observed when defining abdominal obesity based on waist circumference.
CONCLUSIONS: MHO is associated with a higher likelihood of LVG remodeling, suggesting that this phenotype may not be benign for the heart in children. Due to its simplicity and practicality, WHtR may be a preferable tool for the rapid screening of children with abdominal obesity and associated cardiac risk.

International Journal of Obesity; https://doi.org/10.1038/s41366-025-01800-x

Graphical Abstract



A full list of author affiliations appears at the end of the paper.

Received: 19 November 2024 Revised: 18 April 2025 Accepted: 28 April 2025
Published online: 22 May 2025

INTRODUCTION

Obesity is a well-established major risk factor for cardiovascular disease (CVD) and has become a worldwide public health issue [1]. Obesity-related metabolic abnormalities, including elevated blood pressure (BP), dyslipidemia, and hyperglycemia, further exacerbate the risk of CVD. However, obesity does not always entail metabolic dysfunction, and this phenotype is often termed as metabolically healthy obesity (MHO) [2]. The health implications of MHO remain a subject of ongoing debate. While some studies report no significant difference in cardiovascular risk between adults with MHO and those with metabolically healthy normal weight [3, 4], accumulating evidence indicates that MHO is associated with an increased risk of CVD in adults [5, 6].

Given that CVD in adulthood often originates from childhood and that the prevalence of pediatric obesity has increased dramatically, particularly in China [7] (where the prevalence of overweight and obesity among children aged 7–18 years surged from 1.2% in 1985 to 23.4% in 2019 [8]), it is critically important to address the potential cardiovascular risk of MHO during childhood. However, published studies on MHO in children have focused primarily on its determinants and clinical characteristics [9–11], with limited data on its association with cardiovascular risk [12, 13]. This represents a significant research gap, especially considering the current Expert Consensus in Chinese children, which emphasizes the importance of distinguishing children with MHO from those with metabolically unhealthy obesity and recommends screening only for the latter group [14].

Another important issue in MHO research is the use of body mass index (BMI) as the primary index for defining obesity. BMI is derived from weight and height and does not reflect the distribution of body fat. The inconsistent findings regarding MHO (defined based on BMI) in relation to the risk of CVD also questioned the accuracy of BMI as an obesity measure. In contrast, waist-to-height ratio (WHtR) and waist circumference (WC), which are measures of abdominal obesity, have shown to be strongly correlated with CVD [15, 16]. Previous studies, including our own, have demonstrated that abdominal adiposity is closely linked with left ventricular geometric (LVG) remodeling in children [17, 18]. As is known, LVG remodeling is an independent predictor of cardiovascular morbidity and mortality in adults [19]. Nevertheless, no studies to date have investigated the association between MHO (obesity was assessed using WHtR or WC) and LVG remodeling in the general pediatric population.

With this background, we aimed to examine the association of metabolically healthy abdominal obesity (MHO; obesity was determined by WHtR or WC) with the odds of LVG remodeling among children aged 6–11 years using data from two school-based studies in China.

METHODS

Study population

Data were from two cross-sectional studies in two centers of China (Beijing and Shandong). In Beijing, the study included 1711 children aged 6–8 years in six primary schools (selected using a community-based census-like design) of Shunyi district, Beijing, from October 2018 to June 2019. In Shandong, the study included 1515 children aged 6–11 years in one primary school (selected using a convenient cluster sampling method) in Huantai county, Zibo city, Shandong province, from November 2017 to January 2018. Detailed information about the two studies has been described elsewhere [12, 20]. After excluding children with missing data on anthropometric variables, metabolic factors and cardiac structure parameters, a total of 2866 children (Beijing: 1449; Shandong: 1417) were included in this study (Supplementary Fig. 1).

Ethics approval and consent to participate

For each center, written informed consent was obtained from each child and his/her parents or guardians. The study protocols were approved by the Ethics Committee of Capital Medical University (approval number: 2018SY82) and the Ethics Committee of Shandong University (approval number: 20160308), respectively. All methods were performed in accordance with the relevant guidelines and regulations.

WC, WHtR and metabolic factors measurements

In each center, WC of each child was measured to the nearest 0.1 cm by trained staff using an inelastic tape at the level of 1 cm above the umbilicus, and was recorded at the end of a normal expiration. WC was measured twice and the averaged values were used for data analysis. WHtR was calculated as WC (in cm) divided by height (in cm). BP was measured using a validated sphygmomanometer in each center (Beijing: OMRON-HBP 1300, Dalian, China; Shandong: OMRON-HEM 7012, Osaka, Japan) with an appropriate arm cuff at the heart level of the right arm. BP was measured three times and the mean of the last two values was used for data analysis. Fasting venous blood samples were obtained after at least 10-hour fast, and high-density lipoprotein cholesterol (HDL-C), triglycerides (TG), and fasting blood glucose (FBG) were measured using an autoanalyser in each center (Beijing: Beckman Coulter AU5800, Shizuoka, Japan; Shandong: Cobas c702 instrument, Mannheim, Germany).

Cardiac structure measurements

In each center, cardiac ultrasound examinations were performed by one experienced sonographer following the American Society of Echocardiography Recommendations. The sonographer was blinded to participant details. In Beijing, cardiac parameters were assessed using the Aplio 500 ultrasound device (Canon, Tochigi, Japan) equipped with a 2.5–4 MHz transducer. In Shandong, measurements were performed using the Philips Doppler ultrasound device CX30 (Philips, Bothell, WA, USA) with a 2–4 MHz transducer. Left ventricular mass (LVM) was calculated based on the Devereux's formula, LVM (in grams) = $0.8 \times [1.04 \times ((\text{left ventricular end-diastolic internal diameter} + \text{interventricular septal thickness} + \text{left ventricular posterior wall thickness})^3 - (\text{left ventricular end-diastolic internal diameter})^3)] + 0.6$. Left ventricular mass index (LVMI) was calculated as LVM (in grams) divided by 2.7 power of height (in meters). Relative wall thickness (RWT) was calculated as (interventricular septal thickness + left ventricular posterior wall thickness)/ left ventricular end-diastolic internal diameter.

Definition of abdominal obesity and metabolic status

WC status was classified as normal WC and abdominal obesity using the WC 90th percentile references for Chinese children aged 7–18 years released by the National Health Commission (WS/T 611–2018; available at http://www.nhc.gov.cn/ewebeditor/uploadfile/2018/07/20180704145130574.pdf). For participants aged below 7 years, abdominal obesity was determined using the WC criteria proposed by the Chinese Expert Consensus [21]. The WHtR cut-offs of 0.48 for boys and 0.46 for girls were used to define abdominal obesity [22].

The metabolically healthy phenotype was defined according to the modified National Cholesterol Education Program criteria [23] as having none of the following four cardiovascular risk factors: (1) elevated systolic/diastolic BP (≥ sex-, age-, and height-specific 90th percentile cut-offs for Chinese children aged 7–18 years released by the National Health Commission [WS/T 610–2018; available at https://www.ndcpa.gov.cn/jbkzzx/c100202/common/content/content_1666364801643515904.html]; for participants aged below 7 years, the BP references proposed by the Chinese Expert Consensus [24] were used instead); (2) elevated TG (≥ 1.24 mmol/L); (3) decreased HDL-C (≤ 1.03 mmol/L); and (4) elevated FBG (≥ 6.1 mmol/L).

Based on abdominal obesity (defined by WHtR or WC) and metabolic status, participants were classified as having: metabolically healthy normal WHtR (or WC); metabolically unhealthy normal WHtR (or WC); MHO; and metabolically unhealthy abdominal obesity.

Definition of LVG remodeling

Left ventricular hypertrophy (LVH) was defined as LVMI ≥ sex-, age-, and study center-specific 90th percentile values, and high RWT was defined as RWT ≥ sex-, age-, and study center-specific 90th percentile values [12, 18]. Based on the combinations of LVH and high RWT, four LVG patterns were defined: normal geometry (normal LVMI and normal RWT), concentric remodeling (normal LVMI and high RWT), eccentric hypertrophy (LVH and normal RWT), and concentric hypertrophy (LVH and high RWT).

Covariates

Potential covariates included demographic characteristics (age and sex) and lifestyle behaviors (sleep duration, physical activity, screen time, and intake of fruits and vegetables), which were collected using a validated structured questionnaire. These covariates were selected based on existing literature [9, 10, 25, 26] regarding their known or hypothesized associations with both the exposure and outcomes, as well as their availability in both study centers.

In Beijing, lifestyle information was provided by parents, while in Shandong, this information was reported by children with parental assistance. In each center, sleep duration was determined by subtracting bedtime from wake-up time for both weekdays and weekends. The average daily sleep duration was calculated using the formula: (5 × weekday sleep duration + 2 × weekend sleep duration) / 7. Participants were then classified into two groups based on sleep duration: < 9 h/d and ≥ 9 h/d [27]. In Beijing, physical activity time was evaluated using the Children's Leisure Activities Study Survey Questionnaire. In Shandong, participants reported the frequency (days per week) and duration of light, moderate, and vigorous activities separately. Daily physical activity time was computed as (weekly frequency × daily duration) / 7, with insufficient activity defined as < 1 h/d [28]. Screen time included time spent on watching television, using a computer or playing video games, and long screen time was defined as > 2 h/d [29]. In Beijing, the intake of fruits and vegetables was measured using the Mediterranean Diet Quality Index for children, and categorized as sufficient (≥ 4/d) or insufficient (< 4/d) [30]. In Shandong, the intake over the past 30 days was assessed through a self-designed questionnaire and classified as either < 5 servings/d or ≥ 5 servings/d [31].

Statistical analysis

Continuous variables were presented as mean (standard deviation) or median (interquartile range), and categorical variables were expressed as number (percentage). Differences across the combined groups of abdominal obesity (defined by WHtR or WC) and metabolic status were compared using the variance analysis, the Kruskal-Wallis rank sum test, or the Chi-square test. Multivariable logistic regression models were used to estimate the odds ratios (ORs) and 95% confidence intervals (CIs) of LVH, high RWT, and LVG remodeling (concentric remodeling, eccentric hypertrophy, and concentric hypertrophy) for each combined group of abdominal obesity (defined by WHtR or WC) and metabolic status, using normal WHtR (or WC) with healthy metabolic status as the reference. Models were initially adjusted for age, sex, and study center, and then further adjusted for sleep duration, screen time, physical activity, and intake of fruits and vegetables. Due to the limited number of LVG remodeling cases in certain combined groups of abdominal obesity (defined using WHtR or WC) and metabolic status when stratified by study center (Supplementary Tables 1 and 2), we conducted all logistic regression analyses using pooled data from two centers. Power analysis indicated that there was 99% power to detect an OR (e.g., MHO associated with LVH) of 2.00 at a significance level of 0.05 using a two-sided test.

To examine the robustness of our main results, we then performed several sensitivity analyses. First, we used the international WC 90th percentile cutoffs [32] or the static WHtR cut-off of 0.46 to define abdominal obesity [33], respectively, and the 2017 American Academy of Pediatrics BP guidelines [34] to define elevated systolic/diastolic BP. Second, we used the modified International Diabetes Federation criteria [35] to define metabolic health as having none of the following risk factors: elevated systolic/diastolic BP (≥ 120/80 mmHg [children aged 6–9 years] or ≥ 130/85 mmHg [children aged ≥ 10 years] [36]), elevated TG (≥ 1.7 mmol/L), decreased HDL-C (< 1.03 mmol/L), and elevated FBG (≥ 5.6 mmol/L). Third, we used the modified 2018 consensus-based criteria [37] to define metabolic health: systolic/diastolic BP < sex-, age- and height-specific 90th percentile values [34], TG ≤ 1.7 mmol/L, HDL-C > 1.03 mmol/L, and FBG < 5.6 mmol/L. Fourth, we used LVMI ≥ sex-, age-, and study center-specific 95th percentile values to define LVH and RWT ≥ sex-, age-, and study center-specific 95th percentile values to define high RWT, and LVG remodeling was then re-defined accordingly. Fifth, we performed a meta-analysis to synthesize the findings from two studies using separate analysis. Finally, we further explored the potential association independent of general adiposity.

All analyses were performed using SAS version 9.4 (SAS Institute Inc., Cary, NC) and R version 4.4.1 (R Foundation for Statistical Computing, Vienna, Austria) with statistical significance setting at two-sided $P < 0.05$.

RESULTS

Participant characteristics

A total of 2866 children aged 6–11 years were included in the study, and 543 (18.9%) were identified as having MHO phenotype based on WHtR, while 460 (16.1%) were identified as MHO based on WC. Table 1 presents participant characteristics by combined

Table 1. Characteristics of the study participants according to combined groups of abdominal obesity (defined by WHtR) and metabolic status.

Characteristics	Overall	Normal WHtR		Abdominal obesity		*P* value
		Metabolically healthy	Metabolically unhealthy	Metabolically healthy	Metabolically unhealthy	
N	2866	1489	413	543	421	
Boys, *n* (%)	1470 (51.3)	756 (50.8)	214 (51.8)	271 (49.9)	229 (54.4)	0.523
Age, years	7.3 (1.6)	7.2 (1.5)	7.4 (1.7)	7.2 (1.5)	7.6 (1.7)	<0.001
Height, cm	129.3 (10.9)	127.6 (10.2)	130.2 (10.8)	130.0 (11.3)	133.6 (11.7)	<0.001
WC, cm	59.7 (9.4)	54.6 (4.8)	56.3 (5.0)	67.0 (8.4)	71.4 (9.7)	<0.001
WHtR	0.5 (0.1)	0.4 (0.0)	0.4 (0.0)	0.5 (0.0)	0.5 (0.1)	<0.001
SBP, mmHg	103.6 (9.2)	99.7 (6.7)	111.7 (8.1)	101.3 (7.5)	112.4 (8.9)	<0.001
DBP, mmHg	59.6 (7.4)	57.3 (6.1)	63.8 (7.3)	58.9 (6.9)	64.9 (8.3)	<0.001
TG[a], mmol/L	0.6 (0.5, 0.8)	0.6 (0.5, 0.7)	0.7 (0.5, 0.9)	0.7 (0.5, 0.9)	0.9 (0.6, 1.4)	<0.001
HDL-C, mmol/L	1.6 (0.4)	1.7 (0.3)	1.6 (0.4)	1.5 (0.3)	1.4 (0.4)	<0.001
FBG, mmol/L	4.9 (0.5)	4.9 (0.5)	5.0 (0.6)	4.9 (0.5)	4.9 (0.6)	<0.001
Short sleep duration, *n* (%)	581 (20.3)	291 (19.5)	84 (20.3)	119 (21.9)	87 (20.7)	0.355
Long screen time, *n* (%)	116 (4.0)	48 (3.2)	19 (4.6)	23 (4.2)	26 (6.2)	0.051
Insufficient physical activity, *n* (%)	1593 (55.6)	821 (55.1)	228 (55.2)	322 (59.3)	222 (52.7)	0.450
Insufficient fruits and vegetables, *n* (%)	1746 (60.9)	895 (60.1)	244 (59.1)	326 (60.0)	281 (66.7)	0.064

DBP diastolic blood pressure, *FBG* fasting blood glucose, *HDL-C* high-density lipoprotein cholesterol, *SBP* systolic blood pressure, *TG* triglycerides, *WC* waist circumference, *WHtR* waist-to-height ratio.
Continuous variables are presented as mean (standard deviation), and categorical variables are presented as number (percentage).
[a]Data are presented as median (interquartile range).

groups of abdominal obesity (defined by WHtR) and metabolic status. Compared with children with metabolically healthy normal WHtR, those with MHO had worse metabolic profiles, including higher levels of systolic BP, diastolic BP, TG, and lower levels of HDL-C (all $P < 0.05$). Similar results were obtained by study center (Supplementary Table 3).

LVMI and RWT levels according to combined groups of abdominal obesity and metabolic status

Based on pooled data, compared with children with metabolically healthy normal WHtR, those with MHO had significantly increased LVMI (adjusted mean difference: 3.311 g/m$^{2.7}$, 95% CI: 2.686–3.935) and RWT levels (adjusted mean difference: 0.006, 95% CI: 0.001–0.011) (Table 2). Corresponding values were 4.520 g/m$^{2.7}$ (95% CI: 3.828–5.212) and 0.010 (95% CI: 0.004–0.015), respectively, for LVMI and RWT levels among children with metabolically unhealthy abdominal obesity. In contrast, children with metabolically unhealthy normal WHtR showed no significant differences in LVMI (adjusted mean difference: 0.138 g/m$^{2.7}$, 95% CI: −0.555–0.831) and RWT levels (adjusted mean difference: 0.002, 95% CI: −0.004–0.007) compared with their counterparts with metabolically healthy normal WHtR. Similar patterns were observed when using WC to define abdominal obesity (Table 2).

Prevalence of LVG remodeling according to combined groups of abdominal obesity and metabolic status

Children with MHO exhibited higher prevalence of LVH (18.2% *vs.* 4.5%), high RWT (13.8% *vs.* 8.1%), and each type of LVG remodeling (concentric remodeling: 8.7% *vs.* 7.3%; eccentric hypertrophy: 13.1% *vs.* 3.7%; and concentric hypertrophy: 5.2% *vs.* 0.8%) than children with metabolically healthy normal WHtR (Fig. 1). Children with metabolically unhealthy abdominal obesity also had significantly increased prevalence of LVH, high RWT, and all forms of LVG remodeling compared to those with metabolically healthy normal WHtR, whereas no significant differences were observed among children with metabolically unhealthy normal WHtR. Consistent results were obtained when abdominal obesity was defined using WC (Fig. 1).

Associations between combined groups of abdominal obesity and metabolic status and LVG remodeling

Compared with children with metabolically healthy normal WHtR, those with MHO had higher odds of LVH, high RWT, concentric remodeling, eccentric hypertrophy, and concentric hypertrophy. The fully adjusted ORs (95% CIs) were 4.78 (3.44–6.64), 1.81 (1.33–2.47), 1.45 (1.01–2.08), 4.37 (3.01–6.33), and 7.50 (3.77–14.91), respectively. Corresponding ORs (95% CIs) were 7.38 (5.28–10.31), 2.16 (1.56–2.99), 1.56 (1.04–2.34), 6.71 (4.60–9.80), and 12.09 (6.11–23.93), respectively, for children with metabolically unhealthy abdominal obesity. In contrast, children with metabolically unhealthy normal WHtR did not possess increased odds of these adverse cardiac outcomes, with adjusted ORs (95% CIs) of 1.09 (0.65–1.82), 0.88 (0.58–1.34), 0.83 (0.53–1.30), 1.00 (0.56–1.79), and 1.43 (0.50–4.10), respectively (Fig. 2). The results were similar based on WC (Fig. 3).

Sensitivity analyses

Sensitivity analyses showed similar results to our main analyses, including using the international children WC (or WHtR) references to define abdominal obesity and using the 2017 American Academy of Pediatrics BP guidelines to define elevated BP (Supplementary Tables 4 and 5), using the modified International Diabetes Federation criteria to define metabolic status (Supplementary Tables 6 and 7), using the modified 2018 consensus-based criteria to define metabolic status (Supplementary Tables 8 and 9), using the 95th percentile values to define LVH, high RWT, and LVG remodeling (Supplementary Tables 10 and 11), and using

Table 2. LVMI and RWT levels according to combined groups of abdominal obesity (defined by WHtR or WC) and metabolic status.

Outcomes	Mean (SD)				Adjusted mean difference (95% CI)[a]		
	Metabolically healthy non-abdominal obesity	Metabolically unhealthy non-abdominal obesity	Metabolically healthy abdominal obesity	Metabolically unhealthy abdominal obesity	Metabolically unhealthy non-abdominal obesity *vs.* metabolically healthy non-abdominal obesity	Metabolically healthy abdominal obesity *vs.* metabolically healthy non-abdominal obesity	Metabolically unhealthy abdominal obesity *vs.* metabolically healthy non-abdominal obesity
WHtR							
LVMI, g/m$^{2.7}$	30.21 (5.94)	30.06 (6.55)	33.36 (6.77)	33.92 (6.81)	0.138 (−0.555–0.831)	3.311 (2.686–3.935)*	4.520 (3.828–5.212)*
RWT	0.34 (0.06)	0.34 (0.06)	0.35 (0.06)	0.34 (0.06)	0.002 (−0.004–0.007)	0.006 (0.001–0.011)*	0.010 (0.004–0.015)*
WC							
LVMI, g/m$^{2.7}$	30.43 (5.94)	30.25 (6.38)	33.19 (7.12)	34.22 (7.00)	0.094 (−0.572–0.760)	2.706 (2.038–3.370)*	4.548 (3.817–5.280)*
RWT	0.34 (0.06)	0.34 (0.05)	0.35 (0.06)	0.34 (0.06)	0.001 (−0.004–0.007)	0.007 (0.002–0.012)*	0.011 (0.005–0.017)*

CI confidence interval, *LVMI* left ventricular mass index, *RWT* relative wall thickness, *SD* standard deviation, *WC* waist circumference, *WHtR* waist-to-height ratio.
[a]Adjusted mean differences were calculated using multivariable linear regression models with adjustment of sex, age, study center, sleep duration, screen time, physical activity, and intake of fruits and vegetables.
*P value < 0.05.

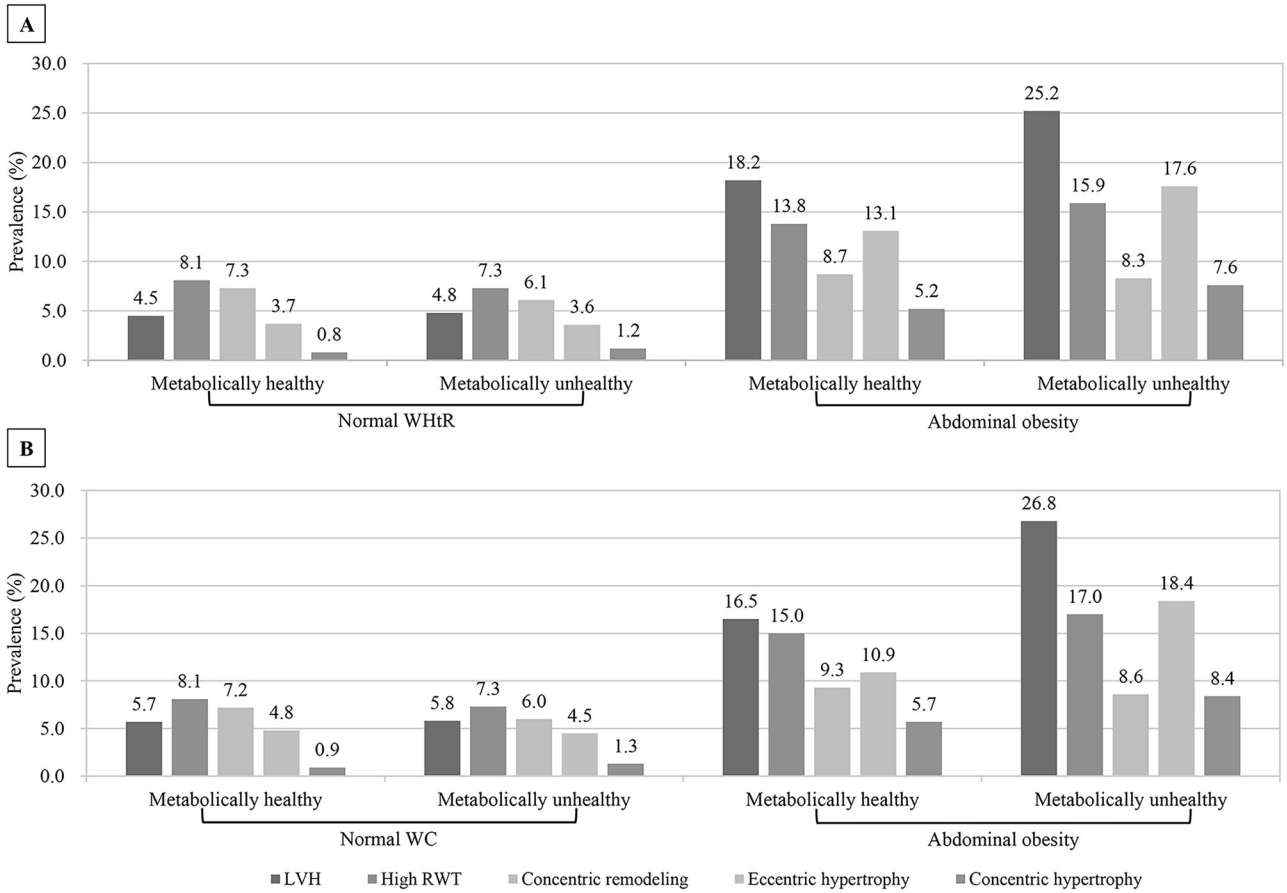


Fig. 1 Prevalence of left ventricular geometric remodeling according to combined groups of abdominal obesity and metabolic status in Chinese children. A Abdominal obesity was defined by WHtR. **B** Abdominalobesity was defined by WC. *LVH* left ventricular hypertrophy, *RWT* relative wall thickness, *WC* waist circumference, *WHtR* waist-to-height ratio.

meta-analysis to synthesize the findings from two studies (Supplementary Tables 12 and 13). In addition, after additional adjustment for general obesity, the association of MHO (defined by WHtR) with LVH or eccentric hypertrophy was attenuated but remained statistically significant; however, the association for WC became non-significant (Supplementary Table 14).

DISCUSSION

In this large population-based study of more than 2800 Chinese children, we found that children with MHO (defined based on WHtR or WC) were at increased odds of LVH, high RWT, and each type of LVG remodeling, including concentric remodeling, eccentric hypertrophy, and concentric hypertrophy, compared with their counterparts with metabolically healthy normal WHtR (or WC). Conversely, children with metabolically unhealthy normal WHtR or WC did not show a significantly increased risk of these conditions.

The cardiovascular risk associated with MHO remains controversial. Some early studies in adults reported that individuals with MHO did not have an increased risk of CVD compared with those with metabolically healthy normal weight [3, 4]; however, growing evidence demonstrated that MHO was not a low-risk condition [5, 6]. Most previous studies have used BMI only to define obesity, a metric that may inadequately capture adiposity status, which could partially account for the inconsistent results. Our study extended this question to the pediatric population by using abdominal obesity measures (WHtR or WC) and demonstrated that children with MHO had a higher likelihood of abnormal LVG patterns than their peers with metabolically healthy normal WHtR or WC. Consistently, the International Childhood Vascular Structure Evaluation Consortium study (children aged 6–17 years, $N = 3497$) reported that MHO (defined based on WHtR) was associated with higher odds of increased carotid intima-media thickness (another subclinical CVD measure; OR: 3.95, 95% CI: 3.00–5.21) compared with metabolically healthy normal WHtR [12]. Moreover, the Tehran Lipid and Glucose Study, which included 6430 Iranian adults (≥ 30 years), found that MHO (defined based on WC) was linked to a higher risk of cardiovascular events (hazard ratio: 1.64, 95% CI: 1.09–2.47) compared with individuals with metabolically healthy normal WC [38]. Despite differences in study design, population characteristics, and outcome measures, these findings collectively suggest that having a normal metabolic profile does not guarantee a lower cardiovascular risk among individuals with abdominal obesity, and call into question the clinical usefulness of stratifying obesity by metabolic status in both children and adults.

Interestingly, we found that children with metabolically unhealthy normal WHtR or WC did not exhibit an increased risk of abnormal left ventricular structure. This finding aligns with one prior study involving 459 children with obesity, where the prevalence of LVH in those with metabolically unhealthy obesity (defined by BMI) was not significantly higher than in those with MHO (40.0% *vs.* 31.1%; $P = 0.06$) [13]. Similarly, a cohort study of 1220 children reported no significant association between metabolically unhealthy normal weight (defined based on BMI) and increased carotid intima-media thickness in early adulthood (risk ratio: 1.02, 95% CI: 0.45–2.30) [39]. The Bogalusa Heart Study

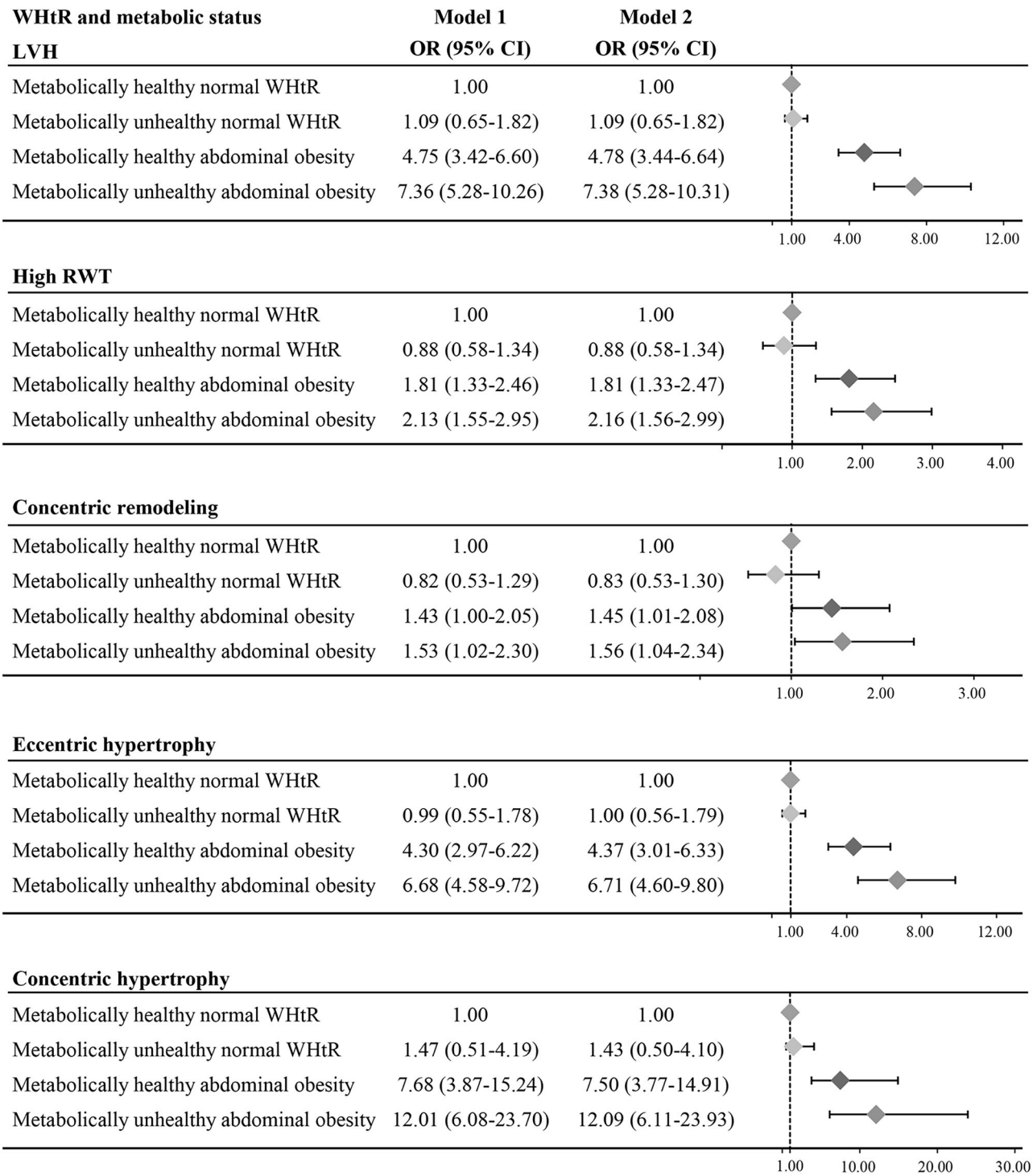


Fig. 2 Odds ratios and 95% confidence intervals of left ventricular geometric remodeling according to combined groups of abdominal obesity (defined by WHtR) and metabolic status in Chinese children. *CI* confidence interval, *LVH* left ventricular hypertrophy, *OR* odds ratio, *RWT* relative wall thickness, *WHtR* waist-to-height ratio. Model 1: Adjusted for sex, age, and study center. Model 2: Adjusted for sex, age, study center, sleep duration, screen time, physical activity, and intake of fruits and vegetables.

and the Cardiovascular Risk in Young Finns Study also demonstrated that pediatric metabolic syndrome did not predict adult increased carotid intima-media thickness or diabetes better than BMI alone [40]. All these data indirectly support our findings, suggesting that abdominal or general obesity may be a more important determinant of cardiovascular risk than metabolic status.

It is worth mentioning that WHtR was equally effective as WC in identifying subclinical cardiac structural damage in this study, consistent with several previous studies [41]. Defining pediatric abdominal obesity using WC requires multiple sex- and age-specific percentile cut-offs, which can be cumbersome for routine clinical practice and challenging for children and their caregivers to understand. In contrast, WHtR offers a more straightforward

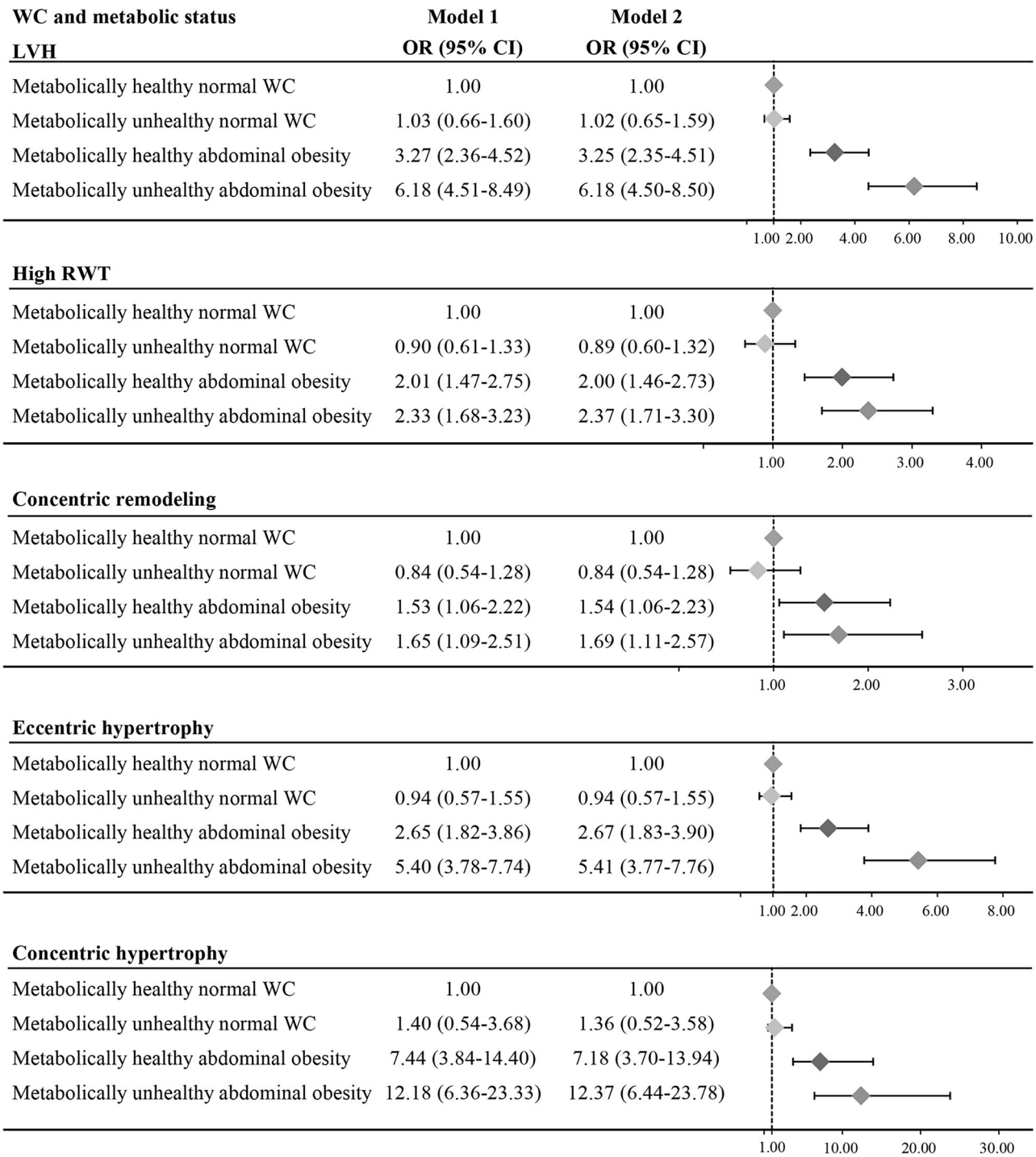


Fig. 3 Odds ratios and 95% confidence intervals of left ventricular geometric remodeling according to combined groups of abdominal obesity (defined by WC) and metabolic status in Chinese children. *CI* confidence interval, *LVH* left ventricular hypertrophy, *OR* odds ratio, *RWT* relative wall thickness, *WC* waist circumference. Model 1: Adjusted for sex, age, and study center. Model 2: Adjusted for sex, age, study center, sleep duration, screen time, physical activity, and intake of fruits and vegetables.

method by using static cut-offs to assess abdominal obesity. Indeed, static WHtR cut-offs have already been incorporated into the definition of pediatric metabolic syndrome as a simpler alternative to the complex WC percentile-based thresholds [42]. Furthermore, the association between MHO defined by WHtR and LVH or eccentric hypertrophy remained significant even after adjusting for general obesity, whereas the association for WC became non-significant. Based on these findings, we advocate for the use of static WHtR cut-offs to identify adiposity, irrespective of metabolic status, in pediatric population. This simplified definition is expected to facilitate quick assessment and treatment in both clinical and public health settings.

STRENGTHS AND LIMITATIONS

Our study has several strengths including the relatively large sample size, the use of WHtR and WC to define abdominal obesity (as one component of MHO), and the use of several sensitivity analyses to

validate main results. However, our study also has several limitations. First, because our study was based on cross-sectional data, the causal association of MHO with LVG remodeling could not be determined. However, it is unlikely that LVG remodeling can influence abdominal obesity or metabolic status. Second, given that MHO is a transient condition, there is a potential risk of exposure misclassification. Third, since our study did not measure insulin levels or inflammation-related markers [43, 44], we could not account for these metabolic factors, which may compromise the accuracy of metabolically healthy classification. Fourth, our study only included Chinese children aged 6–11 years, and the results may not be applicable to other age groups and populations from other races/ethnicities. Finally, although we have adjusted for several potential covariates, we could not completely exclude residual confounding related to unmeasured variables, such as genetic factors, cardiorespiratory fitness, pubertal status, and drug treatment.

CONCLUSION

In conclusion, children with MHO (obesity was determined by WHtR or WC) had increased odds of LVH, high RWT, and abnormal LVG patterns (concentric remodeling, eccentric hypertrophy, and concentric hypertrophy), compared with children with metabolically healthy normal WHtR (or WC). Our findings suggest that MHO is not a healthy condition in the pediatric population, emphasizing the importance of maintaining a normal waist size (irrespective of metabolic status) to promote cardiac health in children. Moreover, WHtR is recommended as an alternative to WC for quickly screening children with abdominal obesity and associated cardiac risk in clinical practice.

DATA AVAILABILITY

The data described in the article will be made available upon request pending application and approval.

CODE AVAILABILITY

The code used in this study will be made available upon request pending application and approval.

REFERENCES

1. Rubino F, Cummings DE, Eckel RH, Cohen RV, Wilding JPH, Brown WA, et al. Definition and diagnostic criteria of clinical obesity. Lancet Diabetes Endocrinol. 2025;13:221–62.
2. Schulze MB, Stefan N. Metabolically healthy obesity: from epidemiology and mechanisms to clinical implications. Nat Rev Endocrinol. 2024;20:633–46.
3. Hamer M, Stamatakis E. Metabolically healthy obesity and risk of all-cause and cardiovascular disease mortality. J Clin Endocrinol Metab. 2012;97:2482–8.
4. Zembic A, Eckel N, Stefan N, Baudry J, Schulze MB. An empirically derived definition of metabolically healthy obesity based on risk of cardiovascular and total mortality. JAMA Netw Open. 2021;4:e218505.
5. Eckel N, Meidtner K, Kalle-Uhlmann T, Stefan N, Schulze MB. Metabolically healthy obesity and cardiovascular events: a systematic review and meta-analysis. Eur J Prev Cardiol. 2016;23:956–66.
6. Eckel N, Li Y, Kuxhaus O, Stefan N, Hu FB, Schulze MB. Transition from metabolic healthy to unhealthy phenotypes and association with cardiovascular disease risk across BMI categories in 90 257 women (the Nurses' Health Study): 30 year follow-up from a prospective cohort study. Lancet Diabetes Endocrinol. 2018;6:714–24.
7. Yuan C, Dong Y, Chen H, Ma L, Jia L, Luo J, et al. Determinants of childhood obesity in China. Lancet Public Health. 2024;9:e1105–e14.
8. Dong Y, Chen L, Liu J, Ma T, Zhang Y, Chen M, et al. Epidemiology and prediction of overweight and obesity among children and adolescents aged 7-18 years in China from 1985 to 2019. Chin J Prev Med. 2023;57:11–9.
9. Prince RL, Kuk JL, Ambler KA, Dhaliwal J, Ball GD. Predictors of metabolically healthy obesity in children. Diabetes Care. 2014;37:1462–8.
10. Li L, Yin J, Cheng H, Wang Y, Gao S, Li M, et al. Identification of genetic and environmental factors predicting metabolically healthy obesity in children: data from the BCAMS Study. J Clin Endocrinol Metab. 2016;101:1816–25.
11. Çelik N, Ünsal G, Taştanoğlu H. Predictive markers of metabolically healthy obesity in children and adolescents: can AST/ALT ratio serve as a simple and reliable diagnostic indicator? Eur J Pediatr. 2024;183:243–51.
12. Zhao M, López-Bermejo A, Caserta CA, Medeiros CCM, Kollias A, Bassols J, et al. Metabolically healthy obesity and high carotid intima-media thickness in children and adolescents: International Childhood Vascular Structure Evaluation Consortium. Diabetes Care. 2019;42:119–25.
13. Genovesi S, Tassistro E, Giussani M, Lieti G, Patti I, Orlando A, et al. Association of obesity phenotypes with left ventricular mass index and left ventricular hypertrophy in children and adolescents. Front Endocrinol. 2022;13:1006588.
14. Association for Maternal and Child Health Study, Expert Committee on Obesity Controlling for Women and Children, Expert Committee on Definition of Metabolically Heathy Obesity and Screening Metabolicaly Unheathy Obesity in Chinese Children. The expert consensus on definition of metabolically healthy obesity and screening metabolically healthy obesity in Chinese children. Chin J Woman Child Health Res. 2019;30:1487–90.
15. Xue R, Li Q, Geng Y, Wang H, Wang F, Zhang S. Abdominal obesity and risk of CVD: a dose-response meta-analysis of thirty-one prospective studies. Br J Nutr. 2021;126:1420–30.
16. Feng Q, Bešević J, Conroy M, Omiyale W, Woodward M, Lacey B, et al. Waist-to-height ratio and body fat percentage as risk factors for ischemic cardiovascular disease: a prospective cohort study from UK Biobank. Am J Clin Nutr. 2024;119:1386–96.
17. Brady TM. The role of obesity in the development of left ventricular hypertrophy among children and adolescents. Curr Hypertens Rep. 2016;18:3.
18. Zhang Y, Zhao M, Bovet P, Xi B. Association of abdominal obesity and high blood pressure with left ventricular hypertrophy and geometric remodeling in Chinese children. Nutr Metab Cardiovasc Dis. 2021;31:306–13.
19. Kawel-Boehm N, Kronmal R, Eng J, Folsom A, Burke G, Carr JJ, et al. Left ventricular mass at MRI and long-term risk of cardiovascular events: the Multi-Ethnic Study of Atherosclerosis (MESA). Radiology. 2019;293:107–14.
20. Li M, Shu W, Zunong J, Amaerjiang N, Xiao H, Li D, et al. Predictors of non-alcoholic fatty liver disease in children. Pediatr Res. 2022;92:322–30.
21. Zong X, Li H, Zhang Y. Percentile reference value of waist circumference for Chinese children aged 3–7 years. Chin J Epidemiol. 2020;41:1286–90.
22. Fu J, Liang L. Definition and prevention of metabolic syndrome in children and adolescents in China. Chin J Matern Perinat Med. 2012;50:420–2.
23. Cook S, Weitzman M, Auinger P, Nguyen M, Dietz WH. Prevalence of a metabolic syndrome phenotype in adolescents: findings from the Third National Health and Nutrition Examination Survey, 1988-1994. Arch Pediatr Adolesc Med. 2003;157:821–7.
24. Fan H, Yan Y, Mi J. Updating blood pressure references for Chinese children aged 3-17 years. Chin J Hypertens. 2017;25:428–35.
25. Agbaje AO. Accelerometer-based sedentary time and physical activity from childhood through young adulthood with progressive cardiac changes: a 13-year longitudinal study. Eur J Prev Cardiol. 2024;31:1480–92.
26. Kraav J, Zagura M, Viitasalo A, Soininen S, Veijalainen A, Kähönen M, et al. Associations of cardiovascular health metrics in childhood and adolescence with arterial health indicators in adolescence: the PANIC Study. J Am Heart Assoc. 2024;13:e035790.
27. Paruthi S, Brooks LJ, D'Ambrosio C, Hall WA, Kotagal S, Lloyd RM, et al. Recommended amount of sleep for pediatric populations: a consensus statement of the American Academy of Sleep Medicine. J Clin Sleep Med. 2016;12:785–6.
28. World Health Organization. Global recommendations on physical activity for health. https://www.who.int/publications/i/item/9789241599979. Accessed Dec 18 2024.
29. Council on Communications and Media. Children, adolescents, and the media. Pediatrics. 2013;132:958–61.
30. Li M, Amaerjiang N, Li Z, Xiao H, Zunong J, Gao L, et al. Insufficient fruit and vegetable intake and low potassium intake aggravate early renal damage in children: a longitudinal study. Nutrients. 2022;14:1228.
31. World Health Organization. Effectiveness of interventions and programmes promoting fruit and vegetable intake. https://iris.who.int/handle/10665/43147. Accessed Dec 18 2024.
32. Xi B, Zong X, Kelishadi R, Litwin M, Hong YM, Poh BK, et al. International waist circumference percentile cutoffs for central obesity in children and adolescents aged 6 to 18 years. J Clin Endocrinol Metab. 2020;105:e1569–83.
33. Zong X, Kelishadi R, Hong YM, Schwandt P, Matsha TE, Mill JG, et al. Establishing international optimal cut-offs of waist-to-height ratio for predicting cardiometabolic risk in children and adolescents aged 6-18 years. BMC Med. 2023;21:442.
34. Flynn JT, Kaelber DC, Baker-Smith CM, Blowey D, Carroll AE, Daniels SR, et al. Clinical practice guideline for screening and management of high blood pressure in children and adolescents. Pediatrics 2017;140:e20171904.
35. Zimmet P, Alberti G, Kaufman F, Tajima N, Silink M, Arslanian S, et al. The metabolic syndrome in children and adolescents. Lancet. 2007;369:2059–61.

36. Xi B, Zhang T, Li S, Harville E, Bazzano L, He J, et al. Can pediatric hypertension criteria be simplified? A prediction analysis of subclinical cardiovascular outcomes from the Bogalusa Heart Study. Hypertension. 2017;69:691–6.
37. Damanhoury S, Newton AS, Rashid M, Hartling L, Byrne JLS, Ball GDC. Defining metabolically healthy obesity in children: a scoping review. Obes Rev. 2018;19:1476–91.
38. Keihani S, Hosseinpanah F, Barzin M, Serahati S, Doustmohamadian S, Azizi F. Abdominal obesity phenotypes and risk of cardiovascular disease in a decade of follow-up: the Tehran Lipid and Glucose Study. Atherosclerosis. 2015;238:256–63.
39. Tasdighi E, Barzin M, Mahdavi M, Valizadeh M, Dehghan P, Moghaddam AM, et al. Association of childhood obesity phenotypes with early adulthood carotid intima-media thickness (cIMT): Tehran Lipid and Glucose Study. Nutr Metab Cardiovasc Dis. 2022;32:249–57.
40. Magnussen CG, Koskinen J, Chen W, Thomson R, Schmidt MD, Srinivasan SR, et al. Pediatric metabolic syndrome predicts adulthood metabolic syndrome, subclinical atherosclerosis, and type 2 diabetes mellitus but is no better than body mass index alone: the Bogalusa Heart Study and the Cardiovascular Risk in Young Finns Study. Circulation. 2010;122:1604–11.
41. Zong X, Kelishadi R, Kim HS, Schwandt P, Matsha TE, Mill JG, et al. Utility of waist-to-height ratio, waist circumference and body mass index in predicting clustered cardiometabolic risk factors and subclinical vascular phenotypes in children and adolescents: a pooled analysis of individual data from 14 countries. Diabetes Metab Syndr. 2024;18:103042.
42. Zong X, Kelishadi R, Kim HS, Schwandt P, Matsha TE, Mill JG, et al. A proposed simplified definition of metabolic syndrome in children and adolescents: a global perspective. BMC Med. 2024;22:190.
43. Jung CH, Lee MJ, Kang YM, Jang JE, Leem J, Hwang JY, et al. The risk of incident type 2 diabetes in a Korean metabolically healthy obese population: the role of systemic inflammation. J Clin Endocrinol Metab. 2015;100:934–41.
44. Lin L, Peng K, Du R, Huang X, Lu J, Xu Y, et al. Metabolically healthy obesity and incident chronic kidney disease: the role of systemic inflammation in a prospective study. Obesity. 2017;25:634–41.

ACKNOWLEDGEMENTS

We acknowledge all participants and their parents/guardians and the staff responsible for conducting the study.

AUTHOR CONTRIBUTIONS

BX, YFH and LLY conceptualized and designed the study. LLY, MLL and HW curated the data, and performed statistical analysis and data visualization. LLY drafted the manuscript. BX, YFH, CGM, and MZ critically revised the manuscript for important intellectual content. BX, YFH and LLY obtained funding. BX and YFH supervised the study. All authors have read and approved the final version of the manuscript.

FUNDING

This work was supported by the National Natural Science Foundation of China (82173538, 82473653 and 82073574), the Capital's Funds for Health Improvement and Research (2022-1G-4262), Beijing Natural Science Foundation (7202009), China Postdoctoral Science Foundation (2023M742061), and Shandong Postdoctoral Science Foundation (SDBX2023003). The funders had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41366-025-01800-x.

Correspondence and requests for materials should be addressed to Yifei Hu or Bo Xi.

Reprints and permission information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

[1]Department of Epidemiology, School of Public Health, Qilu Hospital, Cheeloo College of Medicine, Shandong University, Jinan, China. [2]Department of Child, Adolescent Health and Maternal Care, School of Public Health, Capital Medical University, Beijing, China. [3]Institute of Child and Adolescent Health, School of Public Health, Peking University, Beijing, China. [4]Department of Nutrition and Food Hygiene, School of Public Health, Cheeloo College of Medicine, Shandong University, Jinan, China. [5]Baker Heart and Diabetes Institute, Melbourne, VIC, Australia. [6]Baker Department of Cardiometabolic Health, Faculty of Medicine, Dentistry and Health Sciences, University of Melbourne, Melbourne, VIC, Australia. [7]Research Centre of Applied and Preventive Cardiovascular Medicine, University of Turku, Turku, Finland. [8]Centre for Population Health Research, University of Turku and Turku University Hospital, Turku, Finland. ✉email: huyifei@yahoo.com; xibo2007@126.com