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RESEARCH

Prevalence of childhood hypertension and associated factors in Zhejiang Province: a cross-sectional analysis based on random forest model and logistic regression

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Abstract

With childhood hypertension emerging as a global public health concern, understanding its associated factors is crucial. This study investigated the prevalence and associated factors of hypertension among Chinese children. This cross-sectional investigation was conducted in Pinghu, Zhejiang province, involving 2,373 children aged 8–14 years from 12 schools. Anthropometric measurements were taken by trained staff. Blood pressure (BP) was measured in three separate occasions, with an interval of at least two weeks. Childhood hypertension was defined as systolic blood pressure (SBP) and/or diastolic blood pressure (DBP) ≥ age-, sex-, and height-specific 95th percentile, across all three visits. A self-administered questionnaire was utilized to collect demographic, socioeconomic, health behavioral, and parental information at the first visit of BP measurement. Random forest (RF) and multivariable logistic regression model were used collectively to identify associated factors. Additionally, population attributable fractions (PAFs) were calculated. The prevalence of childhood hypertension was 5.0% (95% confidence interval [CI]: 4.1–5.9%). Children with body mass index (BMI) ≥ 85th percentile were grouped into abnormal weight, and those with waist circumference (WC) > 90th percentile were sorted into central obesity. Normal weight with central obesity (NWCO, adjusted odds ratio [aOR] = 5.04, 95% CI: 1.96–12.98), abnormal weight with no central obesity (AWNCO, aOR = 4.60, 95% CI: 2.57–8.21), and abnormal weight with central obesity (AWCO, aOR = 9.94, 95% CI: 6.06–16.32) were associated with an increased risk of childhood hypertension. Childhood hypertension was attributable to AWCO mostly (PAF: 0.64, 95% CI: 0.50–0.75), followed by AWNCO (PAF: 0.34, 95% CI: 0.19–0.51), and NWCO (PAF: 0.13, 95% CI: 0.03–0.30). Our results indicated that obesity phenotype is associated with childhood hypertension, and the role of weight management could serve as potential target for intervention.

Keywords Childhood hypertension, Random forest model, Logistic regression model, Associated factors

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Introduction

Hypertension, characterized by persistently high blood pressure (BP), used to be considered as a condition prevalent among adults but is now increasingly diagnosed in children [1, 2]. Unlike adulthood hypertension, several guidelines have recommended childhood hypertension should be defined as elevated BP over three separate occasions [3, 4]. Globally, the prevalence of childhood hypertension was estimated to be 4%, with an increasing rate of 75–79% between 2000 and 2015 [5]. In China, this trend is compounded by the rapid economic development and rising incidence of childhood obesity [6, 7]. Although symptoms of childhood hypertension are often mild, it can lead to organ damage [8–10] and later progress into adulthood toward premature cardiovascular diseases [9, 11–15]. Therefore, the early detection, prevention, and management of hypertension from childhood are critical to mitigate these long-term risks and to improve cardiovascular health across the lifespan.

Currently, since the diagnosis criterion of childhood hypertension presents a methodological challenge in early and accurate identification, previous studies have predominantly focused on elevated BP rather than hypertension diagnosed over three separate occasions [16–18]. Lacking of three separate occasions diagnosis would result in an overestimation of the prevalence of childhood hypertension. There are many factors influencing the prevalence of childhood hypertension. Previous studies have predominantly focused on biological and individual behavioral factors, such as obesity, family history of hypertension, low birth weight, and an unhealthy diet [19–25], while paying less attention to the macro- and meso-level factors. Social-ecological perspective is an essential framework to better understand and effectively improve children's health issues [26, 27], which conceptualizes the interactions and influences on individual health outcomes at the individual, interpersonal, family, community and policy levels. Therefore, the social-ecological perspective serves as a framework for exploring the multidimensional associated factors of childhood hypertension.

Among previous cross-sectional studies exploring the associations between factors with childhood hypertension, most of them relied on multivariable logistic regression models to quantify the associations and use odds ratios (ORs) for clear interpretation, which often analyzes factors in isolation, without assessing their relative importance [21, 24, 28]. Random Forest (RF) is a machine learning algorithm characterized by its capacity to assess the importance of numerous variables without overfitting, which offers a solution to this issue [29]. Yet, RF's complexity makes its findings less straightforward than ORs provided by logistic regression. Combining RF with logistic regression could enhance our understanding by providing a detailed assessment and comparison of the effects of various factors on childhood hypertension [30, 31]. Furthermore, previous studies paid less attention on the attributable fractions of each associated factors. Population attributable fractions (PAFs), is a counterfactual estimate method, which has been widely employed to reveal the population-level impact of preventive interventions on diseases [32–35].

To address these research gaps, our study aimed to: (1) offer an overview of childhood hypertension prevalence, based on three separate visits, in Zhejiang province, China; (2) assess and compare the effects of various factors associated with childhood hypertension using an integrated approach that combines RF and logistic regression; and (3) calculate the PAFs for significant associated factors and evaluate the theoretical prevalence of childhood hypertension if these specific factors were addressed.

Methods

Study design and participants

This study is based on the project titled "Effect of Intensive Lifestyle Intervention on Overweight and Obesity in Children and Adolescents", a school-based project since 2022. Our study used data from the baseline information of this project. Stratified cluster sampling was employed to enroll students aged 8–14 years in Pinghu, Zhejiang Province. Subjects were cluster sampled from grade three to four in primary schools and grade seven in middle schools from randomly chosen 12 schools (six primary schools and six middle schools). Sample size formula for cross-sectional studies was used, $n = z_{\alpha}^{2} * p * q/\sigma^{2}$, where $\alpha = 0.05$, $z_{\alpha} = 1.96$, $p = 4\%$, $q = 1 - p = 96\%$, $\sigma = 0.2, p = 0.08$. Non-response rate was estimated to be 10% and the total sample size for the study was at least 2507 children.

Our study enrolled non-random sample who had voluntarily completed the questionnaire. Those with intellectual disabilities, severe mental disorders, and other conditions that prevented them from participating in questionnaire survey and physical examinations were excluded. A total of 1366 children in grade three to four were enrolled from six primary schools, while 1007 children in grade seven were enrolled from six middle schools. Of these, 235 were excluded for unplausible information on anthropometrics and parental information filled by caregivers other than parents. The ultimate analytical sample consisted of 2373 children aged 8–14 years (Fig. 1).

This study was approved by the Ethical Committee of Zhejiang University School of Medicine, Zhejiang, China (2021–029). Written informed consents were provided by the guardians of the included children.

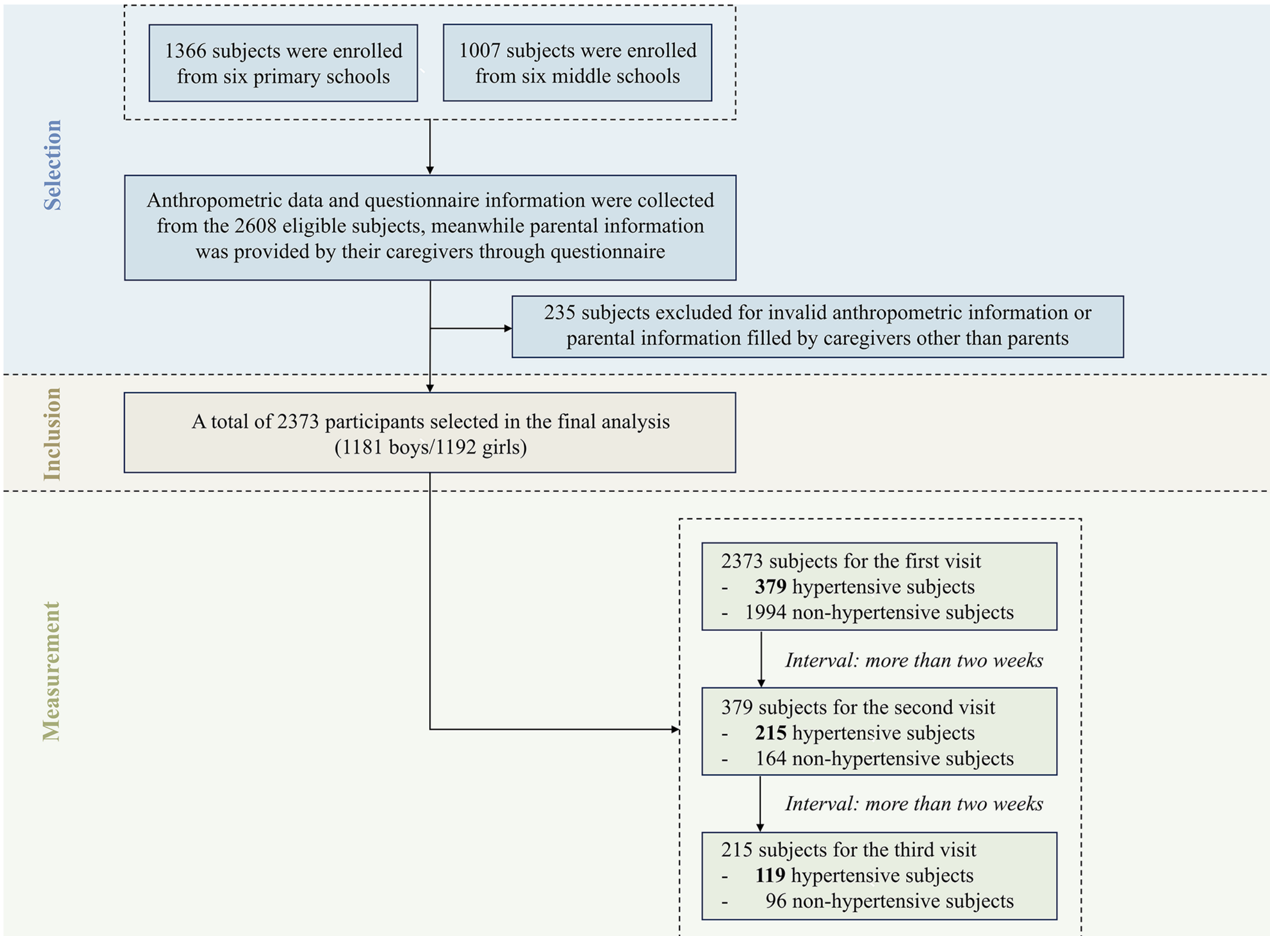

Fig. 1 Flowchart for selecting subjects in this study
Note: the exclusion criteria were in an order as listed in the box, some subjects might meet several exclusion criteria simultaneously

Data collection

At the first visit of BP measurement, a self-administered questionnaire was designed to collect demographic and socioeconomic data, as well as health behaviors information for all included children from primary and middle schools (Questionnaire S1). Before administering the questionnaire, researchers introduced its content and allowed sufficient time for children to fully understand it. The questionnaires were completed under the supervision of pre-trained teachers, with researchers on hand to provide necessary assistance and guidance. Meanwhile, parental information (e.g., family income, education level, vocation) was provided by their caregivers through questionnaires (Questionnaire S2).

All anthropometric measurements were performed by trained staff from the local Centers for Disease Control and Prevention, following the national standard protocol. While standing upright, height and body weight of the children were measured under standard protocols, and in increments of 0.1 cm and 0.1 kg, respectively. Waist circumference (WC) was measured in the natural standing position at the umbilical level to the nearest 0.1 cm using a non-flexible tape. Body mass index (BMI) was calculated by dividing body weight (kg) by the square of the height (m). After at least 5 min of seated rest, BP was measured three consecutive times with 1 min intervals in a seated position, with the OMRON HBP-1300 automated device (OMRON Corporation, Kyoto, Japan) and medium cuff size, and the averages of three readings were taken. According to the Chinese BP reference standards for children and adolescents based on the levels of systolic blood pressure (SBP) and diastolic blood pressure (DBP) in 2017 [36], children with SBP and/or DBP ≥ age-, sex-, and height-specific 95th percentile underwent a second round of BP measurements at least two weeks later, and then a third round of measurements if BP was more than 95th percentile at the second screening.

Definitions

Based on previous evidence for childhood hypertension, we focused on associated factors that are routinely available or easily ascertained through anthropometric measurements or questionnaires. Finally, a total of 30 independent variables in six categories were included as potential associated factors for childhood hypertension, and were put into the social-ecological framework for better understanding of their levels (Fig S1).

(1) Demographics (residence, sex, and age groups): residence was divided into urban and rural; sex was categorized into two groups: boy and girl; age groups included primary school and middle school.
(2) Socioeconomics (monthly household income/expense, maternal occupation, and maternal education): monthly household income/expense was categorized into three groups: < CNY 10,000, CNY 10,000–20,000, and > CNY 20,000; maternal occupation was divided into four groups: administrator or manager or professional and technical, sales or service workers or self-employed, agriculture or worker, and unemployed or other; maternal education was categorized into three groups: middle school and below, high school (including secondary), and tertiary and undergraduate and above.
(3) Family (family structure, family history of hypertension, maternal BMI status, mother's smoke/drink use, mother's moderate-to-vigorous physical activity [MVPA] adherence, and parental migration): family structure was categorized into three groups: nuclear families, large families, and single or reconstituted families; family history of hypertension could be coded as no and yes; maternal BMI status was assessed through self-reported status, and could be sorted into: normal, overweight, and obesity; mother's smoke/drink use could be coded as no and yes; mother's MVPA adherence could be categorized into two groups: insufficient MVPA (the total time of MVPA < 150 min per/week) and sufficient MVPA (the total time of MVPA ≥ 150 min per/week); parental migration could be coded as no and yes.
(4) Birth (maternal reproductive age, natural delivery, breastfeeding, term birth, birthweight category, and one-child): maternal reproductive age was grouped into < 35 years and ≥ 35 years; natural delivery, breastfeeding, term birth, and one-child could be coded as no and yes; birthweight was recorded as continuous values, and could be categorized into normal (birthweight ≥ 2.5 kg and ≤ 4.0 kg) and abnormal (birthweight < 2.5 kg or > 4.0 kg).
(5) Anthropometrics (obesity phenotype): obesity phenotypes were defined as the combinations of general and central obesity statuses. Children were grouped into normal weight (BMI < 85th percentile for age and sex), overweight (85th percentile for age and sex ≤ BMI < 95th percentile for age and sex), and general obesity (BMI ≥ 95th percentile for age and sex), according to the Chinese National Standard (*WS/T 586–2018*) [37]". Overweight and general obesity were merged into abnormal weight. Besides, children with WC > 90th percentile for age and sex were sorted into central obesity [38]. Then all children were further grouped into four mutually exclusive groups: normal weight with no central obesity (NWNCO), normal weight with central obesity (NWCO), abnormal weight with no central obesity (AWNCO), and abnormal weight with central obesity (AWCO).
(6) Lifestyle (children's sleep quality, children's sleep/screen time/MVPA adherence, children's commuting modes, children's habit of breakfast/midnight snack, and home snack): children's sleep quality were grouped into bad and well; if the sleep duration of children aged 5–13 years was in the range of 9–11 h and for children aged 14–17 years was in the range of 8–10 h, then they could be grouped as having adequate sleep duration, otherwise could be categorized into having inadequate sleep duration [39]; children's screen time adherence could be categorized into two groups: unlimited screen time (> 2 h per day spent in total watching TV, playing video games, using the computer, or using portable electronic devices) and limited screen time (≤ 2 h per day of screen time) [39]; children's MVPA adherence could be categorized into two groups: insufficient MVPA (daily MVPA for < 60 min) and sufficient MVPA (daily MVPA for ≥ 60 min) [39]; children's commuting modes could be categorized into two groups: walk or bike, and car or others; children's habit of breakfast was assessed by asking respondents "do you eat breakfast every day", and responses were categorized into no and yes; children's habit of midnight snack was assessed by asking respondents "do you eat midnight snack every day", and responses were categorized into no and yes; home snack was evaluated by question "are there any snacks at home", and responses were categorized: no and yes.

Hypertension status was considered as an outcome variable and was defined as SBP and/or DBP ≥ age-, sex-, and height-specific 95th percentile from visit one to visit three, according to the Chinese BP reference standards for children and adolescents [36].

Statistical analysis

Continuous variables were presented as median with interquartile range (IQR) if the parameter exhibited skewness in normality tests and as mean ± SD when the parameter was normally distributed. Categorical variables were reported as number (n) with percent (%). Differences in basic characteristics by sex were evaluated using T-tests for normally-distributed continuous variables and Mann-Whitney test for skewed-distributed continuous variables, respectively. In terms of categorical variables, Chi-square (χ^2) tests were conducted.

RF model and multivariable logistic regression model were used in combination to rank the importance of various associated factors and then provide intuitive explanations through ORs and 95% confidence intervals (CIs) [30, 31]. RF is a non-parametric machine learning model that enables establishing a series of decision trees and outputs the classes of a single tree, which could avoid overfitting and rank the importance of variables so that the key variables can be focused [31]. The original data were divided into training set and test set, respectively. Then, RF generated bootstraps through randomly resampling from the training set, and ultimately aggregating the results [31]. Out-of-bag (OOB) refers to a dataset that is not included in resampling during the construction of a decision tree, which serves as a validation set to assess the performance of the decision tree and estimate RF's goodness of fit [40]. Given the averages of the predictions made by all decision trees, the model predicts the output as follows:

$$-\bar{f}=\frac{1}{m}\sum_{i=1}^{m} f_i\left(x'\right)$$

where m is the total number of decision trees, $f_i\left(x'\right)$ is the prediction of *i*-th decision tree given input x'.

Mean decrease accuracy (MDA) was used to evaluate the importance of associated factors [41]. A higher MDA value indicates that the corresponding associated factor is more significant [41]. Based on the results of MDA values, the 10-fold cross-validation was used to obtain the number of variables that displayed the best performance. Therefore, in our multivariable logistic regression, the top seven variables were selected as independent variables, and childhood hypertension was regarded as the outcome variable. Additionally, sex, age groups, and residence were incorporated into the multivariable logistic regression and were used for stratified analyses. Model 1 was the crude model without any adjustment. Model 2 was further adjusted for sex, age groups, residence, children's habit of breakfast, children's sleep adherence, children's screen time adherence, children's midnight snack habit, obesity phenotypes, family history of hypertension, one-child, home snacks, type of delivery, and children's MVPA adherence. Subsequently, the multicollinearity of the factors in the adjusted model was assessed by using generalized Variance Inflation Factor (gVIF). To evaluate the fitness of model and detect any potential issues with the residuals, a quantile residuals plot was generated. The PAF (%) and its corresponding 95% confidence intervals (CI) were calculated employing adjusted odds ratios [aOR] derived from those mentioned above in the multivariable logistic regression model, and the detailed formula was shown in Supplementary Eq. S1. After adjusting for age, sex, residence, and other factors mentioned in model 2, the PAFs and their 95% CI were shown by age, sex, and residence groups. The theoretical prevalence of childhood hypertension under the hypothesis of elimination of certain risk factor was calculated utilizing the formula of the actual prevalence of hypertension multiplied by (1-PAF).

Data were analyzed in Stata version 17.0 (StataCorp) and R version 4.3.0 (R Foundation for Statistical Computing). A two-sided P of less than 0.05 indicated statistical significance.

Results

Characteristics of study participants

Table S1 displayed the characteristics of the included children by hypertension status. There were 1181 boys (49.8%), 1192 girls (50.2%), and a total of 119 (5.0%) children who ultimately met the diagnostic criteria for childhood hypertension based on BP measurements in three separate visits. The median age of the children was 9.5 (IQR: 9.0, 12.5) years. The proportions of urban location and primary school students were 76.3% and 57.6%, respectively.

Significant differences were observed between hypertension and normotension in terms of anthropometric indicators, family disease history, and type of delivery. Children with hypertension had higher height (Median: 150.4 [IQR: 135.7, 159.2] cm vs. Median: 143.1 [IQR: 134.5, 156.0] cm, $P=0.024$), weight (Median: 50.0 [IQR: 37.8, 65.7] kg vs. Median: 38.5 [IQR: 30.0, 47.8] kg, $P<0.001$), SBP (Median: 126.2 [IQR: 120.5, 133.0] mmHg vs. Median: 104.8 [IQR: 98.7, 111.3] mmHg, $P<0.001$), and DBP (Median: 76.3 [IQR: 71.0, 79.0] mmHg vs. Median: 65.7 [IQR: 61.3, 70.0] mmHg, $P<0.001$) than those with normotension. The proportions of family history of hypertension, mother being overweight, mother being obese, and non-natural labor were higher in children with hypertension than their normotensive counterparts (8.4% vs. 4.1%, 26.1% vs.17.3%, 9.2% vs.3.5%, and 66.4% vs. 53.0%, respectively). Meanwhile, compared with those with normotension, children with hypertension had higher rates of NWCO, AWNCO, and AWCO (5.0% vs. 3.5%, 21.0% vs.14.2%, and 53.8% vs. 17.7%, respectively).

Associated factors of childhood hypertension

The importance of associated factors assessed by RF was displayed in Figure S2. The top ten associated factors based on the MDA from high to low are age groups, habit of breakfast, children's sleep adherence, children's screen time adherence, habit of midnight snack, residence, obesity phenotype, family history of hypertension, one-child, and parental migration. According to the results of 10-fold cross-validation, we included the top seven variables, together with sex, age groups, and residence into the logistic regression to derive ORs and 95% CIs. As shown in Table 1, NWCO (OR=4.61, 95% CI: 1.83–11.59), AWNCO (OR=4.74, 95% CI:2.67–8.41), AWCO (OR=9.73, 95% CI: 6.01–15.76), having family history of hypertension (OR=2.16, 95% CI: 1.09–4.26), and natural labour (OR=1.75, 95% CI: 1.19–2.58) were associated with a higher odd of childhood hypertension based on univariate model. Meanwhile, after adjusting for age, sex, residence, and all other factors, NWCO (aOR=5.04, 95% CI: 1.96–12.98), AWNCO (aOR=4.60, 95% CI:2.57–8.21), and AWCO (aOR=9.94, 95% CI: 6.06–16.32) were associated with higher odds of childhood hypertension. Table S2 showed the results of the multicollinearity test and the mean adjusted gVIF was 1.05, indicating low collinearity. The quantile-quantile (Q-Q) plot indicated well fitness of model, with no significant deviations (KS test p=0.878, dispersion test p=0.976), while significant outliers were detected (outlier test p=0.002) (Figure S3). The residual vs. predicted values plot showed a generally uniform distribution of residuals across the range of predicted values (Figure S3).

Table 1 Associations between associated factors and childhood hypertension

Variables	OR (95%CI)	
	Model 1[a]	**Model 2[b]**
Age group		
Primary school	Reference	Reference
Middle school	1.40 (0.97, 2.03)	1.25 (0.79, 1.98)
Sex		
Boy	Reference	Reference
Girl	0.84 (0.58, 1.22)	1.00 (0.67, 1.48)
Residence		
Urban	Reference	Reference
Rural	0.76 (0.48, 1.21)	0.67 (0.41, 1.09)
Children's habit of breakfast		
Yes	Reference	Reference
No	1.38 (0.88, 2.17)	1.24 (0.77, 2.01)
Children's habit of midnight snack		
No	Reference	Reference
Yes	1.10 (0.76, 1.60)	1.02 (0.67, 1.55)
Home snack		
No	Reference	Reference
Yes	1.23 (0.81, 1.85)	1.42 (0.93, 2.18)
Children's sleep adherence		
Adequate sleep duration	Reference	Reference
Inadequate sleep duration	1.41 (0.97, 2.04)	1.17 (0.75, 1.84)
Children's screen time adherence		
Limited screen time	Reference	Reference
Unlimited screen time	0.97 (0.63, 1.51)	0.72 (0.45, 1.16)
Children's MVPA adherence		
Sufficient MVPA	Reference	Reference
Insufficient MVPA	1.72 (0.83, 3.57)	1.41 (0.66, 2.99)
Obesity phenotype		
NWNCO	Reference	Reference
NWCO	**4.61 (1.83, 11.59)**	**5.04 (1.96, 12.98)**
AWNCO	**4.74 (2.67, 8.41)**	**4.60 (2.57, 8.21)**
AWCO	**9.73 (6.01, 15.76)**	**9.94 (6.06, 16.32)**
Family history of hypertension		
No	Reference	Reference
Yes	**2.16 (1.09, 4.26)**	1.67 (0.81, 3.43)
One-child		
Yes	Reference	Reference
No	0.86 (0.59, 1.25)	0.89 (0.60, 1.32)
Natural delivery		

Population attributable fractions of associated factors and the theoretical prevalence of childhood hypertension

At the population level, AWCO had the largest PAF (PAF: 0.64, 95% CI: 0.50–0.75), followed by AWNCO (PAF: 0.34, 95% CI: 0.19–0.51), and NWCO (PAF: 0.13, 95% CI: 0.03–0.30) (Fig. 2). Among various age, sex, and residence groups, the magnitudes of PAFs were not dramatically changed. AWCO demonstrated the largest PAF in nearly all subgroups.

Moreover, we estimated the theoretical prevalence of childhood hypertension on the condition that each associated factor was eliminated (Fig. 2). Removing AWCO (0.02, 95% CI: 0.01–0.03), AWNCO (0.03, 95% CI: 0.02–0.04), and NWCO (0.04, 95% CI: 0.04–0.05) were correlated with a large decrease in the theoretical prevalence of childhood hypertension. Among different age, sex, and residence groups, the magnitudes of reduction in the theoretical prevalence were not dramatically varied.

Discussion

This comprehensive study seeks not only to identify significant associated factors of childhood hypertension but also to prioritize interventions based on their potential population impacts among students aged 8–14 years. To the best of our knowledge, this study is one of the first, based on a framework namely social-ecological theory, to

Table 1 (continued)

Variables	OR (95%CI)	
	Model 1[a]	**Model 2[b]**
Yes	Reference	Reference
No	**1.75 (1.19, 2.58)**	1.43 (0.95, 2.14)

Note MVPA, moderate-to-vigorous physical activity. NWNCO, normal weight with no central obesity. NWCO, normal weight with central obesity. AWNCO, abnormal weight with no central obesity. AWCO, abnormal weight with central obesity. OR, odds ratio

[a] Model 1 was the crude model without any adjustment

[b] Model 2 was further adjusted for sex, age group, residence, children's habit of breakfast, children's sleep adherence, children's screen time adherence, children's habit of midnight snack, obesity phenotypes, family history of hypertension, one-child, home snack, type of delivery, and children's MVPA adherence

explore the effects of multidimensional factors associated with childhood hypertension based on three separate visits using an integrated approach that combines RF and logistic regression. Our findings indicated a childhood hypertension prevalence of 5.0%, ascertained through consistent elevated BP across three separate visits. In the crude model, obesity phenotype, having family history of hypertension, and non-natural delivery were associated with increased odds of childhood hypertension, while in the adjusted model, obesity phenotype was associated with it. At the population level, AWCO, AWNCO, and NWCO accounted for about 64%, 34%, and 13% of childhood hypertension cases, respectively.

The revealed childhood hypertension prevalence was markedly lower than prior estimates from single-visit BP measurements in China, which have reported rates ranging from 2.0 to 26.0% [16–18, 42–45]. According to the fourth report from the National High Blood Pressure Education Program Working Group in the United States, the assessment of childhood hypertension should be based on three separate visits [46]. This multi-visit approach is crucial in obtaining an accurate estimate of hypertension prevalence, which reduces the variability of diagnosis from a single-visit measurement. Building upon a meta-analysis conducted to determine a summary prevalence of elevated BP over three visits, the prevalence of elevated BP decreased by 53.7% during visit two and by 77.7% during visit three, compared to visit one [47]. Our results align closely with the global (4.0%) and national (4.0%) prevalence of data derived from three BP occasions [5, 48], suggesting a reliable estimation for informed public health interventions.

Moreover, the prevalence of childhood hypertension was higher in boys than in girls in our study, which was parallel to observed outcomes in other study populations. For instance, a previous study employing data from the China Child and Adolescent Cardiovascular Health demonstrated the prevalence of childhood hypertension was 5% in boys and 3% in girls [48]. Numerous studies suggested that variations in sex and age could exert impacts on the status of childhood hypertension. While before puberty the BP levels tend to be consistent in boys and girls, and after puberty the levels in boys surpassed those in girls [6]. During puberty, children were prone to experiencing transient insulin resistance, which leads to a more rapid elevation of BP levels. Simultaneously, estrogen played a crucial role in enhancing endothelium-dependent vasodilation and regulating smooth muscle cells [49, 50], protecting girls from hypertension. Besides, unhealthy lifestyles were more prevalent among Chinese adolescent boys than girls, which might be the potential explanations for sex difference [51, 52].

Consistent with existing literature, obesity phenotype, having family history of hypertension, and non-natural delivery were associated with an increased odd of childhood hypertension [42, 53, 54]. The pathophysiological link between obesity and hypertension is complex and multifaceted. Firstly, obesity could induce changes in the nervous system and insulin resistance, which together disrupt the function of blood vessels and alter sodium balance, contributing to increased BP [55, 56]. Secondly, excessive visceral adipose tissue accumulation triggers immune responses, leading to elevated free fatty acids (FFAs) levels [57]. These FFAs not only interfere with insulin's ability to reduce blood glucose but also promote the accumulation of angiotensinogen, a precursor to angiotensin, which is known to increase BP. Thirdly, the heightened levels of angiotensinogen contribute to both the constriction of blood vessels and the enhancement of sodium retention, resulting in elevated BP [57]. Furthermore, a family history of hypertension may predispose children to the condition due to genetic factors. A previous study involving 2638 high school adolescent students in Italy demonstrated that certain gene variants, previously linked to hypertension in adults, also affect BP and sodium excretion among adolescents [53]. Additionally, these genetic variants might interact with pro-inflammatory pathways, which are often activated in hypertensive individuals, potentially leading to early cardiovascular damage [53]. In line with previous studies [54, 58], our findings indicated that the type of delivery may impact offspring health outcomes. A Dutch birth cohort showed that children born by cesarean section were 1.52 times more likely to be overweight than those born via natural delivery [54], and another birth cohort study in southern Brazil displayed that those born by cesarean section have higher BP values [58].

Though the decreased urban-rural disparity in BP between 1985 and 2010 [24], and the escalating burden of childhood obesity among urban and rural between 1985 and 2019 [59] were observed, the urban-rural differences in childhood hypertension attributable to obesity phenotype was still unclear. Despite existing studies had figured out the distribution of childhood hypertension

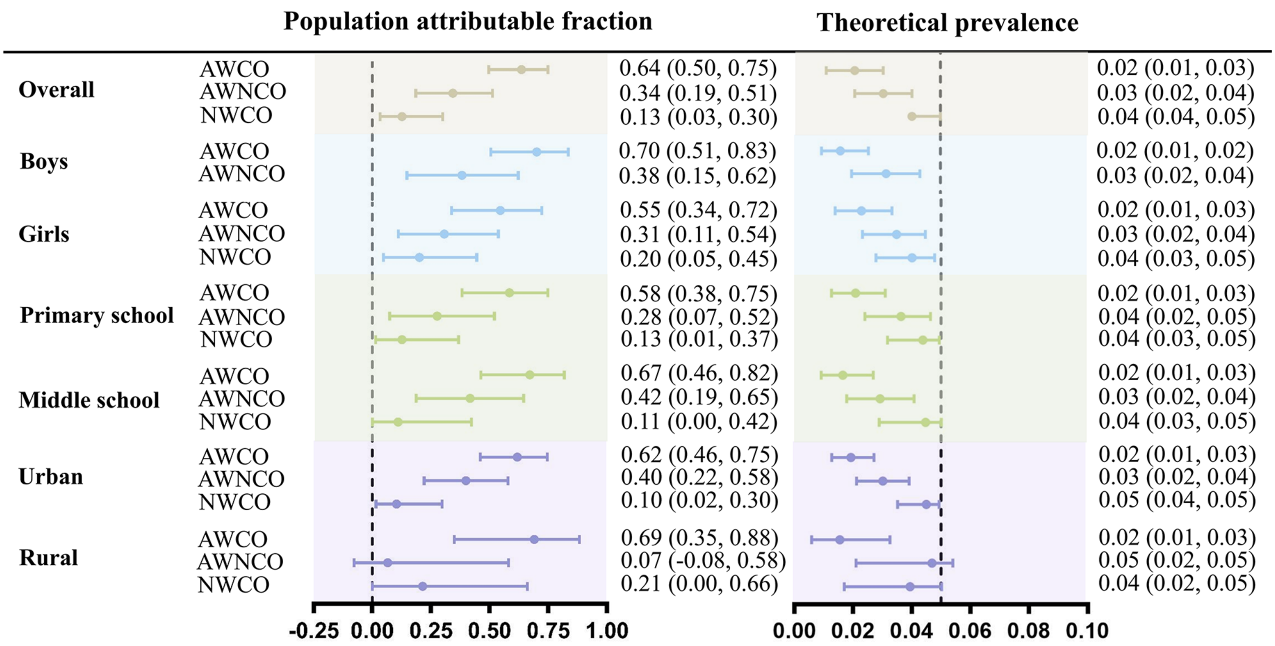

Fig. 2 Adjusted population attributable fractions of associated factors and predicted prevalence of childhood hypertension if the factor was removed
Note: NWNCO, normal weight with no central obesity. NWCO, normal weight with central obesity. AWNCO, abnormal weight with no central obesity. AWCO, abnormal weight with central obesity

in different sex and age groups [5], as well as explored its association with obesity phenotype [42], there were still few studies to investigate the attributable fraction of obesity phenotype to hypertension in children across different sex and age groups. Besides the identification of associated factors of childhood hypertension, we quantified the population impact using the PAFs of each factor to pinpoint potential intervention targets. In accordance with previous evidence, our study indicated that alleviating the problem of general and central obesity (NWCO, AWNCO, and AWCO) is beneficial for managing children's hypertension [42]. Moreover, our study suggested the ranked associated factors for childhood hypertension varied by sex, age, and residence, which warranted population-specific strategies for hypertension prevention and control.

Strengths and limitations of the study

Our study had several strengths. First, the assessment of childhood hypertension was based on BP measurements across three separate occasions, minimizing the influence of white-coat hypertension (an elevated BP in the medical setting, but a normal BP out of the medical setting) and masked hypertension (a normal BP in the medical setting, but an elevated BP out of the medical setting). Besides, the school-based study ensured a high rate of participation, thereby reducing selection bias. Notably, we did not immediately inform children detected with elevated BP. Instead, we provided lifestyle advice only after completing the questionnaire and BP measurements, thereby minimizing the bias introduced by changes in their lifestyle. Additionally, the application of a social-ecological framework and an integrated approach that combines RF and logistic regression could enhance our understanding by ranking the importance of multidimensional associated factors and also provide clear explanations for these associations. Furthermore, the calculation of PAFs was instrumental in identifying and prioritizing targeted interventions, thereby contributing to more effective management of childhood hypertension.

Nevertheless, several limitations warrant mention when interpreting the present findings. First, the sampling was confined to Pinghu, Jiaxing City within Zhejiang Province, which potentially limited the generalizability and representativeness of our findings to the entire province or beyond. Second, the cross-sectional nature of the study also restricted our ability to assess causality between the associated factors and childhood hypertension. Third, involving children those volunteered to participate in might incur selection bias and social desirability bias. Finally, information on associated factors (e.g. family income) at the first visit was gathered by self-administered questionnaires, thus information bias and reporting bias ought to be considered and future studies should be undertaken that incorporate more objective measures.

Conclusions

In summary, among children aged 8–14 years in Pinghu, Zhejiang province, China, positive associations with hypertension were observed in those with NWCO, AWNCO, and AWCO. Our results suggested that targeted modifications to these factors could lead to a decreased prevalence of childhood hypertension. Furthermore, the risk attributed to these factors differed across age, sex, and residence, highlighting the need for tailored approaches in hypertension prevention initiatives.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12889-024-19630-3.

Supplementary Material 1

Supplementary Material 2

Supplementary Material 3

Supplementary Material 4

Supplementary Material 5

Supplementary Material 6

Supplementary Material 7

Supplementary Material 8

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Author contributions

PS designed the study. DZ collected the data, JZ analyzed the data. JZ prepared the first draft. PS, RZ, JZ, WS, CZ, LH, ZL, DJ, BT, CY, DZ and JL critically revised the manuscript. All authors were involved in revising the paper and gave final approval of the submitted versions.

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Data availability

The datasets used and/or analyzed during the current study were available from the corresponding authors on reasonable request.

Declarations

Ethics approval and consent to participate

Ethics for conducting the study was approved by the Ethical Committee of Zhejiang University School of Medicine, Zhejiang, China (2021–029). Written informed consents were provided by the guardians of the included children.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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