

Association of 24 Conventional and Unconventional Anthropometric Indicators with Pre-Hypertension or Hypertension: A Population-Based Cross-Sectional Study in Chinese Population

Ying Han^{1,*}, Huajing Chang^{2,*}, Jingru Huang³, Min Pan⁴⁻⁶, Jin Gong⁴⁻⁶, Bangbang Huang⁴⁻⁶, Liangdi Xie⁴⁻⁶, Xian-E Peng², Huashan Hong⁷

¹Fujian Medical University Union Hospital, Fuzhou, People's Republic of China; ²Department of Epidemiology and Health Statistics, Fujian Provincial Key Laboratory of Environment Factors and Cancer, School of Public Health, Fujian Medical University, Fuzhou, People's Republic of China; ³College of Integrated Chinese and Western Medicine, Fujian University of Traditional Chinese Medicine, Fuzhou, People's Republic of China; ⁴Department of Geriatrics, The First Affiliated Hospital of Fujian Medical University, Fuzhou, People's Republic of China; ⁵Institution of Fujian Hypertension Research, The First Affiliated Hospital of Fujian Medical University, Fuzhou, People's Republic of China; ⁶Fujian Provincial Sub-center of National Clinical Research Center for Geriatric Disorders, The First Affiliated Hospital of Fujian Medical University, Fuzhou, People's Republic of China; ⁷Department of Geriatrics, Fujian Key Laboratory of Vascular Aging (Fujian Medical University), Fujian Institute of Geriatrics, Fujian Clinical Research Center for Senile Vascular Aging and Brain Aging, Fujian Medical University Union Hospital, Fuzhou, People's Republic of China

*These authors contributed equally to this work

Correspondence: Xian-E Peng, School of Public Health, Fujian Medical University, Fuzhou, Fujian, People's Republic of China, Email peng123456@fjmu.edu.cn; Huashan Hong, Fujian Medical University Union Hospital, Fuzhou, Fujian, People's Republic of China, Email 15959159898@163.com

Background: Anthropometric indicators are known to be closely related to pre-hypertension and hypertension. This study aimed to explore the association of conventional and unconventional anthropometric indicators with pre-hypertension and hypertension.

Methods: About 8787 adults (aged ≥ 18 years) who joined in the Chinese Residents Cardiovascular Disease and Risk Factors Surveillance Project (2020) were included. Twenty-four anthropometric indicators were measured and calculated, including conventional anthropometric indicators [eg, weight, fat mass (FM), body mass index (BMI), height-adjusted weight (HtaW), fat mass index (FMI), fat-free mass index (FFMI)] and unconventional anthropometric indicators [eg, atherogenic index of plasma (AIP), triglyceride-glucose index (TyG)]. LASSO regressions were used to identify key anthropometric indicators associated with pre-hypertension/hypertension. Multivariate logistic regression model, RCS regression analysis, subgroup analyses and sensitivity analyses were conducted to explore the association between anthropometric indicators and pre-hypertension/hypertension. ROC and AUC were also utilized to evaluate the performance of anthropometric indicators in identifying pre-hypertension/hypertension.

Results: After adjustment for potential confounders, multivariate logistic regression showed that weight, BMI, HtaW, FMI, FFMI, AIP, and TyG were significantly associated with pre-hypertension, while FM, AIP, and TyG were significantly associated with hypertension. ROC analysis showed that conventional anthropometric indicators were slightly superior to unconventional anthropometric indicators in identifying pre-hypertension and hypertension. RCS models suggested that weight, FMI, FFMI, AIP, and TyG had linear dose-response relationships with pre-hypertension risk, while BMI and HtaW were nonlinearly associated with pre-hypertension risk; FM, AIP and TyG had nonlinear dose-response relationships with hypertension risk ($P_{\text{nonlinear}} < 0.05$). The results from the subgroup analysis and sensitivity analysis basically supported the primary findings.

Conclusion: As one of the first comprehensive comparisons of 24 anthropometric indicators in a large Chinese population, this study found that BMI and TyG were the best anthropometric indicators for identifying pre-hypertension, while TyG showed a significantly stronger association with hypertension.

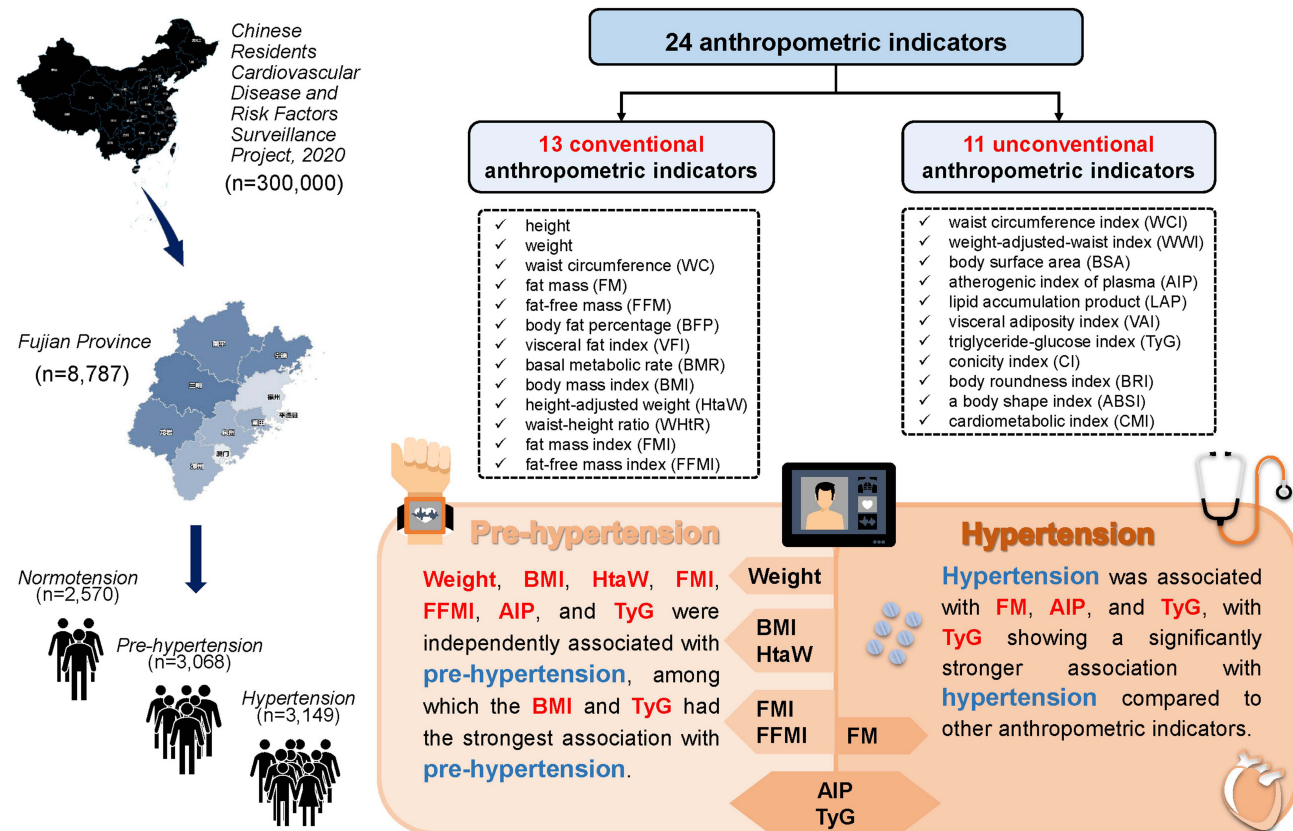
Plain Language Summary: Many studies have shown that common body measures such as body mass index (BMI) and waist circumference can predict whether someone is likely to develop high blood pressure. Recently, researchers have started looking at new body measures like the atherogenic index of plasma (AIP) and triglyceride-glucose index (TyG). However, not many studies have compared how well these new body measures predict high blood pressure compared to the body traditional ones.

In our research, we used data from the Fujian Province part of the Chinese Residents Cardiovascular Disease and Risk Factors Surveillance Project, 2020 (CRCDRFSP-2020), to study how 24 different body measures relate to high blood pressure and its early stage, called pre-hypertension. We used detailed statistical methods to find out which measures are the best predictors of high blood pressure and its early stage. We discovered that weight, BMI, and a few other measures are closely linked to pre-hypertension. Specifically, BMI and TyG were the most strongly connected. For high blood pressure, fat mass, AIP, and TyG were important, with TyG being particularly strong in predicting high blood pressure.

From these results, we have suggested a practical method for doctors to pick the best body measures to predict high blood pressure early, based on a person’s specific situation. We also created a decision diagram to help with this. We believe this approach will help in early recognition of high blood pressure, allowing for better prediction and helping to reduce its occurrence.

Keywords: pre-hypertension, Hypertension, anthropometric indicators, LASSO, ROC, RCS

Graphical Abstract



Introduction

Hypertension, specifically essential hypertension (also known as primary or idiopathic hypertension), is a major contributing risk factor for cardiovascular diseases (CVDs) and other diseases with adverse clinical outcomes, making it the largest single contributor to morbidity and mortality worldwide.¹ Pre-hypertension, defined as the intermediate

stage between normotension and hypertension, is also significantly correlated with a heightened risk of various cardiovascular outcomes including total CVD, coronary heart disease, myocardial infarction, and stroke.² Elevated blood pressure and its consequent cardiovascular and cerebrovascular diseases have become the predominant burden of disease and leading cause of mortality globally and in most regions of the world,³ affecting approximately 1.39 billion individuals and resulting in over 10.8 million deaths annually.⁴ Owing to the efforts of governments and health organizations and the widespread use of anti-hypertensive medications, global mean blood pressure has remained constant or decreased slightly over the past five decades. However, the prevalence of hypertension has still increased, particularly in low- and middle-income countries.⁵ Consequently, moving the prevention gateway forward and implementing targeted preventive measures at the pre-hypertension stage may offer a breakthrough in reducing the incidence of hypertension.

Obesity is proven to be an established risk factor for hypertension and CVDs,^{6–8} and the close association of obesity with blood pressure has long been recognized in diverse populations.^{9–11} As conventional anthropometric indicators of obesity, body mass index (BMI) is widely used in research on predictive factors of pre-hypertension and hypertension.^{12,13} Waist circumference (WC) and waist-height ratio (WHtR) also show good potential to predict pre-hypertension and hypertension.¹⁴ BMI reflects the overall body fat distribution and cannot accurately distinguish between fat and muscle proportions; WC and WHtR indicate abdominal obesity accurately and cannot distinguish between subcutaneous fat and visceral fat. In addition, other conventional anthropometric indicators such as basal metabolic rate (BMR), fat mass (FM), fat-free mass (FFM), fat mass index (FMI), and fat-free mass index (FFMI) are also considered effective predictors of hypertension.^{15–17} However, the effects of these conventional anthropometric indicators on pre-hypertension are still limited. Furthermore, only a few studies reported the relationship between body fat percentage (BFP), visceral fat index (VFI) and pre-hypertension,^{18,19} but the conclusions among them seemed to be controversial.

Recently, a number of new anthropometric indicators have garnered increasing attention due to their higher value in predicting disease risk. Waist circumference index (WCI), weight-adjusted-waist index (WWI), body surface area (BSA), conicity index (CI), body roundness index (BRI), and a body shape index (ABSI) are parameters based on specific combinations and calculations of physical examination indicators such as height, weight, or WC, while atherogenic index of plasma (AIP) and triglyceride-glucose index (TyG) are derived from the arithmetic operation of biochemical indicators such as triglyceride (TG), high-density lipoprotein cholesterol (HDL-C), or fasting plasma glucose (FBG). Lipid accumulation product (LAP), visceral adiposity index (VAI), and cardiometabolic index (CMI) combine physical examination indicators such as height or WC with biochemical indicators such as TG and HDL-C. Some studies showed these unconventional anthropometric indicators are associated with hypertension, pre-hypertension, or blood pressure.^{20–22} Differing from most studies that consider only one single indicator, this study is one of the first studies to compare a broad panel (24 indicators) simultaneously in a large, population-based Chinese survey. It would be of great clinical and practical importance to further explore the best anthropometric indicators for identifying pre-hypertension or hypertension.

Therefore, this study aimed to identify and compare the predictive value of 24 conventional and unconventional anthropometric indicators for pre-hypertension and hypertension among Chinese adults.

Methods

Study Design and Population

In this study, we used data from the Fujian Province part of the Chinese Residents Cardiovascular Disease and Risk Factors Surveillance Project, 2020. The project was carried out on a stratified multi-stage random sampling method, taking into account the economic development level of urban and rural areas, and selected 262 nationally and provincially representative districts and counties in 31 provinces, autonomous regions, and municipalities (excluding Hong Kong, Macao, and Taiwan) on the basis of their administrative divisions as monitoring sites. At each monitoring point, 1200 permanent residents aged 18 and above were selected according to sex and age group. A total of about 300,000 people were eventually surveyed on the status and distribution characteristics of important CVDs and risk factors such as obesity, hypertension, diabetes mellitus, dyslipidemia, coronary heart disease and stroke, etc.

As a result, three cities in urban areas and five counties in rural areas were selected. A total of 9790 participants living in Fujian Province for more than six months and aged 18 years or older were randomly selected to participate in this survey from August 2020 to April 2021. The exclusion criteria were set as follows: (1) participants with missing systolic blood pressure (SBP)/diastolic blood pressure (DBP) data ($n = 59$); (2) participants with missing data on total cholesterol (TC), TG, HDL-C, low-density lipoprotein cholesterol (LDL-C), FBG, or uric acid (UA) ($n = 943$); (3) participants with negative and clearly erroneous values of FFM ($n = 1$). After data filtration, a total of 8787 participants were ultimately selected for subsequent analyses. This study followed STROBE reporting guidelines (see [Supplementary Table 1](#)).

Blood Pressure Measurement and Definition of Pre-Hypertension or Hypertension

BP was measured using the same brand and model of electronic sphygmomanometer (Omron electronic sphygmomanometer HBP-1120U), with an accuracy of ± 1 mm Hg. Participants were uniformly measured on the right upper arm, and three measurements were recorded, with no more than a 10 mm Hg difference in systolic or diastolic readings between any two of the three measurements (1 mm Hg = 0.133 k Pa). SBP or DBP was defined as the average of the three SBP or DBP readings.

The classification of normotension, pre-hypertension and hypertension was based on the criteria from JNC-8.²³ Hypertension was defined as an average SBP ≥ 140 mm Hg, and/or average DBP ≥ 90 mm Hg, and/or previously diagnosed with hypertension, and/or currently taking anti-hypertensive drugs; pre-hypertension was defined as an average SBP in the range of 120 to 139 mm Hg and/or an average DBP in the range of 80 to 89 mm Hg, without being on anti-hypertensive drugs; normotension was defined as an average SBP < 120 mm Hg and an average DBP < 80 mm Hg, without being on anti-hypertensive drugs.

Anthropometric Measurements

Anthropometric measurements were performed by trained staff according to standard procedures. Height was measured using a stadiometer of the same model with a length of 2.0 m and a minimum scale of 1 mm (Suhong BT-24). WC was measured at the superior border of the iliac crests using a waist circumference ruler of the same brand and model with a length of 1.5 m, a width of 1 cm, and a minimum scale of 1 mm. Weight, FM, FFM, BFP, VFI, and BMR were measured using the same brand and model of weight and body fat measuring device (InBody H20B body composition analyzer), with the scale function measuring accurately to 0.1 kg and a maximum weighing capacity of 150 kg. The above parameters must be measured on an empty stomach in the early morning, and participants should be dressed in light clothes. BMI, height-adjusted weight (HtaW), WHtR, FMI, FFMI, WCI, WWI, BSA, AIP, LAP, VAI, TyG, CI, BRI, ABSI, and CMI were calculated according to previous published formulae as followed (HtaW was calculated based on the coefficients of the sex-specific linear regression models of weight on height):

$$BMI = \frac{weight(kg)^{24}}{height(m)^2}$$

$$HtaW(males) = weight(kg) + 0.825 \times (167.4 - height(cm))^2$$

$$HtaW(females) = weight(kg) + 0.541 \times (155.7 - height(cm))^{225}$$

$$WHtR = \frac{WC(cm)^{26}}{height(m)}$$

$$FMI = \frac{FM(kg)}{height(m)^2}$$

$$FFMI = \frac{FFM(kg)^{27}}{height(m)^2}$$

$$WCI = \frac{WC(cm)^{28}}{\sqrt{height(cm)}}$$

$$WWI = \frac{WC(cm)^{29}}{\sqrt{weight(kg)}}$$

$$BSA = \sqrt{\frac{height(cm) \times weight(kg)^{30}}{3600}}$$

$$AIP = \log\left(\frac{TG(\text{mg/dL})}{HDL-C(\text{mg/dL})}\right)^{31}$$

$$LAP(\text{males}) = (WC(\text{cm}) - 65) \times TG(\text{mmol/L})$$

$$LAP(\text{females}) = (WC(\text{cm}) - 58) \times TG(\text{mmol/L})^{32}$$

$$VAI(\text{males}) = \frac{WC(\text{cm})}{39.68 + (1.88 \times BMI(\text{kg/m}^2))} \times \left(\frac{TG(\text{mmol/L})}{1.03}\right) \times \left(\frac{1.31}{HDL-C(\text{mmol/L})}\right)$$

$$VAI(\text{females}) = \frac{WC(\text{cm})}{36.58 + (1.89 \times BMI(\text{kg/m}^2))} \times \left(\frac{TG(\text{mmol/L})}{0.81}\right) \times \left(\frac{1.52}{HDL-C(\text{mmol/L})}\right)^{33}$$

$$TyG = \ln\left(\frac{TG(\text{mg/dL}) \times FBG(\text{mg/dL})}{2}\right)^{34}$$

$$CI = \frac{WC(\text{m})}{0.109 \times \sqrt{\text{weight}(\text{kg})/\text{height}(\text{m})}}^{35}$$

$$BRI = 364.2 - 365.5 \times \sqrt{1 - \left(\frac{WC(\text{cm})/(2\pi)}{(0.5 \times \text{height}(\text{cm}))^2}\right)^2}^{36}$$

$$ABSI = \frac{WC(\text{m})}{BMI(\text{kg/m}^2)^{\frac{1}{3}} \times \text{height}(\text{m})^{\frac{1}{2}}}^{37}$$

$$CMI = \frac{TG(\text{mmol/L})}{HDL-C(\text{mmol/L})} \times \frac{WC(\text{cm})}{\text{height}(\text{cm})}^{38}$$

Covariates

About 21 covariates were identified based on literature. Demographic characteristics, health-related behaviors, and family history were collected by a standardized questionnaire form through face-to-face interviews with trained staff and physical measurements. Demographic characteristics included age, sex, current residence, educational level, annual household income per capita, occupation, medical insurance, household size, marital status. Educational level was categorized into five levels: illiterate, primary school, junior high school, high school/technical secondary school, and junior college/undergraduate or above. Occupation was divided into three categories: unemployed, physical labor, and mental labor. Health-related behaviors included smoking, drinking, physical activity, regular sleep. Smoking was divided into three groups: never (never smoked in a lifetime), former (smoked in the past but not in the past 30 days), and current (smoked in the past 30 days). Drinking was also classified into three levels: never (never drank alcohol in a lifetime), former (used to drink alcohol but do not drink it anymore), and current (drank in the previous 30 days). Physical activity was defined as those who engaged in moderate-intensity or above physical activity for at least 5 days a week and at least 30 minutes per day during the past month. Regular sleep referred to those who slept between 7 and 9 hours per night on average in the past month. Family history involved hypertension and CVDs, and family history of CVDs was defined as one of the parents had coronary heart disease or stroke. Blood biochemical indicators included FBG, TC, TG, HDL-C, LDL-C, and UA, all tested using the Beckman AU680 instruments. The glucose oxidase method was used for FBG, the enzymatic method was used for TC and TG, the direct method was used for HDL-C and LDL-C, and the uricase method was used for serum UA.

Statistical Analysis

Continuous variables were presented as mean \pm standard deviation or median (IQR) as appropriate and compared using the ANOVA, Welch ANOVA test or Kruskal–Wallis rank sum test, which depended on whether the quantitative data were consistent with the normal distribution. Categorical variables were expressed as percentages and analyzed by the Chi-square test or Fisher's exact test as appropriate. Univariate logistic regression was used to judge the relationship between anthropometric indicators and pre-hypertension or hypertension, as well as a correlation matrix was calculated and a heat map was plotted to assess the multicollinearity of independent variables. Least absolute shrinkage and selection operator (LASSO) regression was employed to select independent variables, and multivariate logistic regression was further used to analyze the association between screened anthropometric indicators and pre-hypertension or

hypertension, adjusting for confounders. Receiver-operating characteristic (ROC) curve was used to evaluate the discrimination ability of each screened anthropometric indicators for pre-hypertension or hypertension. The potential dose-response relationships between anthropometric indicators and the risk of pre-hypertension or hypertension was assessed by restricted cubic spline (RCS) models. A two-sided P -value <0.05 was considered significant. All statistical analyses were conducted using R 4.3.3 and DecisionLinnc. 1.0 softwares.

Results

Characteristics of the Study Population

Figure 1 showed a detailed flow chart of participants screening process. As shown in Table 1, among the 8787 participants, the prevalence of pre-hypertension and hypertension were 34.92% (3068/8787) and 35.84% (3149/8787), respectively. Compared with the normotension group, participants with pre-hypertension or hypertension tended to be older. The differences in sex, current residence, educational level, annual household income per capita, occupation, medical insurance, household size, marital status, smoking, drinking, regular sleep, family history of hypertension or CVDs within the blood pressure subgroups were statistically significant (all $P < 0.05$). Besides, the pre-hypertension and hypertension groups displayed notably higher FBG, TC, TG, LDL-C, UA and lower HDL-C in comparison to the normotension group (all $P < 0.05$).

Distributions of Conventional and Unconventional Anthropometric Indicators

Table 2 showed the distributions of 24 conventional and unconventional anthropometric indicators in the normotension, pre-hypertension, and hypertension groups. There were statistically significant differences in height, weight, WC, FM, FFM, BFP, VFI, BMR, BMI, HtaW, WHtR, FMI, FFMI, WCI, WWI, BSA, AIP, LAP, VAI, TyG, CI, BRI, ABSI, and CMI among the blood pressure subgroups (all $P < 0.05$). Compared to the normotension group, the pre-hypertension group exhibited significantly higher height, weight, WC, FM, FFM, VFI, BMR, BMI, HtaW, WHtR, FMI, FFMI, WCI, WWI, BSA, AIP, LAP, VAI, TyG, CI, BRI, ABSI, and CMI; while the hypertension group showed significantly higher

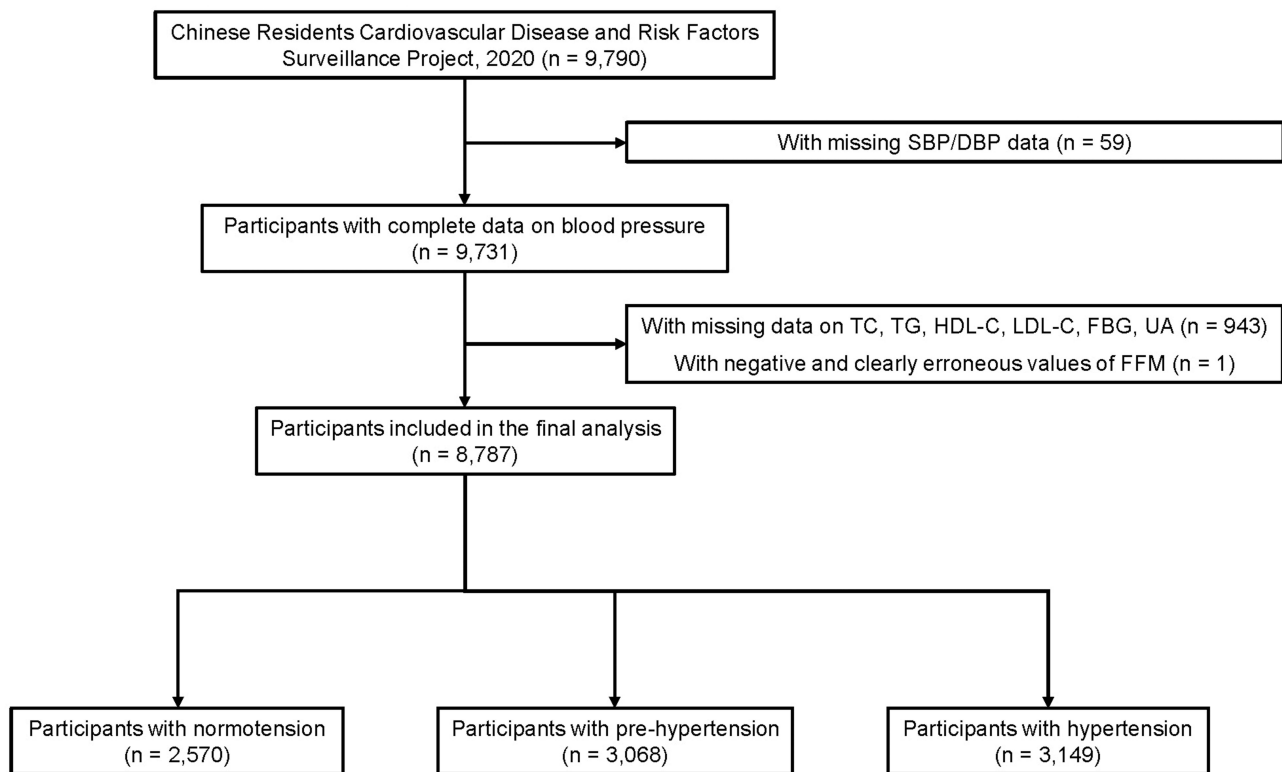


Figure 1 A detailed flow chart of participants screening process.

Table 1 Characteristics of the Study Population

Variables	Overall	Normotension	Pre-Hypertension	Hypertension	F/χ^2	P value
	(n = 8787)	(n = 2570)	(n = 3068)	(n = 3149)		
Age, years	45.35 ± 17.94	35.75 ± 13.63	41.81 ± 15.95	56.65 ± 16.85	1387.066	<0.001
Sex (%)					464.081	<0.001
Male	4432 (50.44)	838 (32.61)	1802 (58.74)	1792 (56.91)		
Female	4355 (49.56)	1732 (67.39)	1266 (41.26)	1357 (43.09)		
Current residence (%)					20.114	<0.001
Urban	3279 (37.32)	1045 (40.66)	1134 (36.96)	1100 (34.93)		
Rural	5508 (62.68)	1525 (59.34)	1934 (63.04)	2049 (65.07)		
Educational level (%)					1232.903	<0.001
Illiterate	1132 (12.88)	120 (4.67)	276 (9.00)	736 (23.37)		
Primary school	1569 (17.86)	235 (9.14)	492 (16.04)	842 (26.74)		
Junior high school	2080 (23.67)	599 (23.31)	737 (24.02)	744 (23.63)		
High school/ technical secondary school	1605 (18.27)	518 (20.16)	651 (21.22)	436 (13.85)		
Junior college/ undergraduate or above	2401 (27.32)	1098 (42.72)	912 (29.73)	391 (12.42)		
Annual household income per capita (%), CNY					321.655	<0.001
<10,000	1065 (12.12)	184 (7.16)	289 (9.42)	592 (18.80)		
10,000–20,000	1928 (21.94)	466 (18.13)	686 (22.36)	776 (24.64)		
20,000–30,000	1990 (22.65)	590 (22.96)	701 (22.85)	699 (22.20)		
30,000–50,000	1705 (19.40)	617 (24.01)	604 (19.69)	484 (15.37)		
50,000–100,000	1374 (15.64)	474 (18.44)	514 (16.75)	386 (12.26)		
≥100,000	725 (8.25)	239 (9.30)	274 (8.93)	212 (6.73)		
Occupation (%)					179.630	<0.001
Unemployed	2802 (31.89)	763 (29.69)	840 (27.38)	1199 (38.08)		
Physical labor	2889 (32.88)	726 (28.25)	1074 (35.01)	1089 (34.58)		
Mental labor	3096 (35.23)	1081 (42.06)	1154 (37.61)	861 (27.34)		
Medical insurance (%)					165.857	<0.001
UEBMI	2644 (30.09)	958 (37.28)	961 (31.32)	725 (23.02)		
URRBMI	5823 (66.27)	1500 (58.37)	1988 (64.80)	2335 (74.15)		
Other medical insurances	62 (0.71)	21 (0.82)	18 (0.59)	23 (0.73)		
Non-medical insurance	258 (2.94)	91 (3.54)	101 (3.29)	66 (2.10)		
Household size (%)					522.243	<0.001
1	329 (3.74)	45 (1.75)	81 (2.64)	203 (6.45)		
2	1065 (12.12)	149 (5.80)	287 (9.35)	629 (19.97)		
3	1894 (21.55)	551 (21.44)	735 (23.96)	608 (19.31)		
4	2346 (26.70)	869 (33.81)	868 (28.29)	609 (19.34)		
5	1331 (15.15)	435 (16.93)	483 (15.74)	413 (13.12)		
6	1203 (13.69)	368 (14.32)	410 (13.36)	425 (13.50)		
≥7	619 (7.04)	153 (5.95)	204 (6.65)	262 (8.32)		
Marital status (%)					608.556	<0.001
Unmarried	1820 (20.71)	807 (31.40)	760 (24.77)	253 (8.03)		
Married/remarried/cohabiting	6438 (73.27)	1686 (65.60)	2176 (70.93)	2576 (81.80)		
Separated/divorced/widowed	529 (6.02)	77 (3.00)	132 (4.30)	320 (10.16)		
Smoking (%)					219.350	<0.001
Never	6373 (72.53)	2128 (82.80)	2164 (70.53)	2081 (66.08)		
Former	340 (3.87)	47 (1.83)	115 (3.75)	178 (5.65)		
Current	2074 (23.60)	395 (15.37)	789 (25.72)	890 (28.26)		
Drinking (%)					75.911	<0.001
Never	5896 (67.10)	1851 (72.02)	1990 (64.86)	2055 (65.26)		
Former	1044 (11.88)	320 (12.45)	393 (12.81)	331 (10.51)		
Current	1847 (21.02)	399 (15.53)	685 (22.33)	763 (24.23)		

(Continued)

Table 1 (Continued).

Variables	Overall	Normotension	Pre-Hypertension	Hypertension	F/ χ^2	P value
	(n = 8787)	(n = 2570)	(n = 3068)	(n = 3149)		
Physical activity (%)					3.257	0.196
No	3912 (44.52)	1182 (45.99)	1342 (43.74)	1388 (44.08)		
Yes	4875 (55.48)	1388 (54.01)	1726 (56.26)	1761 (55.92)		
Regular sleep (%)					169.308	<0.001
No	3723 (42.37)	878 (34.16)	1242 (40.48)	1603 (50.91)		
Yes	5064 (57.63)	1692 (65.84)	1826 (59.52)	1546 (49.09)		
Family history of hypertension (%)					114.357	<0.001
No	6812 (77.52)	2113 (82.22)	2455 (80.02)	2244 (71.26)		
Yes	1975 (22.48)	457 (17.78)	613 (19.98)	905 (28.74)		
Family history of cardiovascular diseases (%)					20.140	<0.001
No	8527 (97.04)	2526 (98.29)	2966 (96.68)	3035 (96.38)		
Yes	260 (2.96)	44 (1.71)	102 (3.32)	114 (3.62)		
FBG (mmol/L)	5.21 [4.77–5.69]	4.98 [4.61–5.37]	5.18 [4.76–5.60]	5.48 [5.00–6.07]	724.427	<0.001
TC (mmol/L)	4.97 ± 1.00	4.71 ± 0.92	4.98 ± 0.97	5.18 ± 1.03	161.416	<0.001
TG (mmol/L)	1.14 [0.79–1.71]	0.90 [0.68–1.27]	1.15 [0.80–1.71]	1.39 [0.95–2.04]	730.485	<0.001
HDL-C (mmol/L)	1.40 ± 0.31	1.45 ± 0.30	1.39 ± 0.30	1.37 ± 0.31	49.905	<0.001
LDL-C (mmol/L)	3.11 ± 0.85	2.91 ± 0.78	3.14 ± 0.83	3.26 ± 0.88	132.405	<0.001
UA (μ mol/L)	355.24 ± 92.69	329.43 ± 82.52	360.9 ± 92.60	370.79 ± 96.17	169.851	<0.001

Abbreviations: CNY, Chinese yuan; UEBMI, urban employees basic medical insurance; URRBMI, urban and rural residents basic medical insurance; FBG, fasting plasma glucose; TC, total cholesterol; TG, triglyceride; HDL-C, high-density lipoprotein cholesterol; LDL-C, low-density lipoprotein cholesterol; UA, uric acid.

Table 2 Distributions of Conventional and Unconventional Anthropometric Indicators in Different Blood Pressure Subgroups

Variables	Overall	Normotension	Pre-Hypertension	Hypertension	F/ χ^2	P value
	(n = 5658)	(n = 2570)	(n = 3068)	(n = 3149)		
Height ^{a,b,c}	161.43 ± 9.04	160.73 ± 8.31	163.40 ± 9.04	160.09 ± 9.28	114.657	<0.001
Weight ^{a,b}	62.59 ± 12.25	57.87 ± 10.05	64.25 ± 12.44	64.83 ± 12.65	346.143	<0.001
WC ^{a,b,c}	80.50 ± 10.70	74.90 ± 9.41	80.52 ± 10.16	85.05 ± 10.02	777.902	<0.001
FM ^{a,b,c}	19.50 ± 6.88	17.60 ± 6.22	19.36 ± 6.96	21.20 ± 6.90	215.010	<0.001
FFM ^{a,b,c}	43.09 ± 9.13	40.27 ± 8.07	44.88 ± 9.19	43.63 ± 9.33	217.384	<0.001
BFP ^{b,c}	30.63 ± 7.68	29.70 ± 7.80	29.71 ± 7.61	32.28 ± 7.36	119.572	<0.001
VFI ^{a,b,c}	8.62 ± 3.78	7.56 ± 3.50	8.45 ± 3.69	9.64 ± 3.81	232.252	<0.001
BMR ^{a,b,c}	1303.87 ± 200.75	1248.82 ± 179.20	1340.38 ± 198.67	1313.22 ± 209.67	174.398	<0.001
BMI ^{a,b,c}	23.93 ± 3.68	22.36 ± 3.20	23.96 ± 3.57	25.17 ± 3.67	483.514	<0.001
HtaV ^{a,b,c}	78.17 [64.34–104.79]	70.56 [58.73–91.64]	78.56 [64.75–107.08]	83.24 [69.60–113.16]	373.914	<0.001
WHtR ^{a,b,c}	0.50 ± 0.07	0.47 ± 0.06	0.49 ± 0.06	0.53 ± 0.06	881.704	<0.001
FMI ^{a,b,c}	12.12 ± 4.27	11.00 ± 3.93	11.88 ± 4.25	13.26 ± 4.29	220.223	<0.001
FFMI ^{a,b,c}	26.52 ± 4.47	24.92 ± 4.01	27.30 ± 4.42	27.07 ± 4.56	271.441	<0.001
WCI ^{a,b,c}	6.34 ± 0.81	5.91 ± 0.72	6.30 ± 0.76	6.72 ± 0.76	849.649	<0.001
WWI ^{a,b,c}	10.22 ± 0.89	9.88 ± 0.83	10.09 ± 0.81	10.62 ± 0.86	624.594	<0.001
BSA ^{a,b}	1.67 ± 0.19	1.60 ± 0.16	1.70 ± 0.20	1.69 ± 0.20	265.799	<0.001
AIP ^{a,b,c}	−0.05 ± 0.30	−0.16 ± 0.25	−0.05 ± 0.29	0.04 ± 0.30	361.364	<0.001
LAP ^{a,b,c}	20.94 [10.53–39.28]	12.60 [6.56–22.11]	21.00 [10.78–37.39]	31.50 [17.82–54.12]	1224.801	<0.001
VAI ^{a,b,c}	1.24 [0.80–2.04]	0.98 [0.70–1.51]	1.21 [0.79–1.96]	1.58 [0.99–2.57]	556.116	<0.001

(Continued)

Table 2 (Continued).

Variables	Overall	Normotension	Pre-Hypertension	Hypertension	F/ χ^2	P value
	(n = 5658)	(n = 2570)	(n = 3068)	(n = 3149)		
TyG ^{a,b,c}	1.18 ± 0.64	0.90 ± 0.53	1.17 ± 0.61	1.42 ± 0.67	536.184	<0.001
C _j ^{a,b,c}	118.97 ± 9.89	114.78 ± 9.57	118.19 ± 9.17	123.15 ± 9.16	584.428	<0.001
BRI ^{a,b,c}	3.43 ± 1.24	2.81 ± 1.03	3.30 ± 1.12	4.05 ± 1.23	855.889	<0.001
ABS ^{a,b,c}	7.65 ± 0.61	7.47 ± 0.61	7.60 ± 0.57	7.85 ± 0.58	325.316	<0.001
CMI ^{a,b,c}	0.41 [0.25–0.72]	0.29 [0.20–0.46]	0.41 [0.26–0.71]	0.56 [0.34–0.92]	938.019	<0.001

Notes: ^aStatistically significant difference between normotension and pre-hypertension groups ($P < 0.05$); ^bStatistically significant difference between normotension and hypertension groups ($P < 0.05$); ^cStatistically significant difference between pre-hypertension and hypertension groups ($P < 0.05$).

Abbreviations: WC, waist circumference; FM, fat mass; FFM, fat-free mass; BFP, body fat percentage; VFI, visceral fat index; BMR, basal metabolic rate; BMI, body mass index; HtaW, height-adjusted weight; WHtR, waist-height ratio; FMI, fat mass index; FFMI, fat-free mass index; WCI, waist circumference index; WWI, weight-adjusted-waist index; BSA, body surface area; AIP, atherogenic index of plasma; LAP, lipid accumulation product; VAI, visceral adiposity index; TyG, triglyceride-glucose index; CI, concity index; BRI, body roundness index; ABSI, a body shape index; CMI, cardiometabolic index.

weight, WC, FM, FFM, BFP, VFI, BMR, BMI, HtaW, WHtR, FMI, FFMI, WCI, WWI, BSA, AIP, LAP, VAI, TyG, CI, BRI, ABSI, and CMI, but lower height (all $P < 0.05$).

Selection of Anthropometric Indicators by LASSO Regression

The results of univariate logistic regression analysis showed that 23 conventional and unconventional anthropometric indicators were associated with pre-hypertension (except for BFP), and all 24 conventional and unconventional anthropometric indicators were associated with hypertension (see [Supplementary Table 2](#)). However, the correlation matrix and heat map revealed multicollinearity among the independent variables (see [Supplementary Table 3](#) and [Supplementary Figure 1](#)). Thus, we used LASSO regression to identify key anthropometric indicators associated with pre-hypertension or hypertension, respectively. As presented in [Figure 2](#), the LASSO regression model identified 15 conventional and unconventional anthropometric indicators for pre-hypertension (including weight, FFM, VFI, BMR, BMI, HtaW, FMI, FFMI, WWI, AIP, LAP, VAI, TyG, BRI, and CMI), and 18 conventional and unconventional anthropometric indicators for hypertension (including height, WC, FM, BFP, VFI, BMR, BMI, HtaW, WHtR, FMI, FFMI, WWI, AIP, LAP, VAI, TyG, BRI, and CMI).

Association of Conventional and Unconventional Anthropometric Indicators with Pre-Hypertension and Hypertension

After excluded the variables with multi-collinearity, multivariate logistic regression analysis was used to analyze the association of conventional and unconventional anthropometric indicators with pre-hypertension and hypertension ([Table 3](#)). The final model adjusted for covariates such as demographic characteristics, health-related behaviors, family history, and blood biochemical indicators, and showed that weight ($OR: 2.082$, 95% CI: 1.280–3.411), BMI ($OR: 4.047$, 95% CI: 1.485–11.107), HtaW ($OR: 0.998$, 95% CI: 0.996–0.999), FMI ($OR: 0.138$, 95% CI: 0.034–0.556), FFMI ($OR: 0.202$, 95% CI: 0.061–0.661), AIP ($OR: 0.331$, 95% CI: 0.132–0.818), and TyG ($OR: 2.467$, 95% CI: 1.704–3.599) were significantly associated with pre-hypertension, while only FM ($OR: 1.373$, 95% CI: 1.004–1.895), AIP ($OR: 0.115$, 95% CI: 0.041–0.309), and TyG ($OR: 5.450$, 95% CI: 3.557–8.435) were significantly associated with hypertension.

Discrimination Ability of Different Anthropometric Indicators by ROC Curves

[Figure 3](#) showed the ROC curves for anthropometric indicators related to pre-hypertension and hypertension, and [Table 4](#) demonstrated the area under curve (AUC), best threshold, sensitivity, and specificity of these anthropometric indicators. After adjusting for covariates, the predictive efficacy of the seven anthropometric indicators in pre-hypertension tended to be consistent, and the AUC of these anthropometric indicators were ranked from high to low as follows: Weight > BMI > FMI > FFMI > HtaW = TyG > AIP. Additionally, three anthropometric indicators had good predictive effects for hypertension, with their AUC ranked from high to low as follows: FM > TyG > AIP.

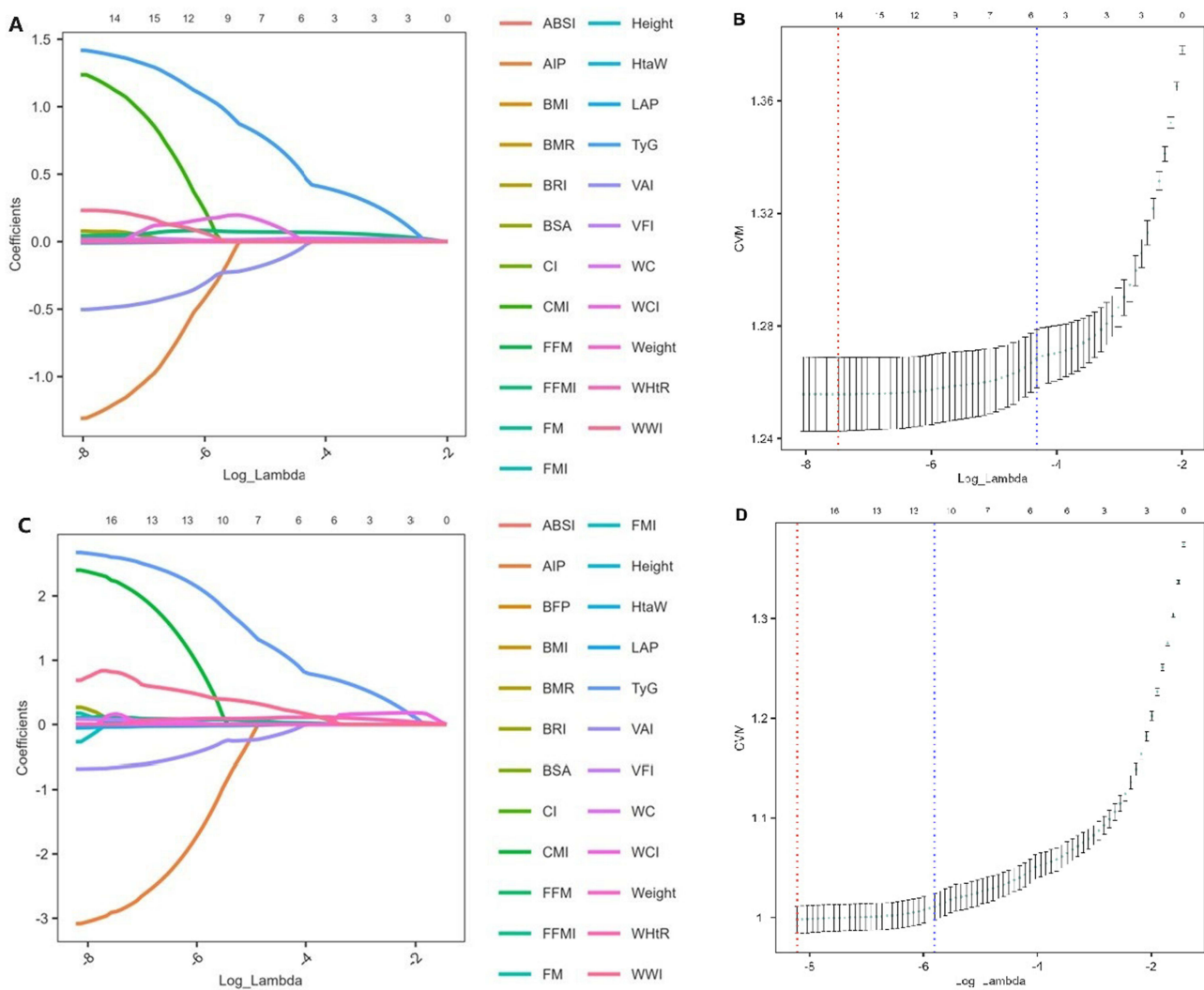


Figure 2 Selection of anthropometric indicators by LASSO Regression. **Notes:** (A) LASSO coefficient profiles of the 23 conventional and unconventional anthropometric indicators in pre-hypertension. A coefficient profile plot was produced against the log lambda sequence. In this study, anthropometric indicators were chosen according to the minimum criteria, where the optimal lambda resulted in 15 nonzero coefficients. (B) A 10-fold cross-validation was used in the LASSO regression for pre-hypertension. Binomial deviance was plotted versus log lambda. The dotted vertical lines were drawn at the optimal values using the minimum criteria (left dotted line) and the one standard error criteria (right dotted line). (C) LASSO coefficient profiles of the 24 conventional and unconventional anthropometric indicators in hypertension. A coefficient profile plot was produced against the log lambda sequence. In this study, anthropometric indicators were chosen according to the minimum criteria, where the optimal lambda resulted in 18 nonzero coefficients. (D) A 10-fold cross-validation was used in the LASSO regression for hypertension. Binomial deviance was plotted versus log lambda. The dotted vertical lines were drawn at the optimal values using the minimum criteria (left dotted line) and the one standard error criteria (right dotted line).

Dose-Response Relationships of Anthropometric Indicators with Pre-Hypertension and Hypertension by RCS Models

According to Figure 4, RCS models suggested that weight, FMI, FFMI, AIP, and TyG had linear dose-response relationships with pre-hypertension risk (P for nonlinear > 0.05), while BMI and HtaW were nonlinearly associated with pre-hypertension risk (P for nonlinear < 0.05); FM, AIP and TyG had nonlinear dose-response relationships with hypertension risk (P for nonlinear < 0.05).

Subgroup Analyses and Sensitivity Analyses

Subgroup analyses revealed that among the conventional and unconventional anthropometric indicators of pre-hypertension, there were statistically significant interactions between age and weight, BMI, HtaW, FFMI, AIP; current residence

Table 3 Multivariate Logistic Regression Analysis of Conventional and Unconventional Anthropometric Indicators with Pre-Hypertension and Hypertension

Variables	Model 1		Model 2		Model 3		Model 4	
	OR (95% CI)	P value	OR (95% CI)	P value	OR (95% CI)	P value	OR (95% CI)	P value
Pre-hypertension								
Weight	2.130 (1.328, 3.441)	0.002	2.136 (1.314, 3.497)	0.002	2.092 (1.287, 3.426)	0.003	2.082 (1.280, 3.411)	0.003
FFM	0.734 (0.567, 0.946)	0.018	0.805 (0.621, 1.039)	0.097	0.804 (0.621, 1.037)	0.095	0.808 (0.624, 1.043)	0.104
VFI	1.029 (0.982, 1.078)	0.229	1.013 (0.967, 1.061)	0.584	1.014 (0.968, 1.063)	0.549	1.012 (0.966, 1.061)	0.606
BMR	0.999 (0.998, 1.000)	0.163	0.999 (0.998, 1.000)	0.077	0.999 (0.998, 1.000)	0.084	0.999 (0.998, 1.000)	0.072
BMI	3.513 (1.350, 9.214)	0.010	4.340 (1.597, 11.876)	0.004	4.098 (1.507, 11.223)	0.006	4.047 (1.485, 11.107)	0.006
HtaW	0.999 (0.998, 1.001)	0.472	0.998 (0.996, 0.999)	0.006	0.998 (0.996, 0.999)	0.006	0.998 (0.996, 0.999)	0.008
FMI	0.133 (0.034, 0.509)	0.003	0.128 (0.031, 0.511)	0.004	0.136 (0.034, 0.545)	0.005	0.138 (0.034, 0.556)	0.006
FFMI	0.245 (0.078, 0.761)	0.015	0.188 (0.057, 0.613)	0.006	0.201 (0.061, 0.656)	0.008	0.202 (0.061, 0.661)	0.008
VVWI	1.038 (0.699, 1.537)	0.855	1.124 (0.747, 1.685)	0.573	1.119 (0.744, 1.679)	0.587	1.102 (0.732, 1.652)	0.641
AIP	0.211 (0.102, 0.433)	<0.001	0.299 (0.142, 0.625)	0.001	0.322 (0.153, 0.674)	0.003	0.331 (0.132, 0.818)	0.017
LAP	0.988 (0.980, 0.996)	0.003	0.999 (0.991, 1.007)	0.767	0.999 (0.991, 1.007)	0.799	0.998 (0.990, 1.007)	0.644
VAI	0.605 (0.489, 0.743)	<0.001	1.081 (0.837, 1.397)	0.549	1.048 (0.810, 1.355)	0.721	1.058 (0.818, 1.368)	0.667
TyG	4.533 (3.384, 6.101)	<0.001	2.622 (1.928, 3.578)	<0.001	2.576 (1.894, 3.518)	<0.001	2.467 (1.704, 3.599)	<0.001
BRI	1.389 (0.878, 2.211)	0.163	0.947 (0.591, 1.526)	0.822	0.951 (0.593, 1.533)	0.836	0.968 (0.604, 1.562)	0.894
CMI	4.111 (2.253, 7.703)	<0.001	0.706 (0.337, 1.492)	0.358	0.762 (0.363, 1.616)	0.474	0.789 (0.375, 1.682)	0.536
Hypertension								
Height	0.971 (0.895, 1.054)	0.482	0.969 (0.885, 1.062)	0.501	0.970 (0.886, 1.063)	0.515	0.967 (0.882, 1.060)	0.475
WC	0.879 (0.718, 1.074)	0.208	0.876 (0.701, 1.092)	0.243	0.892 (0.712, 1.114)	0.317	0.879 (0.702, 1.097)	0.257
FM	1.765 (1.319, 2.389)	<0.001	1.379 (1.012, 1.893)	0.042	1.422 (1.042, 1.959)	0.027	1.373 (1.004, 1.895)	0.049
BFP	0.960 (0.931, 0.990)	0.009	0.993 (0.959, 1.028)	0.681	0.992 (0.958, 1.028)	0.661	0.994 (0.959, 1.030)	0.740
VFI	1.109 (1.048, 1.175)	<0.001	1.015 (0.954, 1.08)	0.645	1.019 (0.958, 1.085)	0.549	1.012 (0.951, 1.079)	0.702
BMR	0.999 (0.998, 1.000)	0.154	1 (0.999, 1.002)	0.558	1.000 (0.999, 1.002)	0.530	1.000 (0.999, 1.001)	0.713
BMI	0.879 (0.435, 1.795)	0.720	0.722 (0.343, 1.539)	0.394	0.801 (0.378, 1.724)	0.565	0.741 (0.347, 1.603)	0.440
HtaW	1.003 (1.001, 1.004)	<0.001	0.999 (0.997, 1)	0.085	0.999 (0.997, 1.000)	0.086	0.999 (0.997, 1.000)	0.105
WHtR	1.465 (0.931, 2.301)	0.098	1.383 (0.85, 2.242)	0.189	1.318 (0.807, 2.141)	0.267	1.292 (0.789, 2.105)	0.306
FMI	0.403 (0.177, 0.895)	0.028	0.829 (0.353, 1.915)	0.661	0.740 (0.311, 1.718)	0.486	0.842 (0.351, 1.970)	0.693
FFMI	1.118 (0.740, 1.679)	0.592	1.352 (0.873, 2.085)	0.173	1.272 (0.816, 1.967)	0.282	1.355 (0.867, 2.106)	0.178
VVWI	1.026 (0.408, 2.674)	0.957	1.281 (0.471, 3.697)	0.634	1.316 (0.481, 3.836)	0.602	1.516 (0.543, 4.532)	0.439
AIP	0.037 (0.017, 0.078)	<0.001	0.149 (0.064, 0.34)	<0.001	0.175 (0.075, 0.401)	<0.001	0.115 (0.041, 0.309)	<0.001
LAP	0.975 (0.968, 0.982)	<0.001	0.996 (0.988, 1.005)	0.403	0.996 (0.987, 1.004)	0.332	0.996 (0.987, 1.005)	0.424
VAI	0.489 (0.396, 0.598)	<0.001	1.05 (0.803, 1.384)	0.724	1.046 (0.801, 1.375)	0.744	1.055 (0.803, 1.404)	0.706
TyG	15.903 (11.536, 22.063)	<0.001	5.092 (3.552, 7.346)	<0.001	4.739 (3.301, 6.846)	<0.001	5.450 (3.557, 8.435)	<0.001
BRI	1.189 (0.514, 2.787)	0.688	0.63 (0.255, 1.579)	0.320	0.683 (0.276, 1.720)	0.414	0.722 (0.291, 1.830)	0.488
CMI	13.729 (7.025, 27.663)	<0.001	0.908 (0.403, 2.106)	0.819	0.927 (0.414, 2.142)	0.857	0.931 (0.408, 2.181)	0.868

Notes: Model 1: Crude model, no adjustment; Model 2: Adjusted for age, sex, current residence, educational level, annual household income per capita, occupation, medical insurance, household size, marital status; Model 3: Adjusted for smoking, drinking, regular sleep on the basis of Model 2; Model 4: Adjusted for family history of hypertension, family history of cardiovascular diseases, TC, LDL-C, UA on the basis of Model 3 (FBG, TG, and HDL-C were included in the calculation formulas of some anthropometric indicators and did not need to be adjusted).

and weight; educational level and weight, BMI, HtaW, FFMI, AIP, TyG; annual household income per capita, occupation, regular sleep and weight, BMI, HtaW, FFMI; medical insurance and weight, HtaW, FFMI; household size and weight, BMI, FFMI, AIP; marital status and weight, FFMI, AIP; smoking and HtaW, FMI, FFMI; drinking and BMI, FMI. Additionally, the interactions between age, occupation, family history of hypertension and AIP, TyG; sex, educational level, smoking and FM, AIP, TyG; medical insurance, marital status and AIP; household size and FM, AIP; drinking and FM were found to be statistically significant for hypertension (see [Supplementary Figure 2](#)). Furthermore, some sets of post hoc sensitivity analyses were performed to verify the robustness of the associations (see [Supplementary Table 4](#)). In most sensitivity analyses, the above associations between conventional and unconventional anthropometric indicators and pre-hypertension or hypertension remained unchanged.

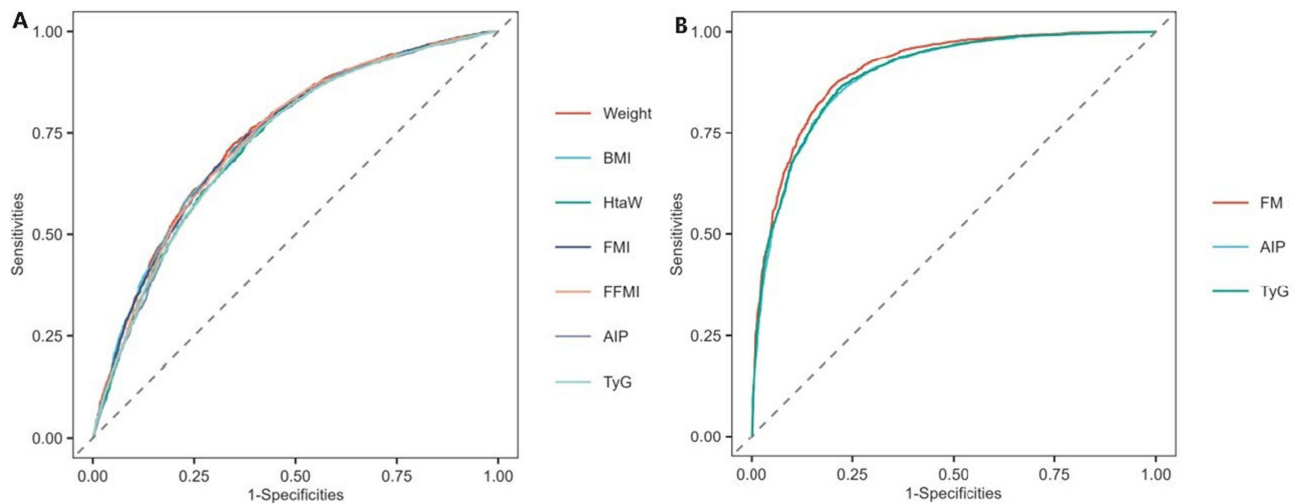


Figure 3 ROC curves of anthropometric indicators for discriminating pre-hypertension (A) and hypertension (B).

Notes: The ROC curves were adjusted for age, sex, current residence, educational level, annual household income per capita, occupation, medical insurance, household size, marital status, smoking, drinking, regular sleep, family history of hypertension, family history of cardiovascular diseases, FBG, TC, TG, HDL-C, LDL-C, UA (TG and HDL-C were not adjusted for AIP because they were included in the formula; TG and FBG were not adjusted for TyG because they were included in the formula).

Discussion

To the best of our knowledge, this is the first study to compare 24 indicators simultaneously in a large Chinese survey. We comprehensively assess the associations between a wide range of conventional and unconventional anthropometric indicators and pre-hypertension or hypertension in Chinese adults. In this study, we found that pre-hypertension was associated with weight, BMI, HtaW, FMI, FFMI, AIP, and TyG, with BMI showing the strongest association, followed by TyG. For hypertension, significant associations were found with FM, AIP, and TyG, with TyG exhibiting a notably stronger association compared to other anthropometric indicators. The ROC results demonstrated that conventional anthropometric indicators such as weight and BMI still had good predictive performance for pre-hypertension, while TyG and AIP, as unconventional anthropometric indicators, also have guiding significance to identify pre-hypertension. For hypertension, FM (a conventional anthropometric indicator), along with AIP and TyG (unconventional anthropometric indicators), showed excellent predictive values. The RCS models revealed that weight, FMI, FFMI, AIP, and TyG were linearly related to the risk of pre-hypertension, whereas BMI and HtaW were nonlinearly related to pre-hypertension risk; FM, AIP, and TyG were nonlinearly related to the risk of hypertension.

Table 4 AUCs and Best Thresholds for Anthropometric Indicators in Relation to Pre-Hypertension and Hypertension

Variables	AUC	95% CI	Best Threshold	Sensitivity	Specificity
Pre-hypertension					
Weight	0.743	(0.730, 0.756)	0.522	0.723	0.653
BMI	0.741	(0.728, 0.753)	0.527	0.713	0.653
HtaW	0.727	(0.714, 0.740)	0.509	0.740	0.607
FMI	0.738	(0.725, 0.751)	0.505	0.739	0.625
FFMI	0.736	(0.723, 0.749)	0.486	0.768	0.593
AIP	0.726	(0.712, 0.739)	0.498	0.759	0.595
TyG	0.727	(0.714, 0.740)	0.523	0.716	0.633
Hypertension					
FM	0.905	(0.897, 0.913)	0.497	0.863	0.800
AIP	0.891	(0.882, 0.899)	0.498	0.848	0.785
TyG	0.893	(0.885, 0.901)	0.501	0.856	0.787

Note: Best threshold of predicted probability was adjusted for covariates.

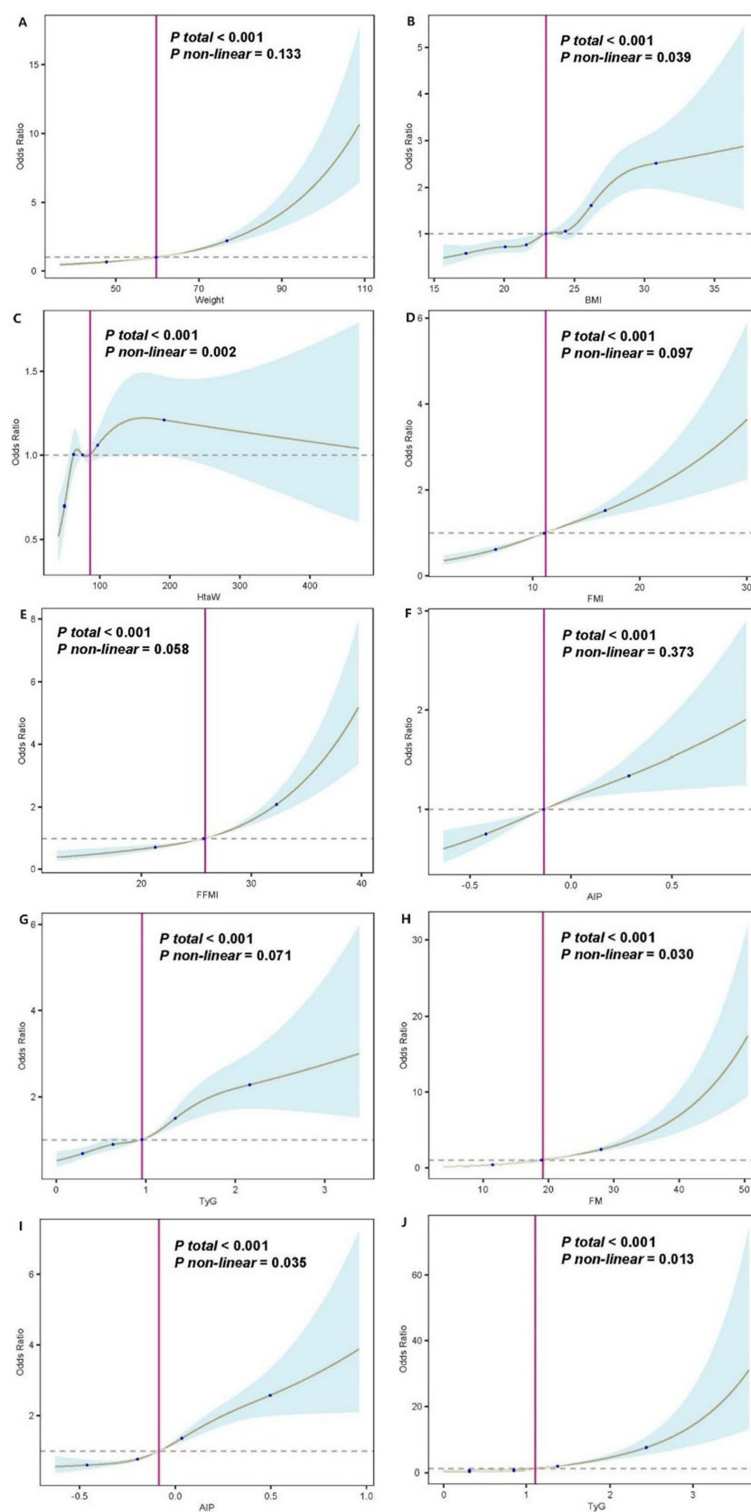


Figure 4 The restricted cubic splines of conventional and unconventional anthropometric indicators with the risk of pre-hypertension or hypertension.

Notes: The restricted cubic spline analyses were adjusted for age, sex, current residence, educational level, annual household income per capita, occupation, medical insurance, household size, marital status, smoking, drinking, regular sleep, family history of hypertension, family history of cardiovascular diseases, FBG, TC, TG, HDL-C, LDL-C, UA (TG and HDL-C were not adjusted for AIP because they were included in the formula; TG and FBG were not adjusted for TyG because they were included in the formula). (A) dose-response relationship between weight and the risk of pre-hypertension; (B) dose-response relationship between BMI and the risk of pre-hypertension; (C) dose-response relationship between HtaW and the risk of pre-hypertension; (D) dose-response relationship between FMI and the risk of pre-hypertension; (E) dose-response relationship between FFMI and the risk of pre-hypertension; (F) dose-response relationship between AIP and the risk of pre-hypertension; (G) dose-response relationship between TyG and the risk of pre-hypertension; (H) dose-response relationship between FM and the risk of hypertension; (I) dose-response relationship between AIP and the risk of hypertension; (J) dose-response relationship between TyG and the risk of hypertension.

Weight, as one of the most fundamental conventional anthropometric indicators, serves as the most straightforward measure of obesity in individuals. Several cohort studies have demonstrated that weight change was associated with the incidence and mortality of metabolic diseases such as diabetes and hypertension,^{39,40} as well as CVDs including coronary heart disease.⁴¹ In addition to being linked to the risk of disease in healthy populations, a prospective cohort study demonstrated that weight variability and weight change were both associated with higher risk of CVD mortality and all-cause mortality in individuals with hypertension.⁴² Another study also found that excessive weight can adversely affect kidney function through metabolic diseases.⁴³ This highlights the importance of daily weight management and monitoring individual weight changes, which are significant for both normotensive and hypertensive individuals. Although this study is a cross-sectional study, we still found that weight is an important predictor for pre-hypertension, suggesting that we should pay attention to our own weight and strive to maintain it within a normal range.

However, weight can only partially reflect overall obesity, and due to individual differences in height, using weight alone to predict hypertension risk is significantly biased. BMI and HtaW take into account the influence of height on weight, thereby partially addressing these shortcomings. Numerous cross-sectional studies have demonstrated that BMI was associated with pre-hypertension or hypertension.^{44–46} A cohort study indicated that the risk of hypertension was not only related to the magnitude of BMI growth but also to the rate of growth, and that the risk of hypertension decreased significantly with the reduction in BMI.⁴⁷ Moreover, either a persistently high BMI or a rapid increase in BMI from childhood to adulthood may have adverse long-term effects on the development of hypertension and CVDs.⁴⁸ However, no studies have yet explored the relationship between HtaW and hypertension or pre-hypertension. Our study found that both BMI and HtaW have good predictive value for pre-hypertension, highlighting the importance of obesity indicators that consider height in the risk assessment of hypertension.

Although this study identified through ROC curve analysis that weight and BMI exhibit the highest predictive efficacy for pre-hypertension compared to other conventional anthropometric indicators, previous research indicated that BMI merely represented overall obesity without distinguishing between the proportions of muscle and fat in an individual's weight, and this limitation gives rise to the obesity paradox, potentially introducing bias into the research outcomes.⁴⁹ FM refers to the total weight of all fat tissue within the body, typically measured using bioelectrical impedance analysis (BIA), dual-energy X-ray absorptiometry (DEXA), or skinfold thickness measurements. These methods provide a more accurate assessment of fat content, thereby evaluating individual obesity without the interference of muscle mass. FMI and FFMI, representing fat mass and fat-free mass adjusted for height, respectively, partially correct the bias caused by comparing FM across individuals of varying heights. Our study demonstrated that FMI and FFMI were predictive indicators for pre-hypertension risk, while FM was an indicator for hypertension risk, which aligns with the results of several other scholarly studies.^{16,50,51} Besides, some researchers investigated the associations between FMI, FFMI and hypertension, but their findings have been inconsistent,^{17,52,53} potentially due to differences in geographic regions, ethnicities, and study periods. However, our study does not support the predictive role of FMI and FFMI for hypertension risk. Future research should consider expanding the sample size to validate these findings in larger populations.

AIP is a biomarker composed of TG and HDL-C, which has been widely used in recent years to predict atherosclerosis and cardiovascular events, and has been demonstrated to have a higher predictive efficacy compared to individual lipid risk factors such as TG, TC, LDL-C, and HDL-C.³¹ Previous studies indicated that AIP was an important predictor of metabolic diseases such as hypertension, diabetes, and hyperuricemia,^{54–56} and was associated with all-cause mortality and CVD-specific mortality in patients with hypertension.⁵⁷ The multivariate logistic regression results of this study showed that AIP was negatively correlated with the risk of pre-hypertension or hypertension, which is contrary to previous research.⁵⁸ However, the results of univariate logistic regression, RCS plots, and subgroup analyses indicated that AIP was positively correlated with the risk of pre-hypertension or hypertension. The possible reason is that despite controlling for multicollinearity among independent variables by screening variables through LASSO regression before conducting multivariate logistic regression, some multicollinearity or interaction among the selected variables still exists due to the intrinsic characteristics of anthropometric indicators, which led to a change in the association direction between AIP and pre-hypertension or hypertension. Further exploration is needed to investigate whether there are interactions between AIP and other anthropometric indicators. TyG is a recently popular “star” anthropometric indicator,

combining TG and FBG, and has been identified as a reliable surrogate biomarker for insulin resistance.^{34,59} Recent studies have also shown that it was closely related to the development and prognosis of CVDs.⁶⁰ Several scholars investigated the association between TyG and hypertension,^{61,62} finding that TyG was an effective predictor of all-cause mortality in hypertensive patients.^{63,64} However, no studies have yet focused on whether TyG is associated with pre-hypertension. Our study found that TyG was associated with both pre-hypertension and hypertension. Moreover, compared to AIP, TyG showed a stronger association and better predictive performance for pre-hypertension and hypertension, further confirming that TyG can serve as an effective predictor of the risk of pre-hypertension and hypertension.

Even if the diagnostic criteria for hypertension are well established, some scholars recently questioned the “one-size-fits-all” approach of only using blood pressure measurements to determine the presence of the condition. This is particularly significant for populous countries like China, where changes in the diagnostic threshold for hypertension could lead to substantial fluctuations in the number of diagnosed patients. Therefore, in the context of precision medicine, we should consider adopting more scientific and reasonable methods for individualized prediction of hypertension. Based on the above discussion, our study suggested that utilizing anthropometric indicators to predict the risk of pre-hypertension/hypertension could provide new insights for more accurate and scientific hypertension prediction in the future. We also attempt to propose a decision chart for individualized prediction of pre-hypertension/hypertension (Figure 5). In future primary care practice, screening strategies should be further refined, for example, by combining BMI with TyG testing to achieve more precise hypertension prediction.

This study innovatively explored the association of 24 conventional and unconventional anthropometric indicators with pre-hypertension or hypertension. By extensively adjusting for known confounding factors, we employed multiple methods to identify the optimal anthropometric indicators for predicting pre-hypertension or hypertension, which enriched the theoretical research on predictive factors for pre-hypertension and hypertension, providing scientific evidence and reasonable recommendations for reducing the incidence of hypertension. However, there are still some limitations in this study. Firstly, as a cross-sectional study, it cannot establish causal relationships. Secondly, despite our efforts to collect currently known anthropometric indicators through literature review, some new indicators might not have been measured. Thirdly, despite extensive covariate adjustment, lifestyle factors (eg, dietary intake, stress, salt consumption) were not captured and could influence blood pressure. Fourthly, due to the lack of hip circumference data, some related anthropometric indicators such as waist-to-hip ratio (WHR), abdominal volume index (AVI), and body adiposity index (BAI) could not be included in this study. We will further improve the survey design in future research.

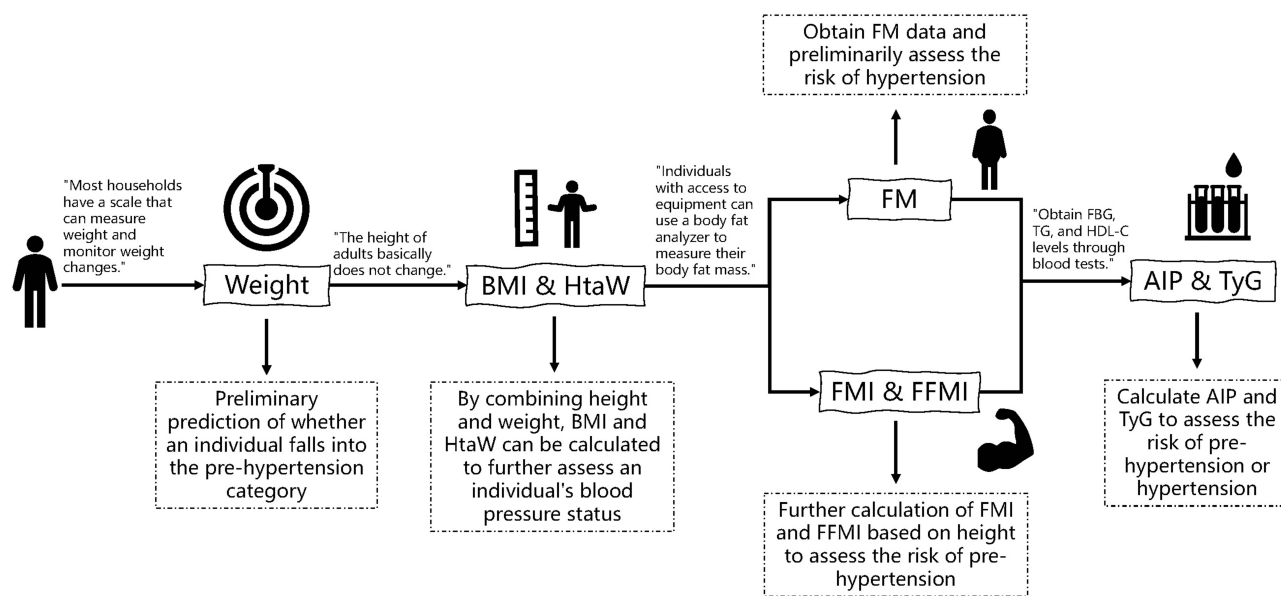


Figure 5 Decision diagram for individualized prediction of pre-hypertension/hypertension.

Lastly, it is undeniable that demographic characteristics may vary across different regions. Although our study subjects were selected through strict multi-stage stratified random sampling, it was limited to the population of Fujian Province. Therefore, caution should be exercised when generalizing the findings, and future studies should expand the sample size for further analysis.

In summary, the TyG index is emerging as a powerful marker for hypertension risk prediction and should be considered alongside conventional measures to strengthen primary care strategies.

Conclusions

In conclusion, this is one of the first comprehensive comparisons of 24 anthropometric indicators in a large Chinese population. We investigated the association of conventional and unconventional anthropometric indicators with the risk of pre-hypertension and hypertension in Chinese adults. Our results indicated that weight, BMI, HtaW, FMI, FFMI, AIP, and TyG were independently associated with pre-hypertension, among which the BMI and TyG had the strongest association with pre-hypertension, while hypertension was associated with FM, AIP, and TyG, with TyG showing a significantly stronger association with hypertension compared to other anthropometric indicators. Given the high prevalence of hypertension in China, simple conventional anthropometric measures still hold substantial potential for early population-level prevention. Emerging indicators such as TyG also deserve increased attention and could be integrated into existing clinical screening protocols to achieve more precise risk stratification, enabling clinicians to tailor lifestyle or therapeutic interventions accordingly. Future longitudinal studies are warranted to confirm causality and validate the predictive utility of novel indices such as TyG and AIP.

Abbreviations

CVD, cardiovascular disease; BMI, body mass index; WC, waist circumference; WHtR, waist-height ratio; BMR, basal metabolic rate; FM, fat mass; FFM, fat-free mass; FMI, fat mass index; FFMI, fat-free mass index; BFP, body fat percentage; VFI, visceral fat index; WCI, waist circumference index; WWI, weight-adjusted-waist index; BSA, body surface area; CI, conicity index; BRI, body roundness index; ABSI, a body shape index; AIP, atherogenic index of plasma; TyG, triglyceride-glucose index; TG, triglyceride; HDL-C, high-density lipoprotein cholesterol; FBG, fasting plasma glucose; LAP, lipid accumulation product; VAI, visceral adiposity index; CMI, cardiometabolic index; SBP, systolic blood pressure; DBP, diastolic blood pressure; TC, total cholesterol; LDL-C, low-density lipoprotein cholesterol; UA, uric acid; HtaW, height-adjusted weight; LASSO, least absolute shrinkage and selection operator; ROC, receiver-operating characteristic; RCS, restricted cubic spline; CNY, Chinese yuan; UEBMI, urban employees basic medical insurance; URRBMI, urban and rural residents basic medical insurance; AUC, area under curve; BIA, bioelectrical impedance analysis; DEXA, dual-energy x-ray absorptiometry; WHR, waist-to-hip ratio; AVI, abdominal volume index; BAI, body adiposity index.

Data Sharing Statement

The datasets used and/or analyzed during the current study are available from the corresponding author (Xian-E Peng) on reasonable request.

Ethics Approval and Consent to Participate

Ethics approval was obtained from the Ethics Committee of Fuwai Hospital (No. 2020-1360), and written informed consent was obtained from each participant. According to Item 2 of Article 32 of the Measures for Ethical Review of Life Science and Medical Research Involving Human Subjects dated February 18, 2023, our study is exempt from ethical review as it involves anonymized data (https://www.gov.cn/zhengce/zhengceku/2023-02/28/content_5743658.htm).

Acknowledgments

The authors would like to express their sincere gratitude to all the participants who wholeheartedly provided invaluable information and their collaboration in this research.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

Funding

This work was supported by the Project of the National Health Commission of the People's Republic of China (grant numbers: NHC2020-609) and the Special Funding Project of Fujian Provincial Department of Finance (grant numbers: BPB-HY2021).

Disclosure

The authors report no conflicts of interest in this work.

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