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Original Article

Cumulative triglyceride glucose waist-to-height ratio and hypertension risk in middle-aged and older Chinese adults

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Abstract: Objectives: The triglyceride-glucose waist-to-height ratio (TyG-WHtR) is a promising marker of insulin resistance and cardiometabolic risk. However, prospective evidence that links cumulative exposure to TyG-WHtR with incident hypertension is still limited, particularly among ageing populations. This study aimed to examine the prospective association between the cumulative average TyG-WHtR and the risk of developing hypertension in middle-aged and older Chinese adults. Methods: Data relating to 5,803 adults aged ≥ 45 years from the China Health and Retirement Longitudinal Study (CHARLS) was analysed. TyG-WHtR was calculated at baseline (2011) and follow-up (2015) and the exposure variable was the cumulative average. Incident hypertension between 2015 and 2018 was ascertained. RCS (restricted cubic spline) and multivariable logistic regression modelling were utilised to examine the relationship between hypertension risk and cumulative average TyG-WHtR. ROC (receiver operating characteristic) curve analysis was used to further assess predictive accuracy. Results: Hypertension was developed in 1,685 participants (29.0%) over a median follow-up period of 36.5 months. A higher cumulative average TyG-WHtR was substantially linked to an elevated risk of hypertension in a dose-dependent way. People in the highest quartile were found to have markedly higher odds of hypertension (fully adjusted OR = 1.73, 95% CI: 1.17-2.55, P = 0.006) than those in the lowest quartile. A positive linear correlation was validated using RCS analysis (P-overall = 0.007). The ROC curve showed there to be good predictive accuracy and the fully adjusted model yielded an AUC of 0.962 (95% CI: 0.955-0.969). Conclusion: The cumulative average TyG-WHtR is independently linked to incident hypertension in elderly and middle-aged Chinese people. This index could be an economical and accessible means for early risk assessment and prevention in community and clinical settings.

Keywords: TyG-WHtR, hypertension, insulin resistance, prospective cohort study, CHARLS

Introduction

Hypertension is a major modifiable risk determinant for all-cause mortality, stroke, and cardiovascular morbidity worldwide [1, 2]. Its burden is particularly pronounced among elderly and middle-aged people and they experience higher prevalence and complications associated with prolonged disease duration [3, 4]. Hypertension prevalence has progressively risen in China in the last 20 years, and knowledge, control and treatment rates remain suboptimal [5, 6]. Risk assessment and the early detection of those at risk for hypertension are essential if long-term healthcare burdens are to be reduced and to inform targeted public health interventions as China undergoes rapid demographic ageing [7, 8].

Insulin resistance (IR) is considered to be a central pathophysiological mechanism in hypertension development and contributes to elevated sympathetic activity, renal sodium retention and endothelial dysfunction [9-11]. The triglyceride-glucose (TyG) index is a dependable and affordable stand-in for IR and it is computed as ln (fasting triglyceride×fasting glucose/2) [12, 13]. Previous studies show that a higher

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triglyceride-glucose (TyG) index, a surrogate of insulin resistance, is associated with early vascular abnormalities and an increased risk of hypertension [14]. Cohort studies and meta-analyses further demonstrate that elevated TyG levels predict new-onset hypertension, suggesting that TyG-related metabolic disturbances may precede blood pressure elevation [15, 16]. In the Korean National Health and Nutrition Examination Survey, the TyG index was strongly associated with elevated blood pressure and prehypertension as well as established hypertension [17]. Moreover, higher TyG levels have been linked to surrogate markers of early vascular damage, including arterial stiffness and adverse vascular remodeling [18]. Mechanistically, insulin resistance may activate the sympathetic nervous system and the renin-angiotensin-aldosterone system, enhance renal sodium reabsorption, reduce nitric oxide bioavailability, and promote endothelial dysfunction and vascular remodeling, thereby increasing susceptibility to hypertension [19].

Triglyceride-glucose waist circumference (TyG-WC), triglyceride-glucose body mass index (TyG-BMI) and triglyceride-glucose waist-to-height ratio (TyG-WHtR) are composite indices that have recently been established as a means of better assessing the combined effects of central adiposity and metabolic dysfunction [20-22]. These integrated markers have demonstrated improved discriminatory capacity for the prediction of cardiovascular events, metabolic syndrome and type 2 diabetes compared to the TyG index alone [23, 24].

Despite a growing interest in TyG-based indices, the majority of previous studies have been reliant on single-point measurements, which are inherently vulnerable to short-term biological variability and potentially do not reflect chronic metabolic exposure [25, 26]. The use of cumulative average TyG-WHtR, which is derived from repeated assessments over time, provides a more stable indicator of long-term insulin resistance and adiposity. This approach serves to reduce random error, mitigate regression dilution bias and enhance risk estimate accuracy in longitudinal analyses.

The correlation between incident hypertension risk and cumulative average TyG-WHtR has not yet been thoroughly investigated, particularly among Chinese ageing populations. CHARLS is a prospective cohort that is nationally representative and has repeated biomarker assessments, and it provides an ideal platform for this type of investigation [27]. This investigation aims to investigate the connection between cumulative average TyG-WHtR and incident hypertension among elderly and middle-aged Chinese people and to further characterise this association through dose-response modeling.

Methods

Study population

CHARLS is a nationally representative longitudinal survey that was designed for assessing the socioeconomic situation and general health of elderly and middle-aged adults in China and is the basis for this secondary analysis. CHARLS uses multistage, probability-proportional-to-size sampling across 28 provinces to enrol community-dwelling Chinese adults. At the baseline, families with a minimum of one resident aged ≥ 45 years were chosen at random and all eligible members were invited to participate. A total of 150 counties (or districts) and 450 villages (or residential communities) were included in the first state-wide survey, which was conducted in 2011 (wave 1). Successful interviews with 17,708 participants from 257 households were completed. Subsequent follow-up surveys were performed biennially, including waves 2, 3 and 4 in 2013, 2015 and 2018, respectively.

Blood samples were taken from those in waves 1 and 3 and this yielded respective biological specimens from 11,847 and 13,420 individuals. Earlier publications have provided quite thorough documentation of the sampling methodology, anthropometric measurements and blood biomarkers of CHARLS [27].

Inclusion and exclusion criteria: Participants were included if they: (i) were aged ≥ 45 years at baseline; (ii) completed interviews, anthropometric assessments, and provided blood samples in both 2011 and 2015; and (iii) had complete biomarker data (fasting blood glucose, triglycerides, waist circumference, height, and blood pressure) required for TyG-WHtR calculation and hypertension assessment. Participants were excluded if they: (i) had physician-diagnosed hypertension or met blood

pressure criteria for hypertension in 2011 or 2013; (ii) lacked key biomarker or covariate data; or (iii) lacked follow-up hypertension information between 2015 and 2018.

Everyone provided written informed consent and the CHARLS study was authorised by the Institutional Review Board of Peking University. This investigation follows the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement recommendations [28].

Exposure assessment

TyG-WHtR was measured at Wave 1 (2011) and Wave 3 (2015), and the cumulative average - computed as the mean of the two measurements - was used to reflect long-term metabolic exposure. The TyG-WHtR is a composite indicator combining the triglyceride-glucose (TyG) index with the waist-to-height ratio (WHtR) to capture both insulin resistance and central adiposity. The TyG index was calculated as ln [fasting triglycerides (mg/dL) × fasting blood glucose (mg/dL)/2], and WHtR was computed as waist circumference (cm) divided by height (cm). TyG-WHtR was then derived by multiplying the TyG index by WHtR. This integrated indicator has been proposed to enhance risk discrimination by reflecting the combined effects of metabolic dysfunction and visceral fat accumulation. TyG-WHtR measurements from 2011 and 2015 were averaged to obtain the cumulative average value: (TyG-$WHtR_{2011}$ + TyG-$WHtR_{2015}$)/2.

Outcome assessment

The primary finding of this investigation was hypertension occurrence. Incident hypertension is described as a self-reported affirmative answer to the query: "Have you ever been diagnosed with hypertension by a doctor?", which is consistent with earlier studies [29, 30]. In addition, individuals who gave particular responses to questions regarding treatments for hypertension and its complications, including "Traditional Chinese medicine/Western medicine/physical therapy/acupuncture/occupational therapy/none of the above", were classified as hypertensive. Participants with a baseline average Systolic BP of ≥ 140 mmHg or a diastolic BP of ≥ 90 mmHg were also identified as hypertensive [31]. Incident hypertension was ascertained between wave 3 (2015) and wave 4 (2018). Any participants who reported a prior physician diagnosis of hypertension or meeting BP criteria in 2011 or 2013 were excluded from the analytic cohort.

Data collection

Unless otherwise noted, all covariates were obtained at the 2015 baseline interview and physical examination. The data gathered in this investigation is as follows: (i) Demographic data consisting of sex, education, age, marital status and place of residence (household registration). On the basis of educational attainment, three categories of college or higher, elementary school or lower and middle school were formed. Married and other marital statuses (including single, separated, divorced and widowed) were the two marital status categories. (ii) Lifestyle information relating to drinking and smoking patterns, which were categorised as current, never or former, was obtained. (iii) Anthropometric measurements were taken, which included BMI, systolic BP and diastolic BP. (iv) In addition to hypoglycaemic, lipid-lowering and antihypertensive therapies, medical history data was gathered regarding the occurrence of liver and heart diseases, dyslipidaemia and diabetes. (v) Laboratory assessments included glycated haemoglobin (HbA1c), TC, FBG, LDL-c, TG, HDL-c and TC measurements [32].

Handling of missing information

A thorough explanation of the amount of missing data in this analysis is provided in Table S1. Although there was only a slight degree of incompleteness for most variables, multiple imputation was utilised to increase the sample size, which served to enhance the accuracy and representativeness of the findings [33].

Statistical analysis

The study population was stratified into 4 categories (Q1-Q4) based on TyG-WHtR quartiles. Data was displayed as mean ± standard deviation (SD) for analysis of variance (ANOVA) and continuous variables with a normal distribution was used for assessing group differences. Categorical variables were stated as numerical

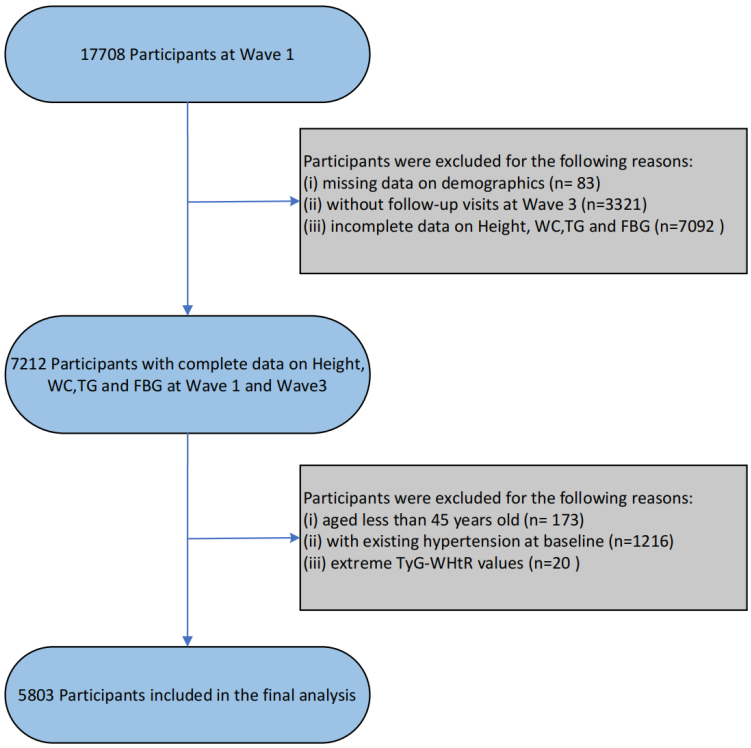

Figure 1. Flowchart of the study population.

values (percentages) and intergroup disparities were analysed using Pearson's chi-square test.

Logistic regression models were utilised for investigating the link between cumulative TyG-WHtR and hypertension. Multiple models were developed and they were each adjusted for a distinct set of covariates in order to offer a nuanced comprehension of the ways these covariates impact the link. The core components used to derive the TyG-WHtR - fasting glucose, triglycerides, height and waist circumference - were eliminated from all regression models to minimise multicollinearity and avoid overadjustment. Model 1 included adjustments for sex and age to control for basic demographic confounders, while Model 2 added more clinical and sociodemographic factors, including residence type, alcohol and smoking consumption status, educational attainment, marital status, a history of diabetes, dyslipidaemia, cardiovascular, renal or hepatic conditions and body mass index. Model 3 further refined the adjustment set through the addition of information relating to medication use (glucose- and lipid-lowering therapies) and laboratory biomarkers such as total cholesterol, HbA1c, LDL-c, and HDL-c. ROC curve analysis was used for assessing the discriminative performance of each model in the prediction of hypertension - the AUC was employed as a summary measure of predictive accuracy.

In the multicollinearity assessment, the variance inflation factors (VIFs) for all determinants that were included in the analysis were determined to be below 5 (Table S2), thereby indicating no significant evidence of multicollinearity [34].

A multivariable-adjusted RCS LR analysis was also performed as a means of analysing the linear correlation and dose-response correlation between hypertension incidence and the cumulative average TyG-WHtR. R software (version 4.3.1) and MSTATA software (www.mstata.com) were used for all analyses. A two-sided *P*-value of less than 0.05 was considered to be statistically significant.

Results

Baseline characteristics of participants

The flowchart for the study population screening procedure is shown in **Figure 1**. There were 5,803 study participants. A total of 3,189 (55.0%) of those in the final analytic cohort were female and there was a mean (SD) age of 63 (9.1) years.

Table 1 shows the baseline participant characteristics, stratified by quartiles of cumulative average TyG-WHtR. All participants had an overall mean (SD) cumulative average TyG-WHtR of 4.71 (0.81). Participants in the upper quartiles of cumulative average TyG-BMI (Q2-Q4) were most likely to be female, live in an urban area and be younger than those in the lowest quartile (Q1). These groups had higher SBP, DBP, FBG, TC, TG, HbA1c and LDL-c values and lower HDL-c levels. In addition, the prevalence of cardiovascular and liver diseases and

Table 1. Baseline characteristics of participants classified by quartiles of the cumulative average TyG-WHtR

Characteristic	Quartiles 1 (n = 1474)	Quartiles 2 (n = 1451)	Quartiles 3 (n = 1457)	Quartiles 4 (n = 1421)	*p*-value
Gender (Female)	530 (36.0%)	731 (50.4%)	883 (60.6%)	1,045 (73.5%)	< 0.001
Age, years	63 ± 9	62 ± 9	62 ± 9	63 ± 9	0.007
Residence (Urban)	377 (25.6%)	434 (29.9%)	543 (37.3%)	578 (40.7%)	< 0.001
Current married	1,227 (83.2%)	1,171 (80.7%)	1,194 (81.9%)	1,158 (81.5%)	0.342
DBP, mmHg	72 ± 12	74 ± 11	76 ± 12	78 ± 11	< 0.001
SBP, mmHg	122 ± 19	126 ± 20	129 ± 20	134 ± 20	< 0.001
FBG, mg/dL	94 ± 22	98 ± 24	103 ± 32	121 ± 52	< 0.001
TC, mg/dL	175 ± 33	182 ± 34	189 ± 35	196 ± 40	< 0.001
TG, mg/dL	91 ± 43	116 ± 58	152 ± 81	219 ± 115	< 0.001
HDL-c, mg/dL	56 ± 14	53 ± 12	50 ± 10	47 ± 9	< 0.001
LDL-c, mg/dL	97 ± 27	104 ± 27	107 ± 29	105 ± 31	< 0.001
HbA1c, %	5.76 ± 0.63	5.81 ± 0.63	5.97 ± 0.92	6.53 ± 1.46	< 0.001
BMI, kg/m^2	20.6 ± 3.0	22.8 ± 5.7	24.6 ± 2.8	28.3 ± 19.7	< 0.001
Diabetes	61 (4.2%)	78 (5.5%)	139 (9.8%)	301 (21.8%)	< 0.001
Dyslipidemia	144 (10.1%)	205 (14.7%)	325 (23.2%)	519 (37.8%)	< 0.001
Heart disease	194 (13.4%)	230 (16.2%)	288 (20.2%)	369 (26.4%)	< 0.001
Kidney disease	159 (11.0%)	150 (10.5%)	145 (10.1%)	149 (10.6%)	0.884
Liver disease	121 (8.2%)	97 (6.7%)	114 (7.8%)	144 (10.1%)	0.008
Glucose-lowering treatment	34 (2.4%)	34 (2.5%)	79 (5.7%)	225 (16.7%)	< 0.001
Lipid-lowering treatment	50 (3.6%)	68 (5.1%)	115 (8.7%)	254 (19.6%)	< 0.001
Education level					0.199
College or above	12 (0.8%)	12 (0.8%)	17 (1.2%)	9 (0.6%)	
Elementary school or below	1,357 (92.1%)	1,319 (90.9%)	1,314 (90.2%)	1,319 (92.8%)	
Middle school	105 (7.1%)	120 (8.3%)	126 (8.6%)	93 (6.5%)	
Smoking status					< 0.001
Current	591 (40.1%)	416 (28.7%)	308 (21.1%)	203 (14.3%)	
Former	267 (18.1%)	245 (16.9%)	240 (16.5%)	203 (14.3%)	
Never	615 (41.8%)	787 (54.4%)	909 (62.4%)	1,014 (71.4%)	
Drinking status					< 0.001
Current	644 (43.8%)	497 (34.3%)	435 (29.9%)	317 (22.4%)	
Former	185 (12.6%)	180 (12.4%)	184 (12.6%)	162 (11.4%)	
Never	641 (43.6%)	773 (53.3%)	838 (57.5%)	938 (66.2%)	

Abbreviations: TyG-WHtR: triglyceride glucose-waist height ratio; DBP: diastolic blood pressure; SBP: systolic blood pressure; BMI: body mass index; FBG: fast blood glucose; HbA1c: glycated haemoglobin; HDL-C: high-density lipoprotein cholesterol; LDL-C: low-density lipoprotein cholesterol; TC: total cholesterol; TG: triglyceride.

dyslipidaemia and diabetes was significantly higher in these groups (all *p*-values < 0.05). However, there was no statistically significant change in the prevalence of kidney disease between quartiles.

Association between hypertension incidence and cumulative average TyG-WHtR

In total, 1,685 participants (29.0%) developed hypertension during a median follow-up period of 36.5 months between 2015 and 2018. The incidence of hypertension showed a progressive increase across the quartiles of cumulative average TyG-WHtR. More specifically, the number of hypertension cases rose steadily from quartile 1 to quartile 4, with 214 cases (14.5%) in quartile 1, 307 cases (21.2%) in quartile 2, 469 cases (32.2%) in quartile 3 and 695 cases (48.9%) in quartile 4 (**Table 2**).

According to the fully adjusted LR model (Model 3), higher cumulative average TyG-WHtR (Q2-Q4) levels were found to be linked to an elevat-

Table 2. Association between cumulative TyG-WHtR and hypertension

Cumulative TyG-BMI	N	Event N	Model 1			Model 2			Model 3		
			OR	95% CI	*p*-value	OR	95% CI	*p*-value	OR	95% CI	*p*-value
Quartiles 1	1474	214	Reference			Reference			Reference		
Quartiles 2	1451	307	1.67	1.37, 2.03	< 0.001	1.36	1.08, 1.70	0.009	1.36	0.86, 2.16	0.191
Quartiles 3	1457	469	3.08	2.55, 3.72	< 0.001	2.15	1.67, 2.75	< 0.001	1.94	1.15, 3.25	0.012
Quartiles 4	1421	695	6.16	5.10, 7.45	< 0.001	3.37	2.50, 4.53	< 0.001	2.25	1.17, 4.34	0.016
P for trend					< 0.001			< 0.001			0.009
Continuous	5803	1685	2.41	2.22, 2.63	< 0.001	1.95	1.66, 2.28	< 0.001	1.73	1.17, 2.55	0.006
Per 1 SD increase											

Model 1: adjusted for Gender and Age. Model 2: adjusted for Gender, Residence, Age, Diabetes, Heart disease, Dyslipidemia, Kidney disease, Education level, Liver disease, Marital status, and Body mass index (BMI). Model 3: adjusted for Gender, Residence, Age, Diabetes, Heart disease, Dyslipidemia, Kidney disease, Hypoglycemic treatment, Lipid-lowering treatment, Total cholesterol (TC), Glycated haemoglobin (HbA1c), Low density lipoprotein cholesterol (LDL-c), and High density lipoprotein cholesterol (HDL-c), Liver disease, Education level, Marital status, Smoking status, Drinking status, and BMI.

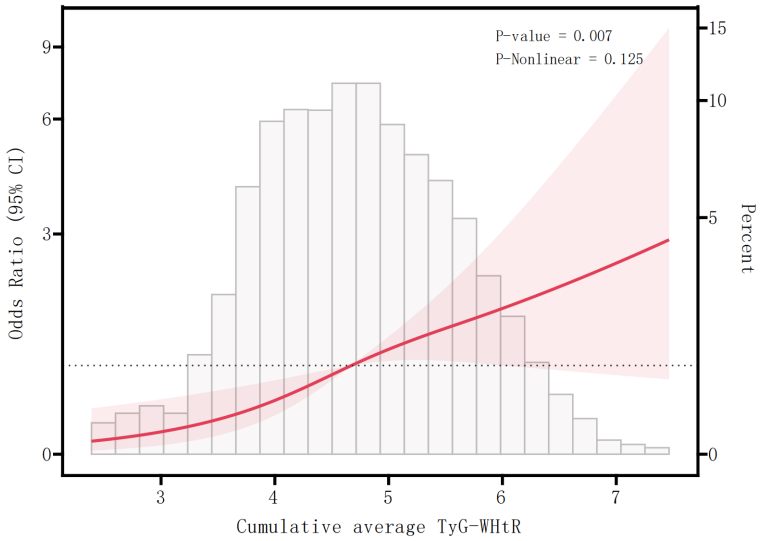

Figure 2. The RCS analysis between the cumulative average TyG-WHtR and hypertension incidence. The model was adjusted for Gender, Residence, Age, Diabetes, Heart disease, Dyslipidemia, Kidney disease, Hypoglycemic treatment, Lipid-lowering treatment, TC, HDL-c, LDL-c, HbA1c, Liver disease, Education level, Marital status, Smoking status, Drinking status, and BMI.

ed OR for the development of hypertension in comparison to Q1 after adjusting for several covariates. Taking cumulative average TyG-WHtR as a continuous variable, each one SD rise was considerably linked to elevated odds of hypertension development. More specifically, the adjusted odds ratio (OR) was 2.41 (95% confidence interval (CI): 2.22-2.63, P < 0.001) in Model 1, 1.95 (95% CI: 1.66-2.28, P < 0.001) in Model 2 and 1.73 (95% CI: 1.17-2.55, P = 0.006) in Model 3. The fully adjusted RCS regression model showed a positive linear link between hypertension incidence and cumulative average TyG-WHtR (overall P =0.007, non-linear P = 0.125) (**Figure 2**). The ROC curve showed that all three models had a high predictive ability for hypertension (AUC > 0.7), Model 3 having the best predictive ability (AUC 0.962, 95% CI 0.955-0.969) (**Figure 3**).

Discussion

A higher cumulative average TyG-WHtR was discovered to be linked to a higher incident hypertension risk among this cohort of elderly and middle-aged Chinese people. This relationship served to demonstrate a positive linear dose-response pattern, which was further confirmed by RCS analysis. Furthermore, the cumulative average TyG-WHtR indicated strong discriminatory power for hypertension prediction, the fully adjusted model yielding an AUC of 0.62, which indicates excellent predictive performance.

This study contributes to the increasing amount of literature that links TyG-derived indices with hypertension risk. Huang et al. conducted a large-scale cross-sectional analysis that used NHANES data from U.S. adults aged 18-60 years, which supports the findings of this study. They noted that each unit rise in TyG-WHtR

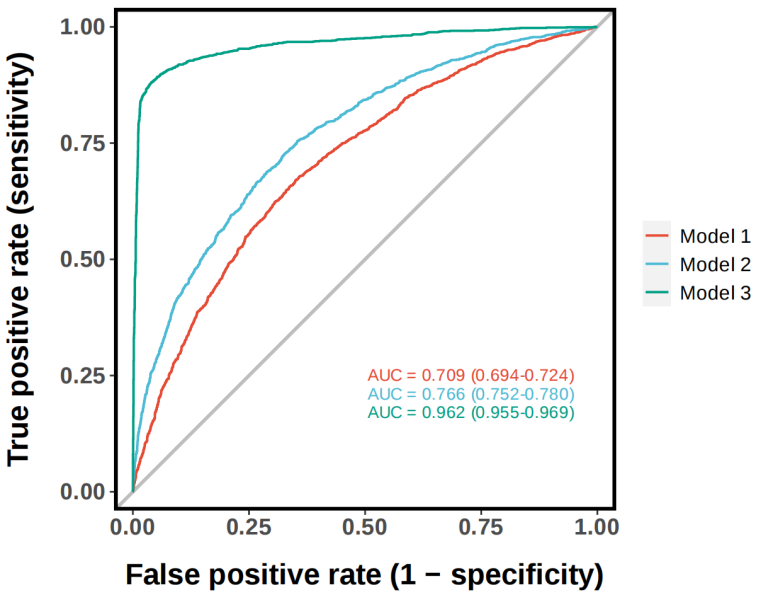

Figure 3. Receiver operating characteristic curves for the 3 Models predicting hypertension.

had a correlation with a 12% higher hypertension risk, with TyG-WHtR exhibiting the best predictive performance among all TyG-based parameters (AUC = 0.694) [35]. Miao et al. investigated various TyG-related indices among a Chinese adult population and noted that higher TyG-WHtR levels have a significant correlation with a higher hypertension risk. Although TyG-WC demonstrated the best diagnostic accuracy for hypertension (AUC = 0.665), TyG-WHtR was still among the top predictive indicators [36].

This study advances existing literature in several important ways, despite the consistency in directionality. Firstly, unlike previous studies, which were reliant on single-point exposure assessment, the cumulative average of TyG-WHtR based on two time points over a four-year period was used, which allowed for a more robust and stable representation of long-term metabolic burden. This approach served to reduce the likelihood of measurement error and improve exposure accuracy, which is of particular relevance for chronic disease aetiology. Secondly, while previous studies were cross-sectional in design, which limited causal inference, this study employed a prospective cohort design, which enabled the temporal analysis of TyG-WHtR and subsequent hypertension incidence. Thirdly, the study focused on elderly and middle-aged Chinese people (≥ 45 years) and used nationally representative data from the CHARLS cohort, which expanded the generalisability of TyG-WHtR to ageing populations in low- and middle-income settings.

Several biological mechanisms could potentially explain the observed correlation between higher cumulative TyG-WHtR and increased hypertension risk. Firstly, the TyG index is a validated substitute marker for IR, which is a major contributor to hypertension pathogenesis. IR can activate the sympathetic NS, promote renal sodium reabsorption and impair endothelial function, which results in increased peripheral VR and elevated blood pressure [37, 38]. Secondly, the waist-to-height ratio component of TyG-WHtR captures central adiposity, which is metabolically active and linked to oxidative stress, chronic low-grade inflammation and dysregulated adipokine secretion. These are factors that further exacerbate vascular dysfunction and blood pressure dysregulation [39, 40].

The use of cumulative average TyG-WHtR reflects long-term exposure to both metabolic disturbance and visceral adiposity, which is an important factor. This approach may better represent the chronic metabolic environment that contributes to sustained vascular damage and progressive elevation in blood pressure, compared to single-point measurements. This long-term burden of insulin resistance and central obesity could lead to vascular remodelling, arterial stiffness and impaired baroreflex sensitivity, which are physiological changes that are often irreversible and central to hypertension development [41].

Beyond these mechanisms, our findings suggest that cumulative average TyG-WHtR may more effectively capture chronic metabolic stress than single measurements. Individuals with persistently elevated TyG-WHtR may be exposed to prolonged insulin resistance and

central adiposity, leading to sustained vascular injury and progressive increases in arterial stiffness. This highlights that metabolic dysregulation is not a static condition but a continuous process requiring ongoing evaluation rather than one-time assessment. From a clinical perspective, the cumulative TyG-WHtR may help identify individuals whose cardiometabolic risk is underestimated by cross-sectional indicators. Our findings support the importance of long-term metabolic monitoring and underscore the potential value of targeting persistent metabolic abnormalities in hypertension prevention strategies.

Due to its simplicity, low cost and reliance on clinical data that is routinely available, the TyG-WHtR index has promise as a feasible screening tool for determining people who have a higher risk of hypertension in community and primary care settings. Hypertension prevalence continues to rise and early detection remains suboptimal in China [42], so the incorporation of cumulative average TyG-WHtR into routine health evaluations may help with risk stratification, early warning and timely lifestyle intervention.

A prospective design, a nationally representative cohort and the use of cumulative average TyG-WHtR to better reflect long-term metabolic exposure proved to be beneficial in this study. The results were also made more credible by thorough covariate adjustment. However, several limitations must be recognised. Firstly, hypertension diagnosis was partly reliant on self-reported drug usage and physician diagnosis, which could have introduced misclassification bias. However, blood pressure measurements were also incorporated to mitigate this concern, but undiagnosed or misreported cases cannot be entirely excluded. Secondly, the exposure metric - TyG-WHtR - was only calculated at two time points, which potentially limited its ability to fully capture long-term metabolic variability. Thirdly, residual confounding remains possible, as certain variables such as physical activity, psychosocial stress, dietary intake and family history of hypertension were unavailable or inadequately captured in the CHARLS dataset. Finally, the outcomes of this study may not apply directly to younger individuals or non-Chinese people, so external validation in other cohorts is warranted.

Conclusion

This investigation offers prospective proof that an elevated cumulative average TyG-WHtR is independently linked to a higher incident hypertension risk among elderly and middle-aged Chinese people. TyG-WHtR is a simple and accessible surrogate marker that reflects the long-term metabolic burden and it may be a helpful tool for early hypertension risk stratification. Future studies should clarify the biological processes that are at play, confirm these results in a variety of groups and investigate the use of TyG-WHtR in targeted prevention and intervention strategies.

Disclosure of conflict of interest

None.

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Table S1. Distribution of variables with missing data

Variables	Number of Missing	Missing proportion
Age	3	0.05%
Diabetes	146	2.52%
Dyslipidemia	219	3.77%
Heart disease	117	2.02%
Kidney disease	97	1.67%
Hypoglycemic treatment	71	1.22%
Lipid-lowering treatment	122	2.10%
Antihypertensive treatment	146	2.52%
DBP	61	1.05%
SBP	61	1.05%
HbA1c	6	0.10%
Smoking status	5	0.09%
Drinking status	9	0.15%

Table S2. Collinearity statistics

Variables	GVIF	Df	$GVIF^{1/2Df}$
Cumulative average TyG-WHtR	2.160736	1	1.469944
Gender	2.831285	2	1.682642
Residence	1.048460	1	1.023943
Age	1.217151	1	1.103246
Diabetes	3.129219	1	1.768960
Heart disease	1.066728	1	1.032825
Dyslipidemia	1.870564	2	1.367686
Kidney disease	1.035871	1	1.017778
Hypoglycemic treatment	1.028438	1	1.014119
Lipid-lowering treatment	1.088268	1	1.043201
TC	1.111862	1	1.054448
HDL-c	2.390991	1	1.546283
LDL-c	1.452788	1	1.205317
HbA1c	4.892351	2	2.211866
Liver disease	1.649356	1	1.284273
Education level	1.340133	1	1.157641
Marital status	3.171702	2	1.780927
Smoking status	1.816118	1	1.347634
Drinking status	1.798458	1	1.434888
BMI	2.697238	1	1.642327

Abbreviations: TyG-WHtR, triglyceride glucose-waist height ratio; HbA1c, glycosylated hemoglobin A1c; TC, total cholesterol; TG triglyceride; HDL-c, high-density lipoprotein cholesterol; LDL-c, low-density lipoprotein cholesterol.