Cardiovascular Diabetology

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The synergistic effect of the triglyceride-glucose index and a body shape index on cardiovascular mortality: the construction of a novel cardiovascular risk marker

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Abstract

Background Insulin resistance, represented by increased triglyceride-glucose (TyG) index levels, shows interplay with visceral obesity and together promotes cardiovascular diseases and mortality. However, significant controversies exist regarding whether modified TyG indices, such as TyG-BMI, TyG-WC, and TyG-WHtR, outperform the TyG index in predicting cardiovascular outcomes. We aimed to explore whether there was a synergistic effect of a body shape index (ABSI), a better parameter reflecting visceral obesity, and the TyG index on cardiovascular mortality.

Methods We analyzed data from the National Health and Nutrition Examination Survey (NHANES) 2001–2018 of 17,329 individuals. The associations of the TyG index and ABSI with cardiovascular mortality were investigated via Cox regression analysis and restricted cubic splines. Receiver operating characteristic (ROC) curve analysis was performed to compare the predictive value. Mediation analysis was used to explore the potential mediator.

Results A total of 673 (3.9%) cardiovascular deaths occurred during a median follow-up of 8.92 years. Individuals with high TyG and high ABSI (TyG > 9.04 and ABSI > 0.085) were at the highest cardiovascular mortality risk both in individuals with (HR = 1.714, 95% CI 1.123–2.616) and without diabetes (HR = 1.402, 95% CI 1.003–1.960), suggesting a synergistic effect. Next, we multiplied these two indicators and established TyG-ABSI. It showed a J-shaped relationship and a positive linear relationship with cardiovascular mortality in individuals with and without diabetes, respectively. Arterial stiffness, represented by estimated pulse wave velocity, partially mediated the effect of TyG-ABSI on cardiovascular mortality, with a mediation proportion of 42.7%. The predictive value of TyG-ABSI was greater than that of the TyG index, TyG-BMI, TyG-WC, and TyG-WHtR (Harrell's C-index: 0.710 *vs* 0.623 *vs* 0.539 *vs* 0.612 *vs* 0.622, all $p < 0.001$).

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Conclusions The simultaneous assessment of the TyG index and ABSI revealed a synergistic effect on cardiovascular mortality. We recommended the use of TyG-ABSI instead of the TyG index and other modified TyG indices in cardiovascular risk assessment.

Keywords Triglyceride-glucose index, A body shape index, Arterial stiffness, NHANES, Cardiovascular mortality

Introduction

Insulin resistance is characterized by a reduced sensitivity of peripheral tissues to insulin action, leading to impaired glucose uptake and utilization. It serves as a significant risk factor for the development of cardiovascular diseases and mortality [1, 2]. Therefore, identifying patients with insulin resistance could help in cardiovascular risk stratification.

Simple, non-invasive methods such as the homeostatic model assessment of insulin resistance (HOMA-IR) [3] and the triglyceride-glucose (TyG) index [4] are frequently employed to assess insulin sensitivity. Among them, the TyG index, unaffected by insulin treatment, is more widely utilized and has been shown to be associated with cardiovascular diseases and outcomes [5, 6]. In addition to metabolic biomarkers such as triglycerides and glucose, which are included in the formula of the TyG index [4], body fat content and distribution (particularly visceral fat) are also closely related to insulin resistance, cardiovascular diseases, and cardiovascular mortality [7–9]. Dyslipidemia and insulin resistance may be manifested in seemingly healthy obese individuals, but they may not have glucose metabolism disorders [10]. Conversely, insulin secretion defects can lead to glucose metabolism disorders and hyperglycemia without the presence of obesity, dyslipidemia, and insulin resistance [10]. Therefore, a comprehensive assessment of glucose levels, lipid levels, obesity, and insulin resistance is essential for accurate cardiovascular risk stratification.

In light of the interplay between insulin resistance and obesity, an increasing number of studies have aimed to elucidate whether combining the TyG index with traditional obesity-related parameters (such as body mass index [BMI], waist circumference [WC], and waist-to-height ratio [WHtR]) can improve the risk stratification of cardiovascular outcomes. Several studies have suggested that the combination of them provides a superior assessment of cardiovascular risk than the TyG index alone [11, 12], whereas others come to contrasting conclusions [13–15]. Consequently, there is currently no consensus on whether to use the combination of the TyG index and traditional obesity-related parameters instead of the TyG index to predict cardiovascular risk.

An important manifestation of visceral obesity is excessive abdominal fat deposition. Traditional anthropometric measures of abdominal obesity, including WC and WHtR, are strongly correlated with BMI, limiting their ability to evaluate visceral fat content independent of BMI [16]. Consequently, none of them are optimal for assessing cardiovascular risk.

To overcome the limitations of traditional obesity-related metrics, Krakauer et al. [17] introduced a new anthropometric measure, a body shape index (ABSI), which standardizes WC using BMI and height and reflects visceral fat content independent of BMI. It has been proven to be independently associated with mortality [17]. Compared with BMI, WC, and WHtR, ABSI focuses more on abdominal obesity, controlling for the confounding effects of weight and height, thereby demonstrating a stronger association with increased cardiovascular risk and mortality [18–21]. However, (1) it remains unclear whether insulin resistance (as represented by the TyG index) and visceral obesity (as represented by ABSI) exert a synergistic effect on cardiovascular mortality; (2) it is uncertain whether the newly constructed parameter, the TyG-ABSI, is superior to the TyG index and other TyG-derived indices; (3) the underlying mechanisms by which TyG-ABSI may contribute to increasing cardiovascular risk remain unknown. Based on the National Health and Nutrition Examination Survey (NHANES) database, this study aims to determine whether the combination of the TyG index and ABSI contributes to improving cardiovascular risk stratification, as well as explores the underlying mechanism of the association of insulin resistance and visceral obesity (as represented by TyG-ABSI) with cardiovascular mortality.

Methods

Study population and design

The NHANES is an ongoing, serial, cross-sectional survey conducted by the National Center for Health Statistics, which uses a complex, stratified, multistage, probability sampling design to select participants representative of the civilian non-institutionalized population of the United States. It was approved by the National Center for Health Statistics Ethics Review Board. Before participation, written informed consent was obtained from all participants. For the current study, we utilized publicly available data from the NHANES 2001–2018. The flowchart of inclusion and exclusion of the participants is shown in Fig. 1. We excluded (1) participants < 20 years (n = 41,150); (2) participants who were pregnant (n = 1258); (3) participants with malignancy (n = 4758); (4) participants with missing data for the variable of interest (variables needed for the TyG index, ABSI, and estimated pulse wave velocity [ePWV] calculation)

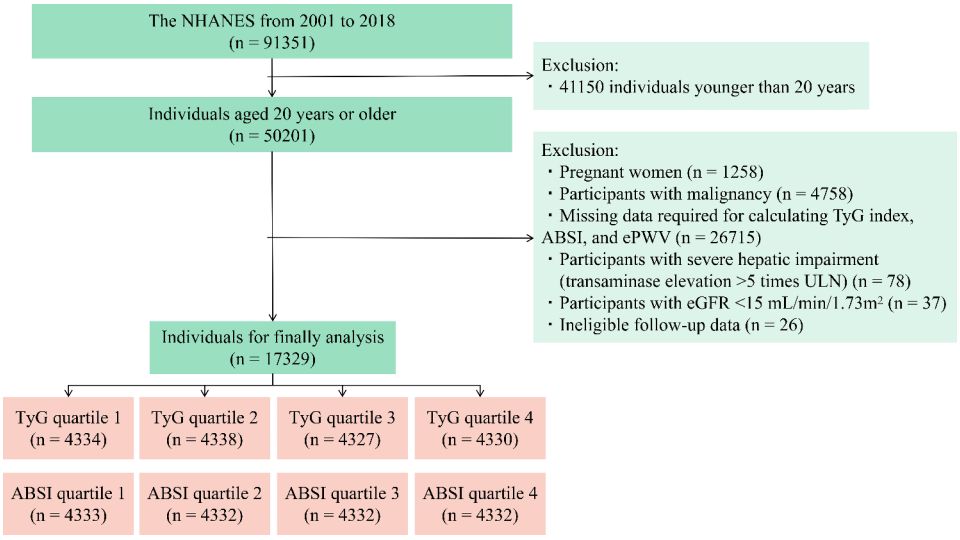

Fig. 1 Flowchart of the inclusion and exclusion process. ABSI, a body shape index; eGFR, estimated glomerular filtration rate; ePWV, estimated pulse wave velocity; NHANES, National Health and Nutrition Examination Survey; TyG, triglyceride-glucose; ULN, upper limit of normal

(n = 26,715); (5) participants with significantly impaired liver (transaminase elevation > 5 times the upper limit of normal) (n = 78) or renal function (estimated glomerular filtration rate [eGFR] < 15 mL/min/1.73 m^2) (n = 37); and (6) participants with incomplete or missing follow-up data (n = 26). The final sample of participants included in this analysis was 17,329.

The calculation of insulin resistance indices and obesity-related parameters.

(1) TyG index = Ln [fasting triglyceride (mg/dL) × fasting glucose (mg/dL)/2] [4];
(2) TyG-BMI = TyG index × BMI [22];
(3) TyG-WC = TyG index × WC (cm) [22];
(4) TyG-WHtR = TyG index × WC (cm)/height (cm) [22];
(5) HOMA-IR = (fasting glucose [mmol/L] × fasting insulin [μU/mL])/22.5 [3];
(6) ABSI = WC (cm)/(BMI $^{2/3}$ × height $^{1/2}$ [cm]) [17].

Previous studies have reported that the anthropometric risk index (ARI), which incorporated 4 anthropometric parameters (height, weight, WC, and hip circumference), outperformed ABSI for predicting mortality in the general population [23]. Therefore, we also calculated ARI for each individual using the method proposed by Krakauer et al. [23]. The complete ARI was calculated as the sum of the natural logarithm of hazard ratio (HR) for cardiovascular mortality based on height, BMI, ABSI, and hip index [23]. However, in the NHANES 2001–2018 sample, only the data from the 2017–2018 circle includes hip circumference, preventing us from computing complete ARI. In the current study, truncated ARI was calculated based only on height, BMI, and ABSI, as has been suggested in prior literature [23].

Well-trained medical professionals performed anthropometric measurements and laboratory tests at the mobile examination centers. The participants fasted overnight (for at least 8 h) to obtain their fasting glucose, fasting triglyceride, and fasting insulin values. A standard method was used to measure height, weight, and WC (detailed anthropometric measurement methods are available at the NHANES website: http://www.cdc.gov/nchs/nhanes).

Definitions of covariates

Information on demographic characteristics, health-related behaviors, medical history, and medication use was collected via standardized questionnaires. Smoking status was categorized as current (≥ 100 lifetime cigarettes and currently smoking), former (≥ 100 lifetime cigarettes and currently not smoking), or never (< 100 lifetime cigarettes). At the individual interview, participants were asked "Has a doctor or other health professional ever told you that you had congestive heart failure/coronary heart disease/angina pectoris/myocardial infarction/stroke?" If one of the answers was positive, the individual was defined as having cardiovascular disease. Diabetes was defined by one of the following criteria: (1) an elevated plasma glucose concentration (fasting ≥ 126 mg/dL, random ≥ 200 mg/dL, or ≥ 200 mg/dL after 2 h of oral glucose tolerance test); (2) glycated hemoglobin A1c (HbA1c) ≥ 6.5%; (3) self-report of a physician diagnosis; or (4) treatment with insulin or oral antidiabetic drugs. Hypertension was defined by one of the following criteria: (1) systolic blood pressure ≥ 140 mmHg or diastolic blood pressure ≥ 90 mmHg; (2) self-report of a physician diagnosis; or (3) treatment with antihypertensive drugs. Antidiabetic drugs include

insulin, metformin, sulfonylureas, thiazolidinediones, dipeptidyl peptidase-4 inhibitors, alpha-glucosidase inhibitors, glucagon-like peptide-1 receptor agonists, and sodium-glucose cotransporter-2 inhibitors. Antihyperlipidemic drugs include statins, ezetimibe, and fibrates. Antihypertensive drugs include angiotensin-converting enzyme inhibitors or angiotensin receptor blockers, beta-blockers, calcium channel blockers, diuretics, and alpha-blockers. The eGFR was calculated using the modified Modification of Diet in Renal Disease equation [24].

Study endpoint

The endpoint in this study was cardiovascular mortality, which was identified according to the International Statistical Classification of Diseases and Related Health Problems, Tenth Revision (ICD-10) codes, including heart diseases (I00-I09, I11, I13, and I20-I51) and cerebrovascular diseases (I60-I69). We used the NHANES Public-Use Linked Mortality File through December 31, 2019, which was linked to the National Death Index to determine mortality status. The period of follow-up was defined as the time between the interview was initially taken and the date of death, the loss to follow-up, or December 31, 2019.

Statistical analysis

Sample weights from the National Center for Health Statistics were used to account for the complex, multistage probability sampling design. Continuous variables were presented as weighted means with standard errors and were compared using one-way analysis of variance; categorical variables were presented as unweighted frequencies but weighted proportions and were compared using chi-square tests.

Cox proportional hazard models were used to investigate the associations of the TyG index and ABSI with cardiovascular mortality. Variables with a p value < 0.05 from the univariate Cox regression analysis and variables that were considered clinically relevant were included in the multivariate analysis. Model 1 was adjusted for age, sex, ethnicity, and BMI. Model 2 was adjusted for Model 1 plus smoking status, alcohol consumption, educational level, hypertension, diabetes, cardiovascular diseases, antidiabetic drugs, antihypertensive drugs, antihyperlipidemic drugs, eGFR, high-density lipoprotein cholesterol (HDL-C), and low-density lipoprotein cholesterol (LDL-C). A restricted cubic spline model with 3 knots was used to determine the potential nonlinear associations of the TyG index and ABSI with cardiovascular mortality. Individuals were divided into quartiles based on levels of the TyG index and ABSI, respectively, with the highest quartile defined as high and the bottom three quartiles defined as low. Based on this, they were categorized into 4 groups (low TyG and low ABSI, high TyG and low ABSI, low TyG and high ABSI, and high TyG and high ABSI). We explored whether the TyG index and ABSI had a synergistic effect on cardiovascular mortality. These two indicators were subsequently multiplied to establish TyG-ABSI (as in the case of TyG-BMI, TyG-WC, and TyG-WHtR). TyG-ARI was also constructed using the same approach as TyG-ABSI to determine the predictive value of TyG-ARI for cardiovascular mortality.

Receiver operating characteristic (ROC) curve analysis was carried out to compare the predictive value of the TyG index and TyG-derived indices for cardiovascular mortality. Several subgroup analyses were performed to assess the robustness of the results regarding the association between TyG-ABSI and cardiovascular mortality. Males with a WC > 102 cm and females with a WC > 88 cm were used to define abdominal obesity in the subgroup analysis [25]. To explore the mechanism underlying the association between TyG-ABSI and cardiovascular mortality, we conducted a mediation analysis using the approach described by VanderWeele for survival data [26]. This method estimated total, direct, and indirect effects as well as the proportion of mediation through multiple regression analyses, with 95% confidence intervals calculated using the bootstrap method with 1000 bootstrap samples. Previous studies demonstrated that insulin resistance and visceral obesity may promote arterial stiffness [27–29], which was recognized as an important contributing factor for cardiovascular diseases and adverse cardiovascular events [30, 31]. Therefore, arterial stiffness (represented by ePWV [32]) was selected as a potential mediating factor for the associations of insulin resistance and visceral obesity with cardiovascular mortality. Statistical analyses were completed using R statistical software (R Foundation for Statistical Computing, Vienna, Austria, version 4.3.1). Significance was set at $p < 0.05$ (*), $p < 0.01$ (†), and $p < 0.001$ (‡).

Results

Baseline characteristics

Table 1 shows the baseline characteristics of the 17,329 study individuals according to the TyG index quartiles. The average age was 45.4 ± 16.1 years, and the proportion of males was 50.1% (weighted). Individuals in the higher TyG index quartiles were older and tended to be male, have a lower education level, and be current/former smokers. They were more likely to have diabetes, hypertension, and cardiovascular diseases and use antidiabetic, antihypertensive, and antihyperlipidemic medications than those with lower quartiles of the TyG index. In addition, they also had higher levels of BMI, WC, fasting glucose, triglyceride, and LDL-C but lower levels of eGFR and HDL-C than those with lower quartiles of the TyG index. The baseline characteristics of the study

Table 1 Baseline characteristics of the study individuals according to the TyG index quartiles

[a]Variables	Overall (n = 17,329)	TyG Q1 < 8.17 (n = 4334)	TyG Q2 8.17–8.59 (n = 4338)	TyG Q3 8.59–9.04 (n = 4327)	TyG Q4 > 9.04 (n = 4330)	*p* value
Demographics						
Age, years	45.4 ± 16.1	40.1 ± 15.4	44.8 ± 16.1	47.7 ± 16.3	49.9 ± 14.9	< 0.001
Age ≥ 70 years, n (%)	2420 (8.6)	350 (4.8)	603 (8.5)	742 (11.0)	725 (10.5)	< 0.001
Sex, n (%)						< 0.001
Male	8730 (50.1)	1734 (39.6)	2134 (48.6)	2309 (53.9)	2553 (60.0)	
Female	8598 (49.9)	2599 (60.4)	2204 (51.4)	2018 (46.1)	1777 (40.0)	
Ethnicity, n (%)						< 0.001
Mexican American	3094 (8.9)	515 (6.6)	707 (8.5)	859 (9.8)	1013 (11.0)	
Other Hispanic	1567 (5.5)	318 (5.2)	368 (5.2)	451 (5.9)	430 (5.7)	
Non-Hispanic White	7373 (66.9)	1640 (62.7)	1861 (67.4)	1927 (68.7)	1945 (69.1)	
Non-Hispanic Black	3535 (11.4)	1380 (18.0)	976 (12.2)	648 (7.7)	531 (6.7)	
Other	1760 (7.4)	481 (7.6)	426 (6.8)	442 (7.9)	411 (7.5)	
Education level, n (%)						< 0.001
Less than high school	4545 (16.7)	815 (12.2)	1067 (16.1)	1245 (18.6)	1418 (20.5)	
High school or equivalent	3982 (23.9)	921 (20.7)	1004 (23.7)	1013 (24.7)	1044 (27.1)	
College or above	8786 (59.4)	2596 (67.1)	2266 (60.2)	2063 (56.7)	1861 (52.4)	
Health-related behaviors						
Smoking, n (%)						< 0.001
Current	3753 (21.5)	788 (17.6)	981 (22.0)	941 (22.0)	1043 (24.6)	
Former	4112 (24.1)	795 (19.2)	947 (23.4)	1099 (25.4)	1271 (29.2)	
Never	9450 (54.5)	2748 (63.2)	2405 (54.6)	2283 (52.6)	2014 (46.2)	
Alcohol consumption, n (%)	12,105 (78.7)	2999 (79.3)	3019 (79.0)	3061 (79.3)	3026 (76.9)	0.159
Physical examination						
BMI, kg/m^2	28.79 ± 6.67	26.15 ± 6.12	28.14 ± 6.27	29.87 ± 6.58	31.44 ± 6.54	< 0.001
Waist circumstance, cm	98.4 ± 16.3	90.1 ± 14.8	96.6 ± 15.2	101.7 ± 15.3	106.8 ± 15.2	< 0.001
ABSI	0.081 ± 0.005	0.079 ± 0.005	0.081 ± 0.005	0.082 ± 0.005	0.083 ± 0.004	< 0.001
SBP, mmHg	121 ± 17	116 ± 16	120 ± 16	123 ± 16	127 ± 17	< 0.001
DBP, mmHg	70 ± 12	68 ± 11	70 ± 11	71 ± 12	73 ± 13	< 0.001
Medical history						
Diabetes, n (%)	3185 (13.0)	223 (3.4)	441 (6.9)	757 (12.4)	1764 (31.6)	< 0.001
Hypertension, n (%)	7011 (34.9)	1113 (20.3)	1609 (31.0)	1920 (40.2)	2369 (50.6)	< 0.001
Cardiovascular diseases, n (%)	1661 (7.3)	229 (4.1)	372 (6.0)	457 (8.3)	603 (11.5)	< 0.001
Medications						
Antidiabetic drugs, n (%)	1816 (7.5)	134 (2.1)	226 (3.4)	417 (6.6)	1039 (19.4)	< 0.001
Antihypertensive drugs, n (%)	5033 (24.5)	721 (13.0)	1126 (21.0)	1378 (28.0)	1808 (38.0)	< 0.001
Antihyperlipidemic drugs, n (%)	2996 (15.5)	379 (7.7)	635 (12.9)	836 (17.7)	1146 (25.1)	< 0.001
Laboratory measurements						
White blood cells, 10^9/L	6.8 ± 2.0	6.2 ± 1.8	6.6 ± 1.9	7.0 ± 2.0	7.4 ± 2.0	< 0.001
Hemoglobin, g/dL	14.4 ± 1.5	14.0 ± 1.4	14.4 ± 1.5	14.6 ± 1.4	14.9 ± 1.4	< 0.001
Platelets, 10^9/L	250 ± 65	241 ± 61	252 ± 66	254 ± 65	255 ± 67	< 0.001
ALT, U/L	25.3 ± 15.6	20.9 ± 12.2	23.6 ± 13.7	26.9 ± 16.1	30.5 ± 18.4	< 0.001
AST, U/L	24.7 ± 11.5	23.4 ± 11.4	23.9 ± 10.8	25.1 ± 11.4	26.4 ± 12.2	< 0.001
Serum creatinine, mg/dL	0.87 ± 0.22	0.84 ± 0.20	0.87 ± 0.21	0.88 ± 0.22	0.90 ± 0.24	< 0.001
eGFR, mL/min/1.73m^2	95.6 ± 23.2	100.0 ± 22.8	95.2 ± 21.9	93.9 ± 23.2	92.9 ± 24.3	< 0.001
Fasting glucose, mg/dL	104.7 ± 29.3	93.8 ± 10.0	98.9 ± 12.8	104.0 ± 17.4	124.7 ± 50.4	< 0.001
HbA1c, %	5.6 ± 0.9	5.3 ± 0.4	5.4 ± 0.5	5.5 ± 0.7	6.1 ± 1.5	< 0.001
Fasting triglyceride, mg/dL	128.8 ± 112.8	56.3 ± 15.8	90.4 ± 13.9	131.4 ± 22.3	253.5 ± 176.5	< 0.001
HDL-C, mg/dL	53.7 ± 15.9	63.0 ± 17.0	56.2 ± 14.6	50.7 ± 13.0	43.4 ± 11.2	< 0.001
LDL-C, mg/dL	114.9 ± 35.0	100.6 ± 29.0	116.7 ± 32.3	122.6 ± 35.1	122.1 ± 39.5	< 0.001
Insulin resistance indices						
TyG	8.60 ± 0.67	7.84 ± 0.27	8.39 ± 0.12	8.80 ± 0.13	9.51 ± 0.46	< 0.001
TyG-BMI	248.9 ± 66.0	205.1 ± 49.7	236.1 ± 53.0	263.0 ± 58.4	299.0 ± 64.4	< 0.001

Table 1 (continued)

[a]Variables	Overall (n = 17,329)	TyG Q1 < 8.17 (n = 4334)	TyG Q2 8.17–8.59 (n = 4338)	TyG Q3 8.59–9.04 (n = 4327)	TyG Q4 > 9.04 (n = 4330)	*p* value
TyG-WC	850.6 ± 177.0	706.5 ± 122.9	810.3 ± 129.2	895.5 ± 137.0	1015.8 ± 157.2	< 0.001
TyG-WHtR	5.03 ± 1.04	4.20 ± 0.74	4.79 ± 0.76	5.31 ± 0.81	5.98 ± 0.93	< 0.001
HOMA-IR	3.39 ± 5.12	1.83 ± 1.73	2.60 ± 3.05	3.57 ± 3.76	5.89 ± 8.70	< 0.001

ABSI, a body shape index; ALT, alanine aminotransferase; AST, aspartate aminotransferase; BMI, body mass index; DBP, diastolic blood pressure; eGFR, estimated glomerular filtration rate; HbA1c, glycated hemoglobin A1c; HDL-C, high-density lipoprotein-cholesterol; HOMA-IR, homeostatic model assessment of insulin resistance; LDL-C, low-density lipoprotein-cholesterol; SBP, systolic blood pressure; TyG, triglyceride-glucose; TyG-BMI, triglyceride glucose-body mass index; TyG-WC, triglyceride glucose-waist circumference; TyG-WHtR, triglyceride glucose-waist-to-height ratio

[a]Survey data were presented as weighted means ± standard errors for continuous variables, and unweighted frequencies (weighted proportions) for categorical variables

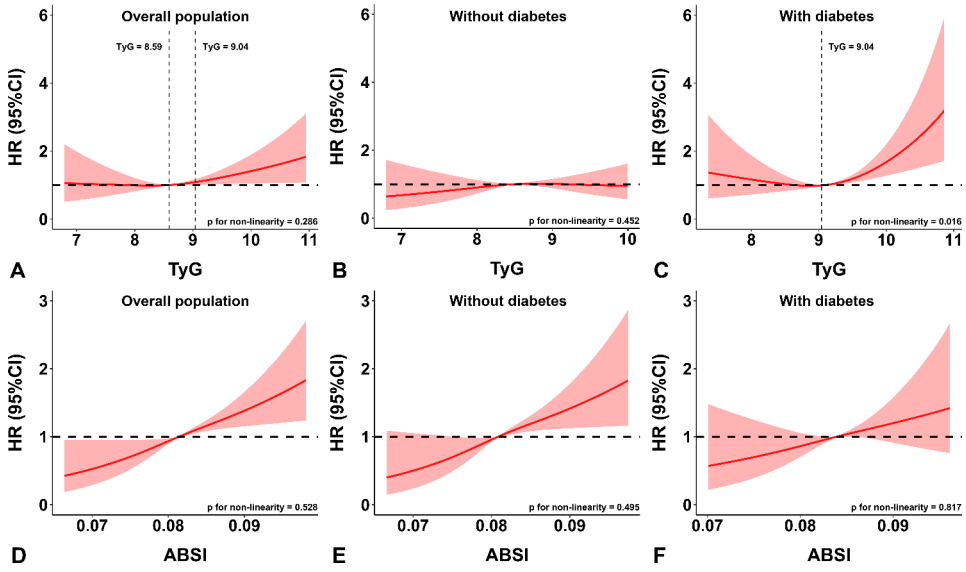

Fig. 2 Dose–response associations of **A**–**C** the TyG index and **D**–**F** ABSI with cardiovascular mortality in the overall population, individuals without diabetes, and individuals with diabetes. Adjusted for Model 2 in the Cox regression analysis. ABSI, a body shape index; CI, confidence interval; HR, hazard ratio; TyG, triglyceride-glucose

individuals according to ABSI quartiles are summarized in Supplementary Table 1.

Association between the TyG index and cardiovascular mortality

Results of the univariate Cox regression analysis are shown in Supplementary Table 2. In the overall population, the TyG index was associated with cardiovascular mortality after adjusting for confounders (HR = 1.128 per 1-standard deviation [SD] increment, 95% confidence interval [CI] 1.003–1.268). A similar result was found in individuals with diabetes (HR = 1.248 per 1-SD increment, 95% CI 1.056–1.476). However, this was not the case for individuals without diabetes (HR = 1.043 per 1-SD increment, 95% CI 0.885–1.229) (Supplementary Table 3).

Kaplain-Meier survival curves according to the TyG index quartiles are shown in Supplementary Fig. 1A. When individuals were stratified by the TyG index quartile, the association between the TyG index and cardiovascular mortality was not significant in either the diabetic or non-diabetic population. The test for trend did not reach statistical significance, indicating a potential nonlinear relationship (Supplementary Table 3). Therefore, we carried out restricted cubic spline analysis to evaluate the nonlinear relationship of the TyG index with cardiovascular mortality and found a J-shaped relationship in individuals with diabetes (*p* for non-linearity = 0.016). When the TyG index was > 9.04, the risk of cardiovascular mortality was significantly elevated (Fig. 2C). However, in individuals without diabetes, we did not identify any association between the TyG index and cardiovascular mortality (Fig. 2B).

Association between ABSI and cardiovascular mortality

ABSI was independently associated with cardiovascular mortality in the overall population (HR = 1.221 per 1-SD increment, 95% CI 1.115–1.337) as well as in individuals with (HR = 1.178 per 1-SD increment, 95% CI 1.005–1.382) and without diabetes (HR = 1.225 per

1-SD increment, 95% CI 1.096–1.368) (Supplementary Table 4).

Kaplain-Meier survival curves according to ABSI quartiles are shown in Supplementary Fig. 1B. When individuals were stratified by ABSI quartile, the test for trend reached statistical significance regardless of whether individuals had diabetes, suggesting a potential linear relationship (Supplementary Table 4). Restricted cubic spline analysis revealed that the association between ABSI and cardiovascular mortality followed a positive linear relationship in the overall population as well as in individuals with and without diabetes (Figs. 2D-F). However, this association was not statistically significant after adjustment in individuals with diabetes (Fig. 2F).

The synergistic effect of the TyG index and ABSI on cardiovascular mortality

Individuals with high TyG and high ABSI values (TyG > 9.04 and ABSI > 0.085) had a higher cardiovascular mortality rate than those with isolated high ABSI values (ABSI > 0.085 alone) or isolated high TyG values (TyG > 9.04 alone) and those with low TyG and low ABSI values (TyG < 9.04 and ABSI < 0.085) in the overall population (10.4 *vs* 8.2 *vs* 3.5 *vs* 1.8%) as well as in individuals with (11.6 *vs* 10.0 *vs* 6.3 *vs* 4.8%) and without diabetes (8.9 *vs* 7.7 *vs* 2.1 *vs* 1.6%) (Fig. 3 and Supplementary Table 5).

In the multivariate Cox regression analysis, individuals with elevations in both the TyG index and ABSI (TyG > 9.04 and ABSI > 0.085) were at the highest cardiovascular mortality risk in the overall population (highest quartile *vs* lowest quartile: HR = 1.451, 95% CI 1.126–1.869) as well as in individuals with (highest quartile *vs* lowest quartile: HR = 1.714, 95% CI 1.123–2.616) and without diabetes (highest quartile *vs* lowest quartile: HR = 1.402, 95% CI 1.003–1.960) (Fig. 3 and Supplementary Table 5). The above results suggested a synergistic effect of the TyG index and ABSI on cardiovascular mortality, regardless of whether individuals had diabetes.

Construction and analysis of TyG-ABSI

Given the synergistic effect of the TyG index and ABSI on cardiovascular mortality, we next multiplied these two indicators and established TyG-ABSI (as in the case of TyG-BMI, TyG-WC, and TyG-WHtR).

When analyzed as a continuous variable, TyG-ABSI was independently associated with cardiovascular mortality in the overall population (HR = 1.270 per 1-SD increment, 95% CI 1.137–1.418) as well as in individuals with (HR = 1.309 per 1-SD increment, 95% CI 1.106–1.549) and without diabetes (HR = 1.238 per 1-SD increment, 95% CI 1.068–1.434) (Table 2).

Kaplain-Meier survival curves according to TyG-ABSI quartiles are shown in Supplementary Fig. 1C. When individuals were stratified by TyG-ABSI quartile, the association between TyG-ABSI and cardiovascular mortality was also significant in the overall population (highest quartile *vs* lowest quartile: HR = 1.724, 95% CI 1.177–2.525) as well as in individuals without diabetes (highest quartile *vs* lowest quartile: HR = 1.678, 95% CI 1.082–2.602). However, this was not the case for individuals with diabetes (highest quartile *vs* lowest quartile: HR = 1.535, 95% CI 0.664–3.548). The test for trend did not reach statistical significance in individuals with diabetes (p for trend = 0.053), indicating a potential nonlinear relationship (Table 2).

In the restricted cubic spline analysis, a positive linear relationship between TyG-ABSI and cardiovascular mortality was observed in the overall population as well as in individuals without diabetes (Figs. 4A and 4B). In individuals with diabetes, TyG-ABSI followed a J-shaped relationship with cardiovascular mortality. The risk of cardiovascular mortality was significantly elevated when TyG-ABSI was > 0.76 (Fig. 4C).

The association between TyG-ABSI and cardiovascular mortality appeared more pronounced in younger individuals (aged < 60 years) (Fig. 5). To further explore whether the impact of TyG-ABSI on cardiovascular mortality varied across different age and sex subgroups, we conducted restricted cubic spline analysis stratified by sex and age. In the subgroup stratified by age (< 60

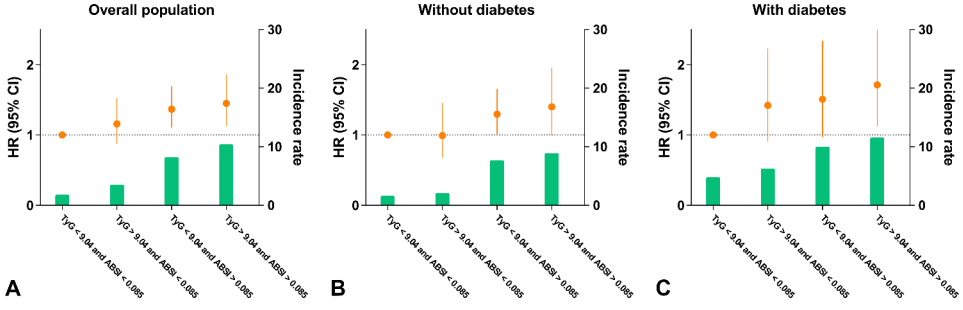

Fig. 3 Synergistic effect of the TyG index and ABSI on cardiovascular mortality in the **A** overall population, **B** individuals without diabetes, and **C** individuals with diabetes. ABSI, a body shape index; CI, confidence interval; HR, hazard ratio; TyG, triglyceride-glucose

Table 2 Association between TyG-ABSI and cardiovascular mortality in individuals with and without diabetes

	Per 1-SD increment	Groups				*p* for trend
		Quartile 1 <0.65	Quartile 2 0.65–0.70	Quartile 3 0.70–0.76	Quartile 4 >0.76	
Overall population						
Unadjusted	1.904 (1.789–2.027)‡	1.000	2.857 (1.973–4.137)‡	5.136 (3.624–7.280)‡	9.775 (6.990–13.668)‡	<0.001
Model 1	1.347 (1.238–1.466)‡	1.000	1.385 (0.953–2.013)	1.542 (1.075–2.214)*	2.055 (1.443–2.928)‡	<0.001
Model 2	1.270 (1.137–1.418)‡	1.000	1.314 (0.898–1.923)	1.422 (0.977–2.070)	1.724 (1.177–2.525)†	0.002
Individuals without diabetes						
Unadjusted	2.155 (1.949–2.384)‡	1.000	2.854 (1.889–4.311)‡	5.219 (3.535–7.705)‡	8.949 (6.099–13.129)‡	<0.001
Model 1	1.289 (1.133–1.468)‡	1.000	1.400 (0.921–2.128)	1.536 (1.020–2.313)*	1.833 (1.214–2.769)†	0.002
Model 2	1.238 (1.068–1.434)†	1.000	1.359 (0.888–2.078)	1.518 (0.993–2.319)	1.678 (1.082–2.602)*	0.023
Individuals with diabetes						
Unadjusted	1.271 (1.136–1.421)‡	1.000	1.380 (0.595–3.203)	1.621 (0.734–3.579)	2.240 (1.052–4.770)*	0.001
Model 1	1.247 (1.098–1.417)‡	1.000	1.002 (0.429–2.340)	1.048 (0.469–2.344)	1.378 (0.636–2.988)	0.057
Model 2	1.309 (1.106–1.549)†	1.000	1.132 (0.468–2.736)	1.078 (0.460–2.528)	1.535 (0.664–3.548)	0.053

SD, standard deviation; TyG-ABSI, triglyceride glucose-a body shape index

Model 1 adjusted for age, sex, ethnicity, and body mass index

Model 2 adjusted for model 1 plus smoking status, alcohol consumption, educational level, hypertension, diabetes, cardiovascular diseases, antidiabetic drugs, antihypertensive drugs, antihyperlipidemic drugs, estimated glomerular filtration rate, high-density lipoprotein cholesterol, and low-density lipoprotein cholesterol

*$p<0.05$, †$p<0.01$, ‡$p<0.001$

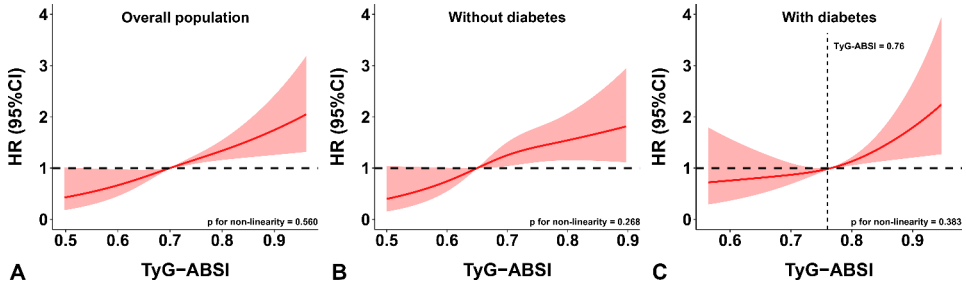

Fig. 4 Restricted cubic splines of the relationship between TyG-ABSI and cardiovascular mortality in the **A** overall population, **B** individuals without diabetes, and **C** individuals with diabetes. Adjusted for Model 2 in the Cox regression analysis. CI, confidence interval; HR, hazard ratio; TyG-ABSI, triglyceride glucose-a body shape index

vs ≥ 60 years and < 65 *vs* ≥ 65 years), TyG-ABSI was significantly associated with cardiovascular mortality for both men and women (Supplementary Figs. 2 and 3), which confirmed the robustness of our findings. However, in females aged ≥ 70 years, TyG-ABSI did not exhibit a predictive value for cardiovascular mortality (Supplementary Fig. 4F).

The incremental predictive ability of TyG-ABSI for cardiovascular mortality beyond conventional risk predictors was observed (Harrell's C-index: 0.873 *vs* 0.870, $p<0.001$), indicating that it is a predictive marker that can be used to estimate residual cardiovascular risk (Table 3).

Comparison of the predictive value of the TyG index and TyG-derived indices for cardiovascular mortality

Compared with the TyG index, TyG-BMI, TyG-WC, and TyG-WHtR, TyG-ABSI had the highest Harrell's C-index for predicting cardiovascular mortality (0.710 *vs* 0.623 *vs* 0.539 *vs* 0.612 *vs* 0.622, all $p<0.001$). In addition, the predictive value of TyG-ABSI was greater than that of the HOMA-IR (0.710 *vs* 0.535, $p<0.001$) (Fig. 6).

The predictive value of TyG-ABSI and TyG-ARI for cardiovascular mortality

The mean value of ARI was near zero, with a standard deviation of 0.169. We next established TyG-ARI. Cox

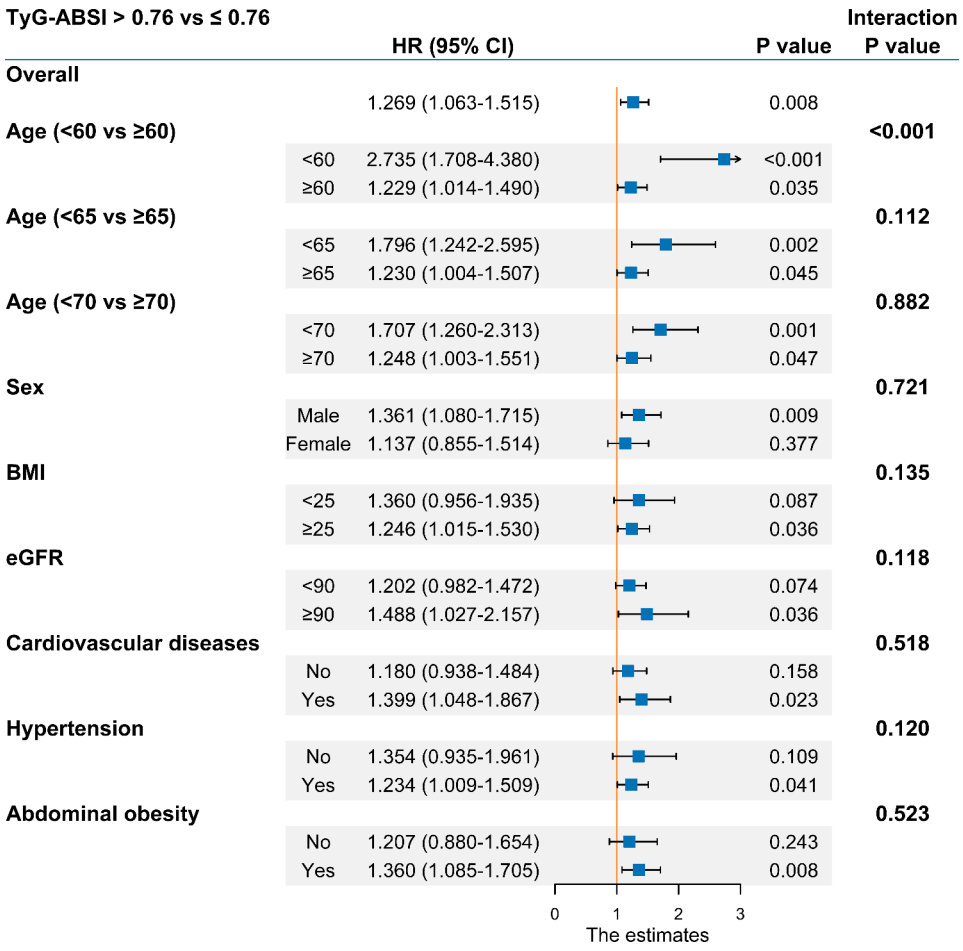

Fig. 5 Forest plot of subgroup analyses of TyG-ABSI for cardiovascular mortality. Adjusted for Model 2 in the Cox regression analysis. BMI, body mass index; CI, confidence interval; eGFR, estimated glomerular filtration rate; HR, hazard ratio; TyG-ABSI, triglyceride glucose-a body shape index

Table 3 Incremental predictive ability of TyG-ABSI for cardiovascular mortality beyond conventional risk predictors

	Harrell's C-index	*p* value
*Model	0.870 (0.865–0.876)	Ref
Model + TyG-ABSI	0.873 (0.867–0.878)	< 0.001

TyG-ABSI, triglyceride glucose-a body shape index

*The model incorporates age, sex, ethnicity, body mass index, smoking status, alcohol consumption, educational level, hypertension, diabetes, cardiovascular diseases, antidiabetic drugs, antihypertensive drugs, antihyperlipidemic drugs, estimated glomerular filtration rate, high-density lipoprotein cholesterol, and low-density lipoprotein cholesterol

regression model identified that the association between TyG-ABSI and cardiovascular mortality (HR = 1.270 per 1-SD increment, 95% CI 1.137–1.418) was stronger than that of TyG-ARI (HR = 1.242 per 1-SD increment, 95% CI 1.130–1.364). Similar results were observed when TyG-ABSI (highest quartile *vs* lowest quartile: HR = 1.724, 95% CI 1.177–2.525) and TyG-ARI (highest quartile *vs* lowest quartile: HR = 1.437, 95% CI 1.120–1.843) were analyzed as categorical variables (Supplementary Table 6).

In the ROC curve analysis, the predictive value of TyG-ABSI for cardiovascular mortality was also greater than that of TyG-ARI (Harrell's C-index: 0.710 *vs* 0.544, $p < 0.001$) (Supplementary Fig. 5).

Mediation analysis

To explore the underlying mechanism of the association between TyG-ABSI and cardiovascular mortality, a mediation analysis was performed. We found that arterial stiffness, as reflected by ePWV, partially mediated the effect of insulin resistance and visceral obesity, as reflected by TyG-ABSI, on cardiovascular mortality, with a mediation proportion of 42.7% (95% CI: 30.8–54.5%) in the fully adjusted model (Table 4).

Discussion

On the basis of the NHANES database, the associations of the TyG index and ABSI with cardiovascular mortality in individuals with and without diabetes were examined in the present study, and we reported the main findings as follows: (1) the synergistic effect of the TyG index and ABSI on cardiovascular mortality was observed both in individuals with and without diabetes; (2) TyG-ABSI

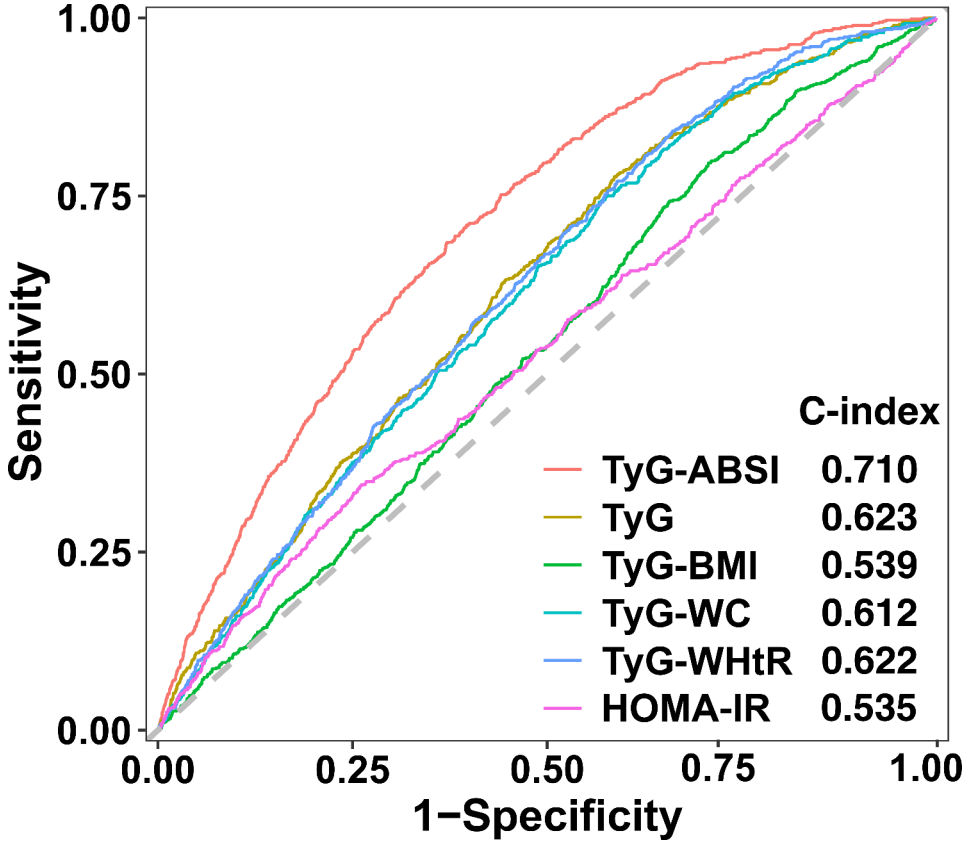

Fig. 6 Comparison of the predictive value of TyG-ABSI with other insulin resistance indices for cardiovascular mortality. HOMA-IR, homeostatic model assessment of insulin resistance; TyG, triglyceride-glucose; TyG-ABSI, triglyceride glucose-a body shape index; TyG-BMI, triglyceride glucose-body mass index; TyG-WC, triglyceride glucose-waist circumference; TyG-WHtR, triglyceride glucose-waist-to-height ratio

Table 4 Mediation analysis of the impact of ePWV on the relationship between TyG-ABSI and cardiovascular mortality

	Total effect HR (95% CI)	Indirect effect HR (95% CI)	Direct effect HR (95% CI)	Proportion mediated (%)	*p* value
Unadjusted	1.899 (1.776–2.021)	1.374 (1.288–1.460)	1.409 (1.310–1.509)	48.1 (38.9–57.2)	< 0.001
*Model 1	1.946 (1.796–2.096)	1.414 (1.305–1.522)	1.416 (1.310–1.522)	49.5 (39.9–59.0)	< 0.001
Model 2	1.663 (1.483–1.842)	1.250 (1.183–1.317)	1.358 (1.223–1.493)	42.7 (30.8–54.5)	< 0.001

CI, confidence interval; ePWV, estimated pulse wave velocity; HR, hazard ratio; TyG-ABSI, triglyceride glucose-a body shape index

Model 1 adjusted for sex, ethnicity, and body mass index

Model 2 adjusted for model 1 plus smoking status, alcohol consumption, educational level, hypertension, diabetes, cardiovascular diseases, antidiabetic drugs, antihypertensive drugs, antihyperlipidemic drugs, estimated glomerular filtration rate, high-density lipoprotein cholesterol, and low-density lipoprotein cholesterol

*Age was excluded in the multivariate analysis due to it was included in the formula of ePWV

integrated the advantages of the TyG index and ABSI: in individuals without diabetes, the risk of cardiovascular mortality increased almost linearly with increasing TyG-ABSI levels; in individuals with diabetes, TyG-ABSI followed a J-shaped relationship with cardiovascular mortality, with a TyG-ABSI > 0.76 indicating a significant increase in risk; (3) the predictive value of TyG-ABSI for cardiovascular mortality was greater than that of the TyG index and other modified TyG indices (TyG-BMI, TyG-WC, TyG-WHtR, and TyG-ARI); and (4) arterial stiffness greatly mediated the association between TyG-ABSI and cardiovascular mortality, with a mediation proportion as high as 42.7%. Taken together, the simultaneous assessment of insulin resistance (as represented by the TyG index) and visceral obesity (as represented by ABSI) showed a synergistic effect on cardiovascular mortality and provided unique advantages for further cardiovascular risk stratification in individuals with and without diabetes, which was better than the TyG index and other modified TyG indices. Therefore, we recommended the

use of TyG-ABSI rather than other TyG-derived indices in cardiovascular risk assessment.

Due to differences in study designs and patient characteristics, significant controversies exist regarding whether modified TyG indices outperform the TyG index in predicting cardiovascular outcomes [11–15]. Our findings revealed that the predictive value of the TyG index was greater than TyG-BMI, TyG-WC, and TyG-WHtR, indicating that there were no advantages in combining the TyG index with traditional obesity-related parameters for predicting cardiovascular mortality.

Compared with traditional obesity-related parameters, ABSI is currently the only one that does not exhibit the "obesity paradox" [28, 33, 34], showing a linear correlation with visceral fat content and the risk of all-cause and cardiovascular mortality [27, 33–35], which was consistent with our findings. Despite these advantages, no studies have yet combined this superior visceral obesity-related parameter with the TyG index to assess cardiovascular mortality risk.

In our study, the levels of the TyG index and ABSI approximate the levels recently reported by Duan et al. [36] (TyG quartiles: < 8.19, 8.19–8.61, 8.61–9.05, and > 9.05) and Sun et al. [35] (ABSI quartiles: < 0.081, 0.081–0.084, 0.084–0.087, and > 0.087), respectively. The association between the TyG index and cardiovascular mortality was not significant in individuals without diabetes, which was consistent with previous studies [37]. While the risk of cardiovascular mortality increased linearly with increasing ABSI, it did not reach statistical significance after multivariate adjustment in individuals with diabetes, which was similar to previous reports [35]. Consequently, limitations exist when evaluating the TyG index and ABSI separately. When we combined these two indicators, a synergistic effect was observed, which has the potential to provide more accurate cardiovascular risk stratification. The TyG-ABSI integrates the advantages of its components. In individuals without diabetes, it reflects the advantages of ABSI, showing a positive linear correlation with the risk of cardiovascular mortality (p for non-linearity = 0.268); in individuals with diabetes, it highlights the advantages of the TyG index, showing a J-shaped relationship with cardiovascular mortality, with the risk significantly increasing after TyG-ABSI > 0.76. In addition, the TyG-ABSI outperformed the TyG index and other TyG-derived indices for predicting cardiovascular mortality, suggesting that the combined assessment of the TyG index and ABSI has unique advantages over the TyG-BMI, TyG-WC, and TyG-WHtR.

In the study by Krakauer et al. [23], the predictive value of ARI for mortality in the general population was superior to ABSI. In addition, ARI was associated with metabolic syndrome and showed a greater predictive value for mortality compared with the metabolic syndrome score. Replacing WC with ARI in the metabolic syndrome score can provide a better predictive value for mortality [38]. However, the value of ARI was not a simple function of its components. Additionally, its value was dependent on the endpoint of the study. Different endpoints can yield varying ARI values [23]. Consequently, using ARI is not as straightforward as using ABSI. In our study cohort, the mean value of ARI was near zero (0.000019), with a standard deviation of 0.169, which was similar to the result obtained by Krakauer et al. (-0.01 ± 0.23) [38]. However, we did not find that the association between TyG-ARI and cardiovascular mortality was stronger than that of TyG-ABSI in the current study. Taken together, our study recommended the application of TyG-ABSI rather than the TyG index and other TyG-derived indices in cardiovascular risk assessment.

In the subgroup analysis stratified by age and sex, we found that TyG-ABSI was not significantly associated with cardiovascular mortality in females aged ≥ 70 years. This may be attributed to the higher prevalence of life-threatening comorbidities in older women, which could obscure the effect of TyG-ABSI on cardiovascular mortality. Therefore, caution should be applied in extending our conclusions to older women.

The underlying mechanisms by which this novel indicator influences cardiovascular risk remain unclear. Arterial stiffness reflects vascular aging and loss of elasticity, serving as a well-established contributing factor for cardiovascular diseases and adverse cardiovascular outcomes [30, 31]. Age and blood pressure are two primary determinants of arterial stiffness [39]. Interestingly, emerging evidence convincingly demonstrated a strong correlation between ePWV, calculated on the basis of age and blood pressure, and arterial stiffness [32]. Multiple studies have confirmed that insulin resistance, as reflected by the TyG index, and visceral obesity, as indicated by ABSI, are closely linked to increased arterial stiffness [27–29]. However, it remains unclear whether arterial stiffness mediates the associations of insulin resistance and visceral obesity with cardiovascular mortality. Our study revealed that arterial stiffness, as reflected by ePWV, served as an influencing mediator of the association between elevated TyG-ABSI and increased risk of cardiovascular mortality, with a mediation proportion as high as 42.7%. In states of obesity and insulin resistance, the levels of plasma insulin and aldosterone are elevated, targeting sodium channels in endothelial cells through mineralocorticoid receptors. The subsequent activation of sodium channels in endothelial cells increases the influx of sodium ions and the stiffening of the cortical actin cytoskeleton, leading to fibrosis and remodeling of the heart and blood vessels [39, 40]. Furthermore, the stiffening of the endothelial cell layer is linked to decreased endothelial nitric oxide synthase

activity, resulting in reduced nitric oxide production and impaired nitric oxide bioavailability, ultimately manifesting as vessel stiffness and vasodilatory dysfunction [40, 41]. These mechanisms cause hemodynamic dysregulation and increase cardiovascular risk. This could be the potential mechanism of increased cardiovascular risk due to elevated TyG-ABSI. However, the precise mechanism requires further investigation.

The TyG-ABSI is a non-invasive and easy-to-calculate indicator that contributes to improving cardiovascular risk stratification in individuals with and without diabetes. It has been reported that improvements in insulin sensitivity and a reduction in visceral fat contribute to decreased arterial stiffness [42, 43]. Therefore, future studies are warranted to explore whether therapeutic strategies aimed at reducing the level of TyG-ABSI can help improve arterial stiffness and lower the risk of cardiovascular events, which holds considerable importance.

Limitations

Our study has several limitations. First, given the observational nature of the study, causal relationships cannot be inferred. Second, the data for this study were derived from the NHANES database, which represented only the United States population, potentially limiting its generalizability. Our conclusions cannot be extrapolated to other populations. Therefore, future validation of our findings in different ethnic populations is necessary. Third, the TyG index and ABSI were assessed only at baseline, while the associations of insulin resistance and visceral obesity with cardiovascular mortality may be influenced by other factors, especially during long-term follow-up. For example, individuals may experience changes in visceral fat content due to lifestyle modifications. However, we lacked dynamic measurements of the TyG index and ABSI to examine the impact of temporal changes in TyG-ABSI on the risk of cardiovascular mortality. It requires further exploration in future prospective studies. Fourth, the mediation analysis assumed a temporal order among the variables; however, the directional analysis of these effects was constrained by the cross-sectional design. In addition, our study focused solely on exploring arterial stiffness as a mediating factor and did not include other potential mediating factors due to the limited space of the article. Other mediators could be further explored in future studies. Fifth, in the current study, we only calculated the truncated ARI due to missing data on hip circumference, which may lead to potential bias. Future studies should further determine the association between TyG-ARI and cardiovascular mortality in datasets that include hip circumference data. Finally, even after adjusting for multiple factors to minimize confounding bias, the potential influence of unmeasured confounders cannot be entirely ruled out.

Conclusions

Compared with the simultaneous assessment of the TyG index and traditional obesity-related parameters (TyG-BMI, TyG-WC, and TyG-WHtR), the combination of the TyG index and ABSI, a superior visceral obesity-related parameter, provided unique advantages, which showed a synergistic effect on cardiovascular mortality and contributed to further cardiovascular risk stratification for individuals with and without diabetes. Therefore, we recommended the use of TyG-ABSI instead of the TyG index and other modified TyG indices in cardiovascular risk assessment.

Abbreviations

ABSI	A body shape index
ARI	Anthropometric risk index
BMI	Body mass index
CI	Confidence interval
cfPWV	Carotid-femoral pulse wave velocity
eGFR	Estimated glomerular filtration rate
ePWV	Estimated pulse wave velocity
HbA1c	Glycated hemoglobin A1c
HDL-C	High-density lipoprotein cholesterol
HOMA-IR	Homeostatic model assessment of insulin resistance
HR	Hazard ratio
ICD-10	International Statistical Classification of Diseases and Related Health Problems: Tenth Revision
LDL-C	Low-density lipoprotein cholesterol
NHANES	National Health and Nutrition Examination Survey
ROC	Receiver operating characteristic
SD	Standard deviation
TyG	Triglyceride-glucose
TyG-ABSI	Triglyceride glucose-a body shape index
TyG-BMI	Triglyceride glucose-body mass index
TyG-WC	Triglyceride glucose-waist circumference
TyG-WHtR	Triglyceride glucose-waist-to-height ratio
WC	Waist circumference
WHtR	Waist-to-height ratio

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12933-025-02604-z.

Supplementary Material 1: Figure 1. Kaplan-Meier survival curves of (A) the TyG index, (B) ABSI, and (C) TyG-ABSI for cardiovascular mortality. Abbreviations: ABSI, a body mass index; TyG, triglyceride-glucose; TyG-ABSI, triglyceride glucose-a body shape index

Supplementary Material 2: Figure 2. Restricted cubic splines of the relationship between TyG-ABSI and cardiovascular mortality in (A) individuals < 60 years, (B) males < 60 years, (C) females < 60 years, (D) individuals ≥ 60 years, (E) males ≥ 60 years, and (F) females ≥ 60 years.Adjusted for Model 2 in the Cox regression analysis. Abbreviations: CI, confidence interval; HR, hazard ratio; TyG-ABSI, triglyceride glucose-a body shape index

Supplementary Material 3: Figure 3. Restricted cubic splines of the relationship between TyG-ABSI and cardiovascular mortality in (A) individuals < 65 years, (B) males < 65 years, (C) females < 65 years, (D) individuals ≥ 65 years, (E) males ≥ 65 years, and (F) females ≥ 65 years.Adjusted for Model 2 in the Cox regression analysis. Abbreviations: CI, confidence interval; HR, hazard ratio; TyG-ABSI, triglyceride glucose-a body shape index

Supplementary Material 4: Figure 4. Restricted cubic splines of the relationship between TyG-ABSI and cardiovascular mortality in (A) individuals < 70 years, (B) males < 70 years, (C) females < 70 years, (D) individuals ≥ 70 years, (E) males ≥ 70 years, and (F) females ≥ 70 years.Adjusted for Model 2 in the Cox regression analysis. Abbreviations: CI, confidence interval; HR,

hazard ratio; TyG-ABSI, triglyceride glucose-a body shape index

Supplementary Material 5: Figure 5. Comparison of the predictive value of TyG-ABSI and TyG-ARI for cardiovascular mortality. Abbreviations: TyG-ABSI, triglyceride glucose-a body shape index; TyG-ARI, triglyceride glucose-anthropometric risk index

Supplementary Material 6

Supplementary Material 7

Supplementary Material 8

Supplementary Material 9

Supplementary Material 10

Supplementary Material 11

Acknowledgements
The authors are grateful to the participants of the NHANES database and all research personnel involved.

Author contribution
ZJ, GY, and HH were responsible for conception and design. HH and XY contributed to data extraction, data proofreading, and statistical analysis. CQ, LY, LX, FS, LN, and HY were involved in data interpretation and figure mapping. HH participated in writing the original draft. GY and HH critically revised the manuscript. ZJ conceived and supervised the work. All authors participated in editing, reviewing, and approving the final manuscript.

Funding
This study was supported by the National High Level Hospital Clinical Research Funding (No. 2024-NHLHCRF-YS-01, 2024-NHLHCRF-JBGS-WZ-06, and 2023-NHLHCRF-YXHZ-ZRMS-09), Beijing Research Ward Construction Clinical Research Project (2022-YJXBF-04-03), Capital's Founds for Health Improvement and Research (No. 2022-1-4062), and National Key Clinical Specialty Construction Project (No. 2020-QTL-009).

Availability of data and materials
The data used in the present study were publicly available from the Centers for Disease Control and Prevention at https://www.cdc.gov/nchs/nhanes/index.htm.

Declarations

Ethics approval and consent to participate
The Ethics Review Committee of the National Center for Health Statistics approved the NHANES study protocol, and all participants provided written informed consent before participation.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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Received: 19 September 2024 / Accepted: 20 January 2025
Published online: 07 February 2025

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