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Multidimensional metabolic risk of the triglyceride-glucose (TyG) index in ocean-going seafarers: a LASSO regression-based cross-sectional study

CAN CUI

Yangtze River Shipping General Hospital

HUI ZHU

274125349@qq.com

Yangtze River Shipping General Hospital

Research Article

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Abstract

Background

The triglyceride-glucose (TyG) index is a simple surrogate marker for insulin resistance (IR), but factors associated with elevated TyG in ocean-going seafarers remain unclear. We aimed to identify factors independently associated with the TyG index in male ocean-going seafarers to inform targeted prevention of cardiometabolic risk.

Methods

In this cross-sectional study, we retrospectively identified 585 male ocean-going seafarers from the Yangtze River Shipping General Hospital from February 2025 to February 2026; after applying predefined exclusion criteria, 533 participants were included. Demographic, anthropometric, biochemical, and lifestyle data were collected using standardized protocols. Feature selection was performed using least absolute shrinkage and selection operator (LASSO) regression with 10-fold cross-validation in R. A multiple ordinary least squares (OLS) linear regression model was then constructed to identify independent associations with the TyG index. Heteroscedasticity was corrected using HC3 robust standard errors, and multicollinearity was assessed via the variance inflation factor (VIF).

Results

LASSO selected 17 variables. In the multiple OLS model, age (standardized β = 0.191, 95% CI 0.096–0.285, $P < 0.001$), waist-to-hip ratio (standardized β = 0.216, 95% CI 0.137–0.296, $P < 0.001$), alanine aminotransferase (ALT) (standardized β = 0.303, 95% CI 0.150–0.456, $P < 0.001$), serum uric acid (SUA) (standardized β = 0.127, 95% CI 0.050–0.204, $P = 0.001$), unhealthy dietary patterns (standardized β = 0.095, 95% CI 0.021–0.169, $P = 0.012$), and unhealthy alcohol consumption (standardized β = 0.074, 95% CI 0.002–0.146, $P = 0.044$) were independently and positively associated with the TyG index. Direct bilirubin (DBIL) was inversely associated (standardized β = -0.206, 95% CI -0.279 to -0.132, $P < 0.001$).

Conclusions

In male ocean-going seafarers, older age, central obesity, higher SUA and ALT levels, unhealthy dietary patterns, and unhealthy alcohol consumption were independently associated with higher TyG index, whereas DBIL was inversely associated. Incorporating the TyG index into maritime health assessments and targeting modifiable factors may support early identification and intervention for cardiometabolic risk in this population.

1. Introduction

- Maritime transportation is a cornerstone of the global supply chain and economic development. Ocean-going seafarers live in confined communal spaces for prolonged periods and are frequently exposed to multiple occupational hazards, including circadian misalignment, restricted physical activity, poor dietary patterns, and psychological stress [1–4]. These overlapping challenges can disrupt metabolic homeostasis, thereby increasing the risk of cardiovascular disease (CVD) and metabolic disorders [5, 6]. Acute cardiovascular events during deep-sea voyages are difficult to manage and are associated with high fatality rates. Such emergencies not only pose serious risks to seafarers' lives but also create considerable challenges for maritime safety, operational efficiency, and the economic viability of the shipping industry [7]. Given the high mobility of this population, unpredictable shipping routes, and the scarcity of emergency medical resources at sea, implementing primary prevention and long-term health management, particularly early screening of cardiometabolic risks, is important for improving their occupational health [8].
- The triglyceride-glucose (TyG) index, a simple surrogate marker for insulin resistance (IR), has shown predictive value in recent epidemiological studies [9–11]. The TyG index has been associated with metabolic syndrome (MetS) and has been reported as an independent predictor of coronary artery disease, cardiovascular mortality, and adverse outcomes after acute cardiovascular events [9–11]. However, although the predictive value of the TyG index has been widely examined in the general population and high-risk metabolic cohorts, few studies have explored its distribution and occupation-specific determinants among ocean-going seafarers. Furthermore, although central obesity and unhealthy lifestyle behaviors are established risk factors for cardiometabolic diseases [12–14], their independent associations with the TyG index and the related determinants in this occupational group have not been systematically examined.
- Focusing on Chinese male ocean-going seafarers, this study integrated the TyG index, lifestyle scales, and fasting biochemical parameters to describe the distribution of the TyG index in this population. We aimed to investigate its independent associations with lifestyle factors and central obesity indicators. The findings may provide epidemiological evidence to support early cardiometabolic risk screening in seafarers and inform targeted behavioral interventions.

2. Methods

2.1 Study design and participants

- This study adopted a cross-sectional design. The target population comprised male seafarers who underwent occupational health examinations for deep-sea voyages at the Yangtze River Shipping General Hospital from February 2025 to February 2026. Ocean-going ship positions are primarily categorized into three main departments: the deck, engine, and catering/service departments. Personnel in the deck and engine departments are primarily responsible for maintenance of the ship's power systems, navigation safety, cargo handling, and hull maintenance. Consequently, they are frequently exposed to mechanical hazards and the physiological stress of demanding

watchkeeping (shift work) routines. In contrast, the service department primarily performs logistical support tasks such as catering, cleaning, and financial management. Given the differences in circadian rhythms and physical microenvironmental exposures between these groups, and to improve the homogeneity of the occupational cohort and reduce potential confounding by sex on endocrine and metabolic profiles, this study restricted the target population to male seafarers in the deck and engine departments.

- The inclusion criteria were: (i) age 18–60 years; (ii) Chinese nationality and official registration with maritime safety administrations at various levels; (iii) primarily engaged in ocean-going maritime transport and currently serving as a seafarer in the deck or engine department. The exclusion criteria were: (i) prior diagnosis of diabetes mellitus (DM) or current use of glucose-lowering medications or insulin; (ii) use of lipid-lowering medications within the past 3 months; (iii) known severe cardiovascular disease (CVD) (e.g., history of myocardial infarction or coronary revascularization) or chronic kidney disease (CKD; estimated glomerular filtration rate [eGFR] < 60 mL/min/1.73 m²); (iv) history of malignant tumors, or recent physiological stress (within 1 month) such as major trauma or acute infection; and (v) missing data for key analytical variables (e.g., fasting plasma glucose, lipid profiles, complete anthropometric measurements, or lifestyle scale items).
- After data cleaning and application of the inclusion and exclusion criteria, 533 participants were included in the final analysis. The study protocol was approved by the Ethics Committee of the Yangtze River Shipping General Hospital (**Approval no. YL2026012**). Written informed consent was obtained from all participants before inclusion.

2.2 Data Collection and Anthropometric Measurements

Data were extracted from the health examination system of the Yangtze River Shipping General Hospital. Personnel involved in data extraction and verification received standardized training. The extracted data included demographic information, biochemical indices, and lifestyle questionnaire data. Anthropometric measurements were performed by trained medical staff using standardized protocols. These measurements included height, weight, waist circumference (WC), and hip circumference, from which body mass index (BMI) and WHR were calculated. Fasting venous blood samples were drawn from the antecubital vein, and a fully automated biochemical analyzer was used to determine FPG, triglycerides (TG), and other biochemical parameters. The TyG index was calculated using the following formula: TyG = ln [TG (mg/dL) × FPG (mg/dL) /2].

Marital status was categorized as married or unmarried (single, divorced, or widowed). Lifestyle behaviors were assessed using a self-reported lifestyle questionnaire covering five domains: diet, physical activity, smoking, alcohol consumption, and sleep quality. Participants completed the questionnaires independently at the examination site. Medical staff provided standardized instructions only and did not interfere with the responses. Upon completion, the questionnaires were automatically

exported and subjected to logical checks. Only questionnaires with complete and logically consistent responses to core items were considered valid.

2.3 Statistical analysis

- All statistical analyses were performed using R version 4.3.1. A two-sided $P < 0.05$ was considered statistically significant. Participants were categorized into tertile groups (T1–T3) according to the TyG index. Continuous variables with a normal distribution were expressed as mean ± standard deviation (SD) and compared using one-way analysis of variance (ANOVA). Continuous variables with a non-normal distribution were presented as median (interquartile range [IQR]) and compared using the Kruskal-Wallis H test. Categorical variables were presented as frequencies (percentages) and compared using the Chi-square test. The Jonckheere-Terpstra test was used to evaluate linear trends across TyG tertiles.
- Because the TyG index is calculated as ln [TG × FPG /2], both TG and FPG were excluded from multivariable analyses to avoid mathematical coupling. TC, HDL-C, and LDL-C were also excluded to focus on modifiable non-lipid factors and reduce potential collinearity. LASSO regression was used for feature selection from the remaining candidate variables. To reduce redundancy, variables with high pairwise correlations were removed prior to model construction. The optimal penalty parameter (λ) was determined via 10-fold cross-validation using the lambda.1se criterion. All continuous variables were standardized to Z-scores before modeling. HC3 robust standard errors were applied to correct for potential heteroscedasticity. Effect sizes were presented as standardized β with 95% confidence intervals (CIs). Model fit was reported using the adjusted R^2. Multicollinearity was assessed using the VIF, with VIF < 5 indicating no severe multicollinearity.

3. Results

3.1 Baseline characteristics of the study population across TyG index tertiles

- Between February 2025 and February 2026, 585 male seafarers were initially identified. After applying the predefined exclusion criteria, 52 individuals were excluded, and 533 participants were included in the final analysis (Fig. 1). Based on TyG index tertiles, participants were stratified into three groups: T1 (n = 178), T2 (n = 177), and T3 (n = 178). The distribution of occupational positions (deck vs. engine department) did not differ significantly among the three groups ($P = 0.392$). Baseline characteristics are summarized in Table 1.

Table 1
Baseline characteristics of seafarers stratified by tertiles of the TyG index.

Variable	TyG tertiles			*P-value*
	T1 (n = 178)	**T2 (n = 177)**	**T3 (n = 178)**	
TyG index	8.15 ± 0.23	8.68 ± 0.13	9.26 ± 0.35	< 0.001
Age (years)	30.37 ± 7.50	34.46 ± 7.22	34.81 ± 6.37	< 0.001
Occupational department				0.392
Deck Department	95 (53.4%)	106 (59.9%)	96 (53.9%)	-
Engine Department	83 (46.6%)	71 (40.1%)	82 (46.1%)	-
Marital status				< 0.001
Unmarried	90 (50.6%)	57 (32.2%)	49 (27.5%)	
Married	88 (49.4%)	120 (67.8%)	129 (72.5%)	-
WC (cm)	80.83 ± 7.94	85.88 ± 8.06	90.02 ± 8.20	< 0.001
HC (cm)	97.24 ± 6.49	100.24 ± 6.47	102.61 ± 7.07	< 0.001
WHR	0.83 ± 0.05	0.86 ± 0.05	0.88 ± 0.05	< 0.001
BMI (kg/m²)	22.99 ± 2.97	24.85 ± 2.89	26.32 ± 3.32	< 0.001
HbA1c (%)	5.58 ± 0.24	5.71 ± 0.47	5.76 ± 0.32	< 0.001
TC (mmol/L)	4.34 ± 0.72	4.81 ± 0.82	5.26 ± 0.92	< 0.001
HDL-C (mmol/L)	1.23 ± 0.24	1.10 ± 0.20	0.99 ± 0.17	< 0.001
LDL-C (mmol/L)	2.45 ± 0.56	2.93 ± 0.61	3.22 ± 0.72	< 0.001
eGFR (mL/min/1.73 m²)	115.82 ± 10.84	112.90 ± 9.70	111.44 ± 10.94	< 0.001
FPG (mmol/L)	5.18 (4.90, 5.45)	5.30 (5.04, 5.62)	5.38 (5.02, 5.66)	< 0.001

Variable	TyG tertiles			*P*-value
	T1 (n = 178)	T2 (n = 177)	T3 (n = 178)	
TG (mmol/L)	0.88 (0.71, 1.00)	1.39 (1.24, 1.52)	2.30 (1.92, 2.81)	< 0.001
ALT (U/L)	19.90 (14.30, 28.25)	23.80 (18.40, 30.90)	30.95 (23.52, 44.92)	< 0.001
AST (U/L)	18.70 (15.95, 22.37)	19.50 (16.50, 23.50)	22.45 (18.83, 26.90)	< 0.001
TBIL (μmol/L)	11.86 (9.20, 16.40)	12.20 (9.40, 15.85)	11.70 (9.30, 15.65)	0.770
DBIL (μmol/L)	3.32 (2.72, 4.70)	3.00 (2.40, 3.82)	2.80 (2.19, 3.50)	< 0.001
SUA (μmol/L)	355.00 (312.50, 412.75)	367.00 (327.00, 426.00)	395.50 (351.75, 439.00)	< 0.001
Dietary score	13.90 ± 2.51	13.44 ± 2.11	14.34 ± 2.31	0.001
Physical activity score	9.48 ± 1.78	9.38 ± 1.66	9.84 ± 1.71	0.033
Smoking score	7.72 ± 8.95	8.31 ± 9.32	11.49 ± 10.00	< 0.001
Alcohol consumption score	6.63 ± 1.00	6.88 ± 1.25	7.15 ± 1.42	< 0.001
Sleep score	10.70 ± 1.52	10.44 ± 1.39	10.97 ± 1.42	0.003
Lifestyle total score	48.43 ± 11.53	48.45 ± 11.50	53.80 ± 12.18	< 0.001

- As the TyG index increased, age showed a significant upward trend (*P* for trend < 0.001). WC, WHR, and BMI also increased progressively across tertiles (all *P* for trend < 0.001). Among biochemical indices, FPG, HbA1c, TG, TC, LDL-C, ALT, and SUA increased significantly, while HDL-C and DBIL decreased significantly (all *P* for trend < 0.001). TBIL did not differ significantly among groups (*P* = 0.770). Dietary, smoking, alcohol consumption, and overall lifestyle scores were significantly higher in the high TyG group than in the low TyG group (all *P* < 0.05). Physical activity (*P* = 0.033) and sleep scores (*P* = 0.003) differed across groups, with the lowest values observed in the moderate TyG tertile; the differences were not monotonic across tertiles.

3.2 Feature selection using LASSO regression

LASSO regression was used to select features associated with the TyG index from 21 candidate variables. Using 10-fold cross-validation and the lambda.1se criterion, the optimal log(λ) was − 4.3 (Fig. 2B). Under this penalty, four variables had coefficients shrunk to zero and were eliminated, and 17

variables with non-zero coefficients were retained (Table 2, Fig. 2A). Among the retained features, TC exhibited the largest absolute standardized coefficient, followed by HDL-C, LDL-C, DBIL, and ALT. Furthermore, key lifestyle characteristics, such as dietary score, smoking score, and alcohol consumption score, were also successfully retained by the model. Given the substantial risk of multicollinearity and mathematical coupling between TG and other lipid components (TC, HDL-C, and LDL-C) within overlapping metabolic pathways, these specific lipid fractions were intentionally excluded from the subsequent multivariable OLS model. These findings collectively suggest that glucolipid metabolic indicators, hepatic biochemical parameters, and unhealthy lifestyle behaviors contribute significantly to explaining the variance in the TyG index.

Table 2
Selection of optimal features associated with the TyG index using LASSO regression

Variable	Standardized Coefficient
TC	0.757
HDL-C	−0.530
LDL-C	−0.382
DBIL	−0.102
ALT	0.099
BMI	0.057
WC	0.056
Age	0.050
Unmarried	−0.041
Smoking score	0.040
SUA	0.032
WHR	0.018
AST	0.016
TBIL	0.013
Alcohol consumption score	0.012
Dietary score	0.010
eGFR	−0.003

3.3 Multivariable linear regression analysis of factors independently associated with the TyG index

The final OLS model included the 10 variables described above (Table 3, Fig. 3). The maximum VIF was 3.63, indicating no severe multicollinearity. HC3 robust standard errors were used to address heteroscedasticity. The model explained 32.1% of the variance in the TyG index (adjusted R^2 = 0.321). In this model, ALT (β = 0.303, 95% CI 0.150–0.456, P < 0.001), WHR (β = 0.216, 95% CI 0.137–0.296, P < 0.001), and SUA (β = 0.127, 95% CI 0.050–0.204, P = 0.001) were positively and independently associated with the TyG index. Age (β = 0.191, 95% CI 0.096–0.285, P < 0.001), dietary score (β = 0.095, 95% CI 0.021–0.169, P = 0.012), and alcohol consumption score (β = 0.074, 95% CI 0.002–0.146, P = 0.044) were also positively associated. DBIL was inversely associated (β = −0.206, 95% CI − 0.279 to − 0.132, P < 0.001). AST (P = 0.577), eGFR (P = 0.674), and smoking score (P = 0.410) were not significantly associated.

Table 3
Multivariable linear regression analysis of independent factors associated with the TyG index

Variable	Standardized β	95% CI	P value	VIF
ALT	0.303	0.150, 0.456	< 0.001	3.63
WHR	0.216	0.137, 0.296	< 0.001	1.26
DBIL	−0.206	−0.279, − 0.132	< 0.001	1.05
Age	0.191	0.096, 0.285	< 0.001	1.72
SUA	0.127	0.050, 0.204	0.001	1.22
Dietary score	0.095	0.021, 0.169	0.012	1.08
Alcohol consumption score	0.074	0.002, 0.146	0.044	1.20
Smoking score	0.033	−0.046, 0.113	0.410	1.25
AST	−0.044	−0.197, 0.110	0.577	3.44
eGFR	−0.019	−0.106, 0.068	0.674	1.44

4. Discussion

- At present, few studies have focused on the early features of cardiometabolic risk in ocean-going seafarers. Applying the TyG index to health assessment in this population may complement traditional glucose and lipid measures and provide an opportunity for early lifestyle intervention. Based on 533 male ocean-going seafarers, this study examined the distribution of the TyG index and its associated factors. The findings describe a metabolic profile related to IR in this occupational group and may support early cardiometabolic risk screening and long-term health management in seafarers.
- The TyG index has been recognized as a simple surrogate marker for IR and is increasingly used to evaluate early metabolic abnormalities [9–11]. Compared with traditional assessments based on

fasting glucose alone, the TyG index uses only two routine biochemical parameters and is therefore feasible for large-scale screening. It is associated with overall cardiometabolic risk and with the onset and adverse outcomes of several cardiovascular and cerebrovascular diseases [9–11]. As an early-warning tool, the TyG index has been associated with MetS and has shown predictive value for the progression from high-normal blood pressure to hypertension [9, 15]. In addition, changes in the TyG index have been linked to stroke risk in adults over 45 years of age, and the index has shown utility in predicting incident type 2 diabetes mellitus (T2DM) and in evaluating long-term glycemic control [16]. An elevated TyG index is not only associated with coronary artery disease but has also been reported as a predictor of major adverse cardiovascular and cerebrovascular events (MACCE) in patients with ST-segment elevation myocardial infarction (STEMI) [17].

4.1 Gradient distribution and risk stratification value of the TyG index in ocean-going seafarers

In this study, participants were divided into three groups based on TyG index tertiles, with mean values of 8.15, 8.68, and 9.26 in the low, moderate, and high groups, respectively. As TyG levels increased, key metabolic indicators including WHR, FPG, HbA1c, SUA, and ALT showed a progressive deterioration. The tests for linear trends were statistically significant (all $P < 0.001$), indicating that the TyG index reflects the severity of metabolic disturbances in this occupational group. Previous studies have shown that an elevated TyG index is associated with increased cardiometabolic risk, with adverse outcomes increasing substantially when the index ranges between 8.88 and 9.18 [18, 19]. In the present study, the mean TyG index in the highest tertile (T3) reached 9.26. Although external risk thresholds derived from general or prediabetic populations cannot be directly applied to this specific occupational cohort, such an elevated TyG level suggests a considerable burden of metabolic abnormalities among seafarers. Furthermore, metabolic indicators deteriorated progressively across TyG tertiles. Therefore, rather than serving as an absolute diagnostic cutoff, the continuous gradient of the TyG index reflects the severity of metabolic disturbances and has practical value for cardiovascular risk assessment in this population.

4.2 Analysis of multidimensional independent associated factors for an elevated TyG index

This study used a two-step approach to construct the multivariable model. After feature selection by LASSO regression and subsequent estimation by OLS with HC3 robust standard errors, the final model accounted for 32.1% of the total variance in the TyG index. The results showed that ALT, WHR, age, SUA, unhealthy dietary patterns, and alcohol consumption were independently and positively associated with an elevated TyG index, whereas DBIL was inversely associated.

4.2.1 Association between hepatic biochemical indices and the TyG index

In the multivariable model, ALT showed a significant independent positive association with the TyG index (standardized β = 0.303, P < 0.001), while DBIL showed a significant independent inverse association (standardized β = -0.206, P < 0.001). These opposing associations of two routine hepatic biochemical indices with the TyG index suggest that early metabolic damage in ocean-going seafarers may involve both hepatic parenchymal injury related to local lipid overload and depletion of the endogenous antioxidant defense system.

The positive association between ALT and the TyG index observed in this study is consistent with previous findings [20–23]. Rana et al. [20] reported an independent positive correlation between the TyG index and ALT levels in 896 patients with MetS, which remained after adjusting for age, sex, BMI, diabetes history, and smoking status. Li et al. [21] found that the TyG index was significantly associated with non-alcoholic fatty liver disease (NAFLD) and performed better than other lipid and glycemic parameters in identifying NAFLD risk in patients with T2DM. From a pathophysiological perspective, because the TyG index directly incorporates fasting TG, it reflects not only IR but also the process of ectopic lipid spillover from insulin-resistant adipose tissue into the liver [22]. When the free fatty acid (FFA) load in hepatocytes exceeds the capacity for oxidative metabolism, abnormal accumulation of diacylglycerol (DAG) occurs. This activates protein kinase C (PKC)-dependent inflammatory pathways, thereby impairing hepatic insulin signaling. In addition, Bonnet et al. [23] found that ALT levels were associated with the severity of hepatic IR, reduced endogenous insulin clearance, and compensatory increases in fasting glucagon, suggesting that elevated liver enzymes reflect broader dysregulation of hepatic glucose metabolism.

Previous studies have demonstrated that mild-to-moderate elevations in serum bilirubin levels are associated with reduced risk of metabolic diseases such as obesity, diabetes, and coronary heart disease [24, 25]. In the present study, DBIL exhibited a significant independent negative correlation with the TyG index, a finding that obliquely highlights the critical role of oxidative stress in the pathological progression of IR among seafarers. Recent research indicates that bilirubin, at physiological concentrations, serves as a vital endogenous antioxidant, effectively scavenging reactive oxygen species (ROS) and inhibiting the lipid peroxidation chain reaction, thereby preserving pancreatic *β*-cell function and improving peripheral insulin sensitivity [24]. Kwon et al. [25] observed that in obese and male populations, an elevated TyG index is accompanied by a decline in bilirubin levels; this concurrent state essentially reflects a dual pathological manifestation of subclinical hepatocyte injury and compromised antioxidant capacity. For ocean-going seafarers chronically exposed to watchkeeping routines and unhealthy dietary behaviors, the burden of systemic oxidative stress and chronic low-grade inflammation is inherently elevated. Consequently, hepatic parenchymal damage associated with lipotoxicity is inevitably accompanied by intense intracellular oxidative stress responses.

Current pre-employment medical standards for Chinese ocean-going seafarers allow relatively high ALT levels, and abdominal ultrasonography is not routinely required for younger seafarers, which may delay early detection. In deep-sea settings with limited medical resources, combined assessment of the TyG

index with ALT and DBIL may provide a feasible approach for multidimensional risk stratification covering glucose and lipid metabolism, liver injury, and antioxidant capacity. This may support early identification of metabolic liver abnormalities and facilitate timely lifestyle and nutritional interventions.

4.2.2 Correlation between waist-to-hip ratio and the TyG index

The multivariable linear regression analysis showed an independent positive association between WHR and the TyG index. Central obesity reflects visceral fat deposition and contributes to IR through lipotoxicity and chronic low-grade inflammation, and may be more informative than BMI for metabolic risk assessment [26, 28]. Although meta-analyses suggest that common obesity indices have comparable associations with incident diabetes, WHR may be particularly useful in populations with abnormal body composition. In the present study, the mean WHR in the high TyG group was 0.88, approaching the proposed high-risk threshold of 0.89 for men in Asian populations [26], indicating that central obesity-related metabolic risk is already considerable in this occupational group.

Visceral fat deposition in ocean-going seafarers is closely related to their occupational exposure patterns. During voyages, disrupted watchkeeping schedules and high-fat diets may promote lipid accumulation [26–29]. Although high-intensity physical labor may partly offset overall weight gain, it may also lead to body composition changes, such as loss of skeletal muscle mass and accumulation of visceral fat. In this context, reliance on BMI alone may underestimate early metabolic abnormalities. Furthermore, during onshore leave, seafarers may show compensatory overeating and reduced physical activity, and this cyclical pattern may lead to recurrent weight fluctuations, which have been associated with elevated cardiometabolic risk [27, 28]. Short-term weight regain may preferentially affect visceral fat depots, potentially amplifying the metabolic effects of central obesity [28]. Mechanistically, visceral fat accumulation and IR may form a bidirectional positive feedback loop [28–30]. Visceral fat delivers FFAs to the liver via the portal vein. When this lipid load exceeds the liver's compensatory capacity, it increases TG levels by promoting very low-density lipoprotein (VLDL) synthesis and raises fasting glucose by impairing insulin signaling and enhancing hepatic gluconeogenesis, thereby increasing the TyG index [29]. Conversely, IR can further exacerbate visceral fat deposition, reinforcing this pathological cycle [30].

4.2.3 Correlation analysis between age and the TyG index

Age was independently and positively associated with the TyG index in the multivariable model. With advancing age, progressive decline of pancreatic β-cell function, loss of skeletal muscle mass, and central redistribution of fat may impair insulin sensitivity through different mechanisms. Recent studies have shown that the TyG index is associated with biological aging, and that once it exceeds certain thresholds, the risks of aging-related cardiovascular diseases and adverse outcomes increase [31, 32]. For example, Zhao et al. [31], using data from 13,291 adults in the National Health and Nutrition Examination Survey (NHANES), found a non-linear association between the TyG index and phenotypic age acceleration, with an inflection point at 9.60. Pan et al. [32] reported similar findings in 12,074 adults, with

an inflection point of approximately 8.66. A marked elevation in TyG levels may reflect substantial metabolic dysfunction associated with accelerated biological aging [33]. At the molecular level, these threshold effects may indicate critical points at which IR contributes to accelerated aging through oxidative stress, chronic inflammation, and mitochondrial dysfunction. For ocean-going seafarers, prolonged occupational stress and circadian misalignment may deplete metabolic reserves and accelerate age-related physiological decline, potentially leading to an earlier onset of abnormal TyG index.

4.2.4 Correlation analysis between serum uric acid and the TyG index

SUA was another independent factor positively associated with the TyG index, reflecting metabolic burden related to environmental exposures. Unlike the general population, the dietary structure of ocean-going seafarers is constrained by the physical isolation of long voyages. Onboard meals are often dominated by frozen meats and seafood, while fresh fruits and vegetables are relatively scarce. This high-purine dietary pattern may provide abundant substrates for uric acid synthesis and may impair excretion due to low intake of factors such as vitamin C. A meta-analysis by Wang et al. [34] showed a strong association between the TyG index and hyperuricemia, with each 1-unit increase in TyG associated with a 2.07-fold higher risk of hyperuricemia. Studies in patients with NAFLD and MetS have also reported higher TyG indices in hyperuricemic individuals than in normouricemic individuals [35, 36].The relationship between SUA and IR is not simply unidirectional. On the one hand, IR may reduce renal uric acid excretion through competitive inhibition and may contribute to renal tubular damage, leading to uric acid accumulation [36]. On the other hand, SUA is not an inert end-product but may actively participate in metabolic dysregulation [34, 37]. Hyperuricemia can downregulate lipid metabolism-related enzymes, induce intracellular oxidative stress, and reduce nitric oxide (NO) bioavailability, thereby impairing microcirculatory perfusion and insulin-mediated glucose uptake, and promoting IR and inflammation [36, 37].

4.2.5 Relationship between dietary and alcohol consumption habits and the TyG index

In terms of behavioral lifestyle, poor dietary scores and alcohol consumption scores were independently associated with a higher TyG index. The dietary structure of ocean-going seafarers is restricted by the physical isolation and cold-chain constraints of deep-sea voyages. Shipboard meals consist primarily of processed meats, frozen fish, and root-based starchy foods, with a notable lack of fresh fruits and vegetables. The Seafarer Nutrition Study reported that the provision of meat, fat, and eggs on merchant ships exceeds recommended levels by more than twofold, while the proportion of fruits, vegetables, and grains is far below dietary guideline recommendations [38]. Consistent with our findings, Liu et al. [39], in a large-scale cohort study, found that a dietary pattern characterized by high intakes of red meat, processed meat, fruit juices, and potatoes, and low intakes of green vegetables, oily fish, yogurt, and nuts, was significantly associated with a higher TyG index and an increased risk of T2DM. Similarly,

dietary patterns high in refined sugars, low-fiber breads, and butter, and low in fruits and vegetables, have been associated with elevated diabetes risk [40].Ingestion of refined carbohydrates and excess sugar can stimulate insulin secretion and upregulate hepatic de novo lipogenesis, converting surplus glucose into triglycerides and directly increasing the TG component of the TyG index. A higher energy contribution from carbohydrates corresponds to a greater risk of TyG elevation; conversely, a moderate increase in the energy contribution from fat has been associated with a decreased TyG index, mainly through a decline in fasting TG [41]. Furthermore, the culinary culture and shift-work systems in the seafaring population may further disrupt circadian rhythms, potentially amplifying the IR-inducing effects of poor diets.

Alcohol consumption, a common behavior for coping with stress among seafarers, also showed an independent positive association with the TyG index in this study. The fructose present in certain alcoholic beverages, such as beer, has been associated with an elevated TyG index and negative effects on glucose homeostasis [42]. Large-scale population studies have shown that alcohol consumption and smoking exert independent and additive effects on the TyG index; individuals with both exposures have significantly higher TyG indices than those with only one exposure and are more likely to develop metabolic abnormalities characterized by TyG ≥ 8.8 [43].

Although univariate analysis revealed elevated smoking scores in the high TyG group alongside non-monotonic variations in sleep and physical activity scores across the tertiles, these behavioral metrics did not retain independent associations with the TyG index in the multivariable model. Importantly, this statistical attenuation does not negate their well-documented metabolic hazards. Extensive literature suggests that smoking can directly impair pancreatic β-cell function and blunt peripheral insulin sensitivity, ultimately driving glucose intolerance and IR [44]. Concurrently, poor sleep is tightly coupled with circadian disruption, autonomic nervous system imbalance, and chronic systemic inflammation, which collectively orchestrate the progression of IR and cardiometabolic diseases [45, 46]. The lack of independent statistical significance in our multivariable model may be partially attributable to the high homogeneity of these specific behavioral exposures (e.g., universal shift-work and confined space limitations) among ocean-going seafarers.

4.3 Clinical implications and limitations

This cross-sectional study identified factors independently associated with an elevated TyG index in seafarers, adding to the epidemiological evidence on IR in this occupational group. Given that the TyG index has been associated with coronary artery calcification and atherosclerotic cardiovascular disease (ASCVD), the risk profile constructed in this study may provide an earlier observational window for primary prevention of cardiovascular events in seafarers. In maritime occupational health practice, the TyG index could be incorporated into pre-employment medical examination (PEME) and annual health monitoring as an auxiliary screening indicator for early metabolic abnormalities. For high-risk individuals, interventions targeting the modifiable factors identified in this study could be implemented through maritime telemedicine systems. Specific measures may include: (i) developing standardized meal plans

emphasizing high-fiber vegetables, low-glycemic-index carbohydrates, and high-quality proteins; (ii) promoting time-efficient exercise prescriptions, such as high-intensity interval training (HIIT) or resistance band training, adapted to confined cabin spaces; and (iii) managing rapid weight fluctuations and heavy alcohol consumption during onshore leave through remote health coaching, thereby slowing the progression from metabolic disturbances to cardiovascular disease.

This study has several limitations. First, the cross-sectional design precludes causal inference; prospective cohorts are needed to determine the predictive value of the TyG index for cardiovascular events in seafarers. Second, the imprecision of behavioral exposure assessment is an important limitation. The simple scoring of smoking, sleep, and physical activity may not accurately capture smoking intensity, shift work-related circadian sleep disruption, and intermittent activity patterns. This imprecision may have underestimated the effects of these established risk factors, partly explaining the non-significant findings. Third, although the multivariable model adjusted for core covariates, residual confounding may still exist from genetic background, psychological stress during voyages, dietary micronutrient intake, and heterogeneous environmental exposures during port calls. Finally, the study included only male deck and engine department seafarers, limiting generalizability to female seafarers and catering/service personnel. Future studies should establish multicenter prospective seafarer cohorts, integrate objective exposure measurement tools such as actigraphy, cotinine assays, and continuous glucose monitoring (CGM), and use multi-omics approaches to clarify the trajectory of metabolic imbalance under extreme occupational environments and its transition to clinical cardiovascular outcomes.

5. Conclusions

This study demonstrates that among ocean-going seafarers, central obesity represented by WHR, elevated ALT and SUA levels, as well as unhealthy dietary and alcohol consumption behaviors, are independently and positively associated with an elevated TyG index, whereas DBIL acts as an independent protective factor. These findings suggest that ectopic visceral fat accumulation and systemic oxidative stress play pivotal roles in early metabolic damage within the specific, confined environment of deep-sea voyages. Proactively implementing targeted interventions centered on waist circumference control, nutritional optimization, and the management of unhealthy behaviors will aid in prematurely halting the progression of cardiometabolic diseases. Such measures are of profound significance for mitigating the risk of sudden acute illnesses during long-haul voyages and comprehensively safeguarding the occupational health of the seafaring population.

Declarations

Ethics approval and consent to participate

This study was conducted in accordance with the principles of the Declaration of Helsinki. The study protocol was reviewed and approved by the Ethics Committee of the Yangtze River Shipping General

Hospital (Approval No. YL2026012).

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available due to concerns regarding participant privacy and confidentiality. Data may be available from the corresponding author upon reasonable request, subject to approval from the Ethics Committee of the Yangtze River Shipping General Hospital.

Competing interests

The authors declare no competing interests.

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Authors' contributions

C.C. and H.Z. conceptualised and designed the study. C.C. performed the formal analysis and software implementation. C.C. and H.Z. curated the data. C.C. drafted the original manuscript. H.Z. reviewed and edited the manuscript. H.Z. supervised the project, administered the study, and acquired the funding. All authors read and approved the final manuscript.

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Authors' information

Not applicable.

STROBE Statement

This cross-sectional study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines. A completed STROBE checklist is provided as Additional file 1.

Pre-registration

This study was a cross-sectional observational analysis and was not pre-registered in a clinical trial registry. The study protocol was reviewed and approved by the institutional ethics committee prior to the commencement of data analysis.

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Figures

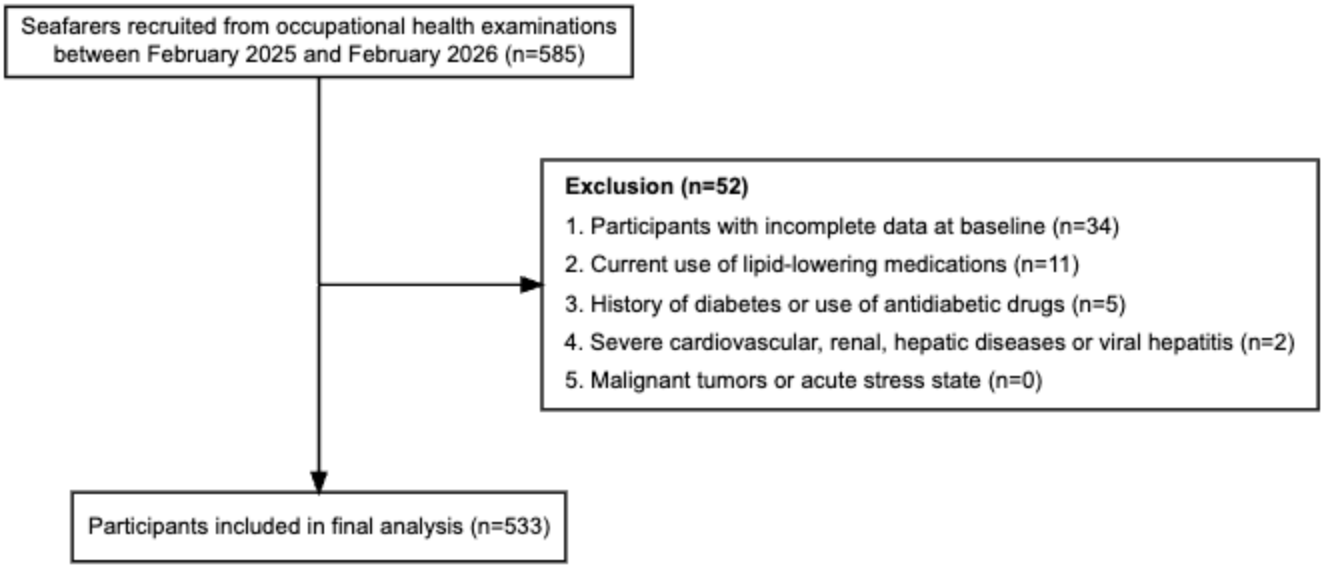


Figure 1

Flowchart of the study population selection process.

A total of 585 male ocean-going seafarers who underwent occupational health examinations between February 2025 and February 2026 were initially screened. After applying the predefined exclusion criteria, 52 individuals were excluded, resulting in a final analytical cohort of 533 participants.

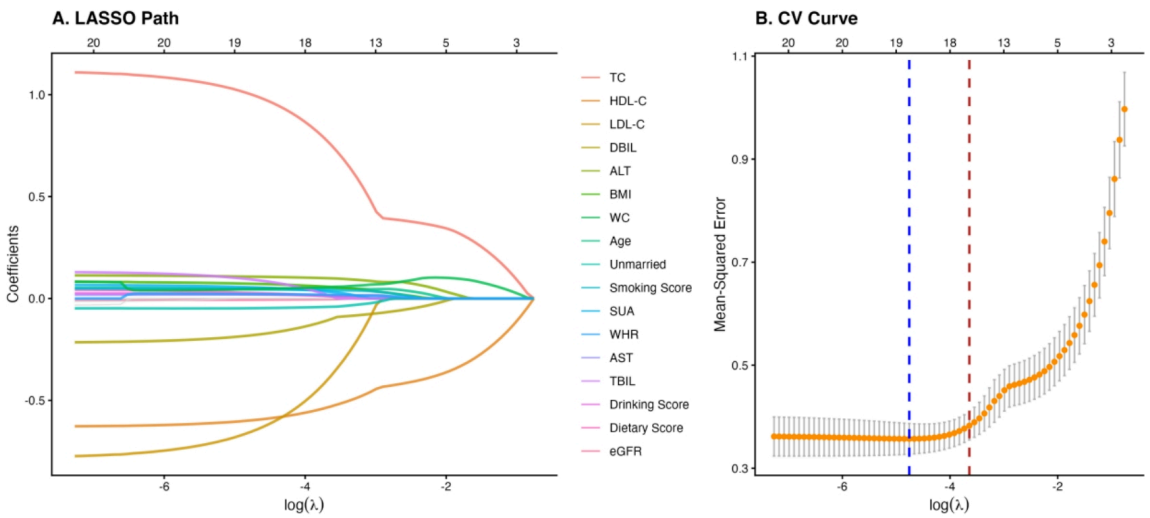


Figure 2

Feature selection using the least absolute shrinkage and selection operator (LASSO) regression model.

(A) LASSO coefficient profiles of the candidate variables. The coefficient profile plot is generated against the log(λ) sequence. Each curve represents a variable, and the path shows how its coefficient shrinks toward zero as the penalty increases. (B) Tuning parameter (λ) selection via 10-fold cross-validation. The solid curve indicates the mean squared error (MSE), and the vertical bars represent the standard error (SE). The dotted vertical lines indicate the optimal values based on the minimum criteria (λ_{min}) and the one-standard error (λ_{1se}) criterion. The optimal log(λ) value of -4.3 was chosen according to the λ_{1se} criteria, resulting in the retention of 17 non-zero features.

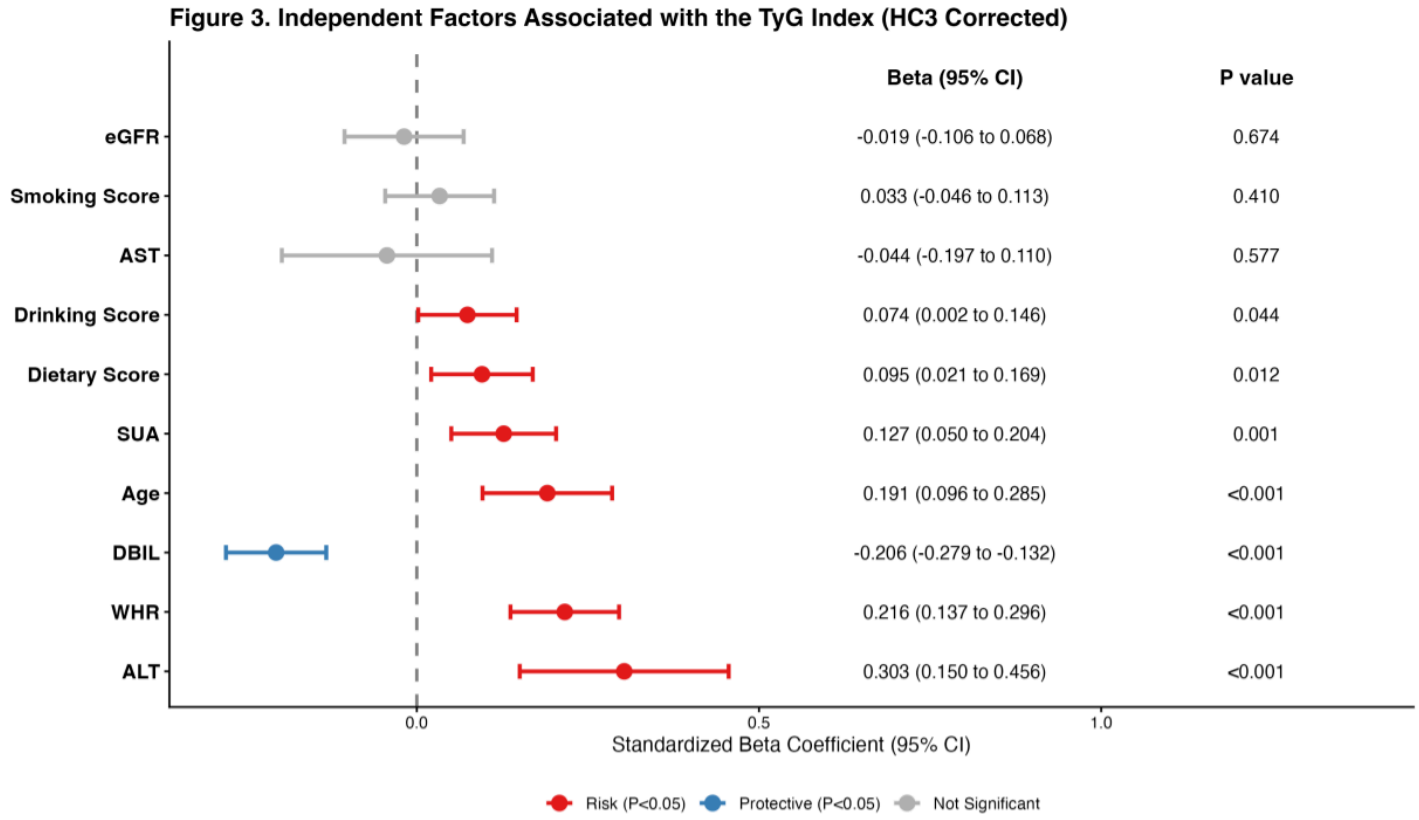


Figure 3

Forest plot illustrating the independent factors associated with the TyG index.

The plot displays the standardized regression coefficients (β, indicated by the square markers) and their corresponding 95% confidence intervals (CIs, indicated by the horizontal error bars) derived from the multivariable ordinary least squares (OLS) regression model. HC3 robust standard errors were applied to adjust for heteroscedasticity. The vertical dashed line at zero represents the null hypothesis (no association). Variables whose 95% CIs do not cross the zero line are considered statistically significant independent associated factors.