Research Square

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Association of the admission albumin–bilirubin score with long-term major adverse cardiovascular events among patients who survived to discharge after percutaneous coronary intervention for non-ST-segment elevation myocardial infarction: a single-center cohort study

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Research Article

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Abstract

Objective

To investigate the association of admission albumin–bilirubin (ALBI) score with long-term major adverse cardiovascular events (MACEs) among patients who survived to discharge after percutaneous coronary intervention (PCI) for non-ST-segment elevation myocardial infarction (NSTEMI), and to assess whether ALBI provides prognostic information beyond the admission GRACE score.

Methods

We retrospectively included 681 patients hospitalized between January 1, 2023, and September 1, 2025, who survived to discharge after PCI for NSTEMI. Patients were categorized into ALBI tertiles (T1, T2 and T3). Kaplan–Meier analysis, multivariable Cox proportional hazards regression and restricted cubic spline analysis were used to evaluate the association between ALBI and long-term MACEs. Missing data were handled using predictive mean matching, generating 50 imputed datasets. Subgroup and sensitivity analyses were performed. The discriminatory performance of the admission GRACE-based model was compared before and after ALBI was added. Follow-up continued through September 6, 2026.

Results

Among 681 patients, the median follow-up duration was 585 days, during which 186 MACEs occurred, representing 27.3% of the cohort. The cumulative proportions of MACEs in T1, T2 and T3 were 18.1%, 29.1% and 34.8%, respectively, differing significantly among groups (all $P < 0.001$). After adjustment, each 1-standard-deviation (1-SD) increase in ALBI was associated with a 25% higher risk of long-term MACEs (HR = 1.25, 95% CI: 1.06–1.46, P = 0.007). Compared with T1, the corresponding HRs were 1.59 for T2 and 1.60 for T3. Restricted cubic spline analysis showed no evidence of a significant nonlinear association. The results were therefore compatible with an approximately linear association within the observed ALBI range. The direction of association remained positive in sensitivity analyses, although the complete-case estimate was less precise and was not statistically significant. Adding ALBI produced small, statistically nonsignificant increases in the GRACE model's C-index and 365-day time-dependent AUC.

Conclusion

Among patients who survived to discharge after PCI for NSTEMI, a higher admission ALBI score was independently associated with increased risk of long-term MACEs, with an approximately linear pattern across the observed range. ALBI may serve as a simple marker of long-term risk. Its incremental predictive value beyond the GRACE score requires validation in multicenter prospective studies.

1 Introduction

Acute non–ST-segment elevation myocardial infarction (NSTEMI) is a common and clinically important manifestation of acute coronary syndrome (ACS) [1]. Although percutaneous coronary intervention (PCI) and guideline-directed medical therapy have improved acute-phase outcomes, some patients still experience major adverse cardiovascular events (MACEs) after discharge, including recurrent ischemia, heart failure (HF), repeat revascularization and death[2]. Long-term risk stratification, secondary prevention and structured follow-up therefore remain important for patients with NSTEMI undergoing PCI[3].

Risk assessment in ACS currently relies mainly on clinical prediction tools, including the Global Registry of Acute Coronary Events (GRACE) score and the Thrombolysis in Myocardial Infarction (MI) risk score [4]. The GRACE score incorporates clinical characteristics and laboratory data obtained at admission and has established prognostic value in ACS[5]. However, long-term outcomes after PCI for NSTEMI may also be influenced by nutritional status, systemic inflammation, organ perfusion and hepatic congestion, in addition to acute ischemic burden and coronary disease severity[6]. Readily available markers derived from routine laboratory tests may therefore complement traditional risk assessment.

The albumin–bilirubin (ALBI) score, calculated from serum albumin and total bilirubin levels, provides an objective assessment of liver function [7] and was originally developed to quantify hepatic functional reserve in patients with hepatocellular carcinoma[8]. It has subsequently been studied in vascular and cardiovascular populations[9–12]. Albumin may reflect malnutrition but is also influenced by inflammation, hepatic synthesis and vascular permeability[13]. Total bilirubin may vary with hepatic congestion, inflammation, oxidative stress, hypoperfusion and endothelial dysfunction[14]. ALBI may therefore capture part of the systemic pathophysiological burden associated with adverse cardiovascular outcomes, including hepatic dysfunction, inflammation and circulatory or metabolic disturbances[15].

Previous studies have associated ALBI with prognosis in liver disease [16, 17], adverse outcomes in acute heart failure (AHF)[10–12]and no-reflow among patients with non-ST-segment elevation ACS undergoing PCI[18]. More recent studies have examined related but distinct questions. Chen et al. evaluated bilirubin components in Chinese patients with ST-segment elevation MI after primary PCI, focusing on in-hospital adverse events[19]. Zhao et al. used the MIMIC-IV database to study critically ill patients undergoing PCI, with ICU mortality and 28-day post-discharge mortality as the main outcomes[20]. Chen et al. studied 982 patients with NSTEMI in Hubei and reported an association between ALBI and post-discharge all-cause mortality over a median follow-up of 27 months[21]. These studies provide important context but differ from the present study in infarction phenotype, clinical setting, exposure definition, endpoint and follow-up horizon. The association between admission ALBI and long-term composite MACEs in patients with NSTEMI who survive to hospital discharge after PCI remains unclear.

Therefore, a structured comparison of related studies is provided in Supplementary Table S4.

Accordingly, this study evaluated the association between admission ALBI and long-term composite MACEs among such patients, aiming to provide population- and endpoint-specific evidence that complements prior mortality, ICU and procedural studies. It was not designed to establish causality or to replace established risk scores. We also examined whether ALBI provided incremental discrimination beyond the admission GRACE score.

2 Materials and methods

2.1 Study design and participants

This single-center, retrospective observational cohort study consecutively enrolled patients who were hospitalized at the Affiliated Hospital of Guangdong Medical University between January 1, 2023, and September 1, 2025, were diagnosed with NSTEMI and underwent PCI.

NSTEMI was diagnosed according to current clinical guidelines, based on ischemic symptoms or ischemic electrocardiographic changes, elevated biomarkers of myocardial injury and the absence of persistent ST-segment elevation.

The exclusion criteria were: (1) age under 18 years; (2) missing follow-up data; (3) severe renal impairment, defined as an estimated glomerular filtration rate (eGFR) below 30 mL/(min·1.73 m²) or receipt of renal replacement therapy; (4) severe hepatic dysfunction, defined as an alanine aminotransferase (ALT) ≥ 250 U/L, corresponding to five times the upper reference limit of 50 U/L in the study laboratory; (5) chronic infectious disease or malignancy; (6) missing information required to define the exposure, eligibility or primary outcome; and (7) in-hospital death.

Because this study evaluated post-discharge prognosis, only patients who survived hospitalization and had ascertainable post-discharge outcomes were eligible. Patients without a MACE were required to have at least 365 days of potential follow-up, whereas patients who experienced a MACE were followed until the first event. This design estimates post-discharge risk among discharge survivors and does not estimate the risk of in-hospital death. Ultimately, 681 patients were included, of whom 186 experienced a long-term MACE.

This study was approved by the Medical Ethics Committee of the Affiliated Hospital of Guangdong Medical University (Approval Number: PJKT2026-279) and was conducted in accordance with the principles of the Declaration of Helsinki. As this was a retrospective study and all data were de-identified, the ethics committee waived the requirement for written informed consent.

2.2 Collection of clinical data

Demographic data, vital signs, medical history, laboratory test results, echocardiographic findings, coronary angiography and PCI treatment data, medications administered during hospitalization, and in-hospital outcomes were collected through the hospital's electronic medical record system.

Demographic and general clinical data included age, sex, height, weight, body mass index (BMI), heart rate, systolic blood pressure and diastolic blood pressure. BMI was calculated as body weight (kg) divided by height squared (m^2). Medical history included hypertension, diabetes mellitus, hyperlipidemia, stroke, chronic kidney disease (CKD), chronic obstructive pulmonary disease (COPD), malignancy and atrial fibrillation (AF). Smoking and alcohol consumption status were classified according to the medical records.

Hypertension was defined as a previously confirmed diagnosis of hypertension, current antihypertensive therapy, or repeated measurements showing systolic blood pressure ≥ 140 mmHg and/or diastolic blood pressure ≥ 90 mmHg. Diabetes mellitus was defined as a previously confirmed diagnosis of diabetes, current glucose-lowering therapy, fasting plasma glucose ≥ 7.0 mmol/L or random plasma glucose ≥ 11.1 mmol/L.

Echocardiographic parameters included left ventricular ejection fraction (LVEF) and left ventricular end-diastolic diameter (LVEDD). The Killip classification was used to assess cardiac function on admission, and the GRACE score was recorded for clinical risk assessment. Coronary angiography and PCI were performed according to the patient's clinical condition and current guidelines. The number and distribution of diseased coronary vessels, the presence of left-main disease, management of the culprit vessel and whether PCI was performed during hospitalization were recorded. Selected baseline characteristics relevant to the primary analysis are provided in Table 1. The complete set of collected variables is provided in Supplementary Table S5.

2.3 Laboratory tests and derived indices

Venous blood samples were collected after admission for laboratory testing. The measured parameters included white blood cell, neutrophil, lymphocyte and monocyte counts; hemoglobin; platelet count; C-reactive protein (CRP); creatine kinase; creatine kinase-MB (CK-MB); high-sensitivity cardiac troponin T (hs-cTnT); N-terminal pro–B-type natriuretic peptide (NT-proBNP); glycated hemoglobin; fasting blood glucose; urea; creatinine; uric acid; total bilirubin; albumin; total cholesterol; triglycerides; high-density lipoprotein cholesterol (HDL-C); and low-density lipoprotein cholesterol (LDL-C).

The estimated glomerular filtration rate (eGFR) was calculated using the CKD-EPI equation based on serum creatinine, age and sex. The blood urea nitrogen-to-creatinine ratio (BUN/Cr) was calculated as the ratio of blood urea nitrogen to serum creatinine. Because CRP values were right-skewed, they were natural logarithmically transformed using the following formula: LnCRP = ln(CRP). CRP values below the detection limit were assigned a value of 0.05 mg/L before natural logarithmic transformation.

2.4 Calculation of the ALBI score

The primary exposure measure in this study was the albumin-bilirubin (ALBI) score at admission. The ALBI score was calculated using the following formula: ALBI = 0.66 × log10 [total bilirubin (μmol/L)] − 0.085 × albumin (g/L).

A higher ALBI score indicates a lower albumin level and/or a higher bilirubin level, suggesting poorer liver function and nutritional status. ALBI was analyzed as both a continuous and a categorical variable. Continuous ALBI was standardized per 1-SD increase. Categorical ALBI was divided into tertiles (T1, T2 and T3), with 227 patients in each group, and T1 was used as the reference group.

2.5 Study outcomes and follow-up

The primary outcome was time to the first post-discharge MACE, defined as all-cause death, acute MI, HF readmission, angina requiring PCI, or an acute cerebrovascular event. Only the first event was counted. The five components occurred in 52, 15, 12, 106 and 1 patients, respectively, totaling 186 events. The available analytic endpoint was a composite MACE indicator; individual component-specific hazard models were not performed.

After discharge, patients were followed through outpatient visits, rehospitalization records and telephone follow-up. Clinical outcomes were recorded at 30, 180 and 365 days and during longer-term follow-up. For horizon-specific comparisons, follow-up was administratively truncated at the corresponding time point. Patients without a MACE were required to have at least 365 days of potential follow-up, whereas those who experienced a MACE were followed until the first event. Participants without an endpoint event were censored at the last follow-up or the administrative study cutoff date of September 6, 2026. No patients were excluded because of missing follow-up data (n = 0; Fig. 1). Follow-up time was calculated from the date of discharge.

2.6 Handling of missing data

First, missingness was assessed for all study variables, with the number and proportion of missing values reported for each variable. Detailed results are presented in Supplementary Table S1.

Variables were not excluded solely because their missingness exceeded 30%. Although BMI and CRP had relatively high proportions of missing data, both have clear clinical relevance. BMI reflects physical and nutritional status, whereas CRP reflects systemic inflammation; both may also confound the association between ALBI and long-term MACEs. Based on their clinical importance and the prespecified confounder-selection criteria, BMI and CRP were retained in the multivariable analysis. Creatine kinase had 99.56% missing values and was not included as a covariate in Model 3; it was retained only in the complete descriptive table for transparency.

Under the missing-at-random (MAR) assumption, missing data were handled using multiple imputation by chained equations with predictive mean matching (PMM), generating 50 imputed datasets. The imputation model included ALBI, the MACE indicator, observed follow-up time, demographic characteristics, medical history, laboratory results, GRACE scores, echocardiographic parameters and other auxiliary variables associated with missing variables or clinical outcomes.

BMI was recalculated after height and weight were imputed. CRP was natural log-transformed after imputation to obtain LnCRP, and fasting blood glucose was included as an imputation target. All 50

imputed datasets had complete values for the Model 3 covariates. Statistical analyses were performed separately in each imputed dataset, and Rubin's rules were used to pool regression coefficients, standard errors, HRs and 95% confidence intervals. The event indicator and observed follow-up time were retained as auxiliary variables, and no missing follow-up time was present in the final analytic cohort. Fifty imputations were used to improve estimate stability in the presence of substantial BMI and CRP missingness. Sensitivity analyses compared the estimated ALBI effects with and without adjustment for BMI and LnCRP.

2.7 Statistical analysis

Continuous variables were expressed as mean ± standard deviation or median and interquartile range, depending on their distribution, while categorical variables were expressed as counts and percentages. Continuous variables were compared among the three ALBI groups using analysis of variance or Kruskal–Wallis test, and categorical variables were compared using χ^2 or Fisher's exact tests.

Kaplan–Meier curves were used to depict the cumulative incidence of MACEs across ALBI groups, and between-group differences were assessed using the log-rank test. MACEs were also assessed at 30, 180 and 365 days and throughout the entire follow-up period.

Cox proportional hazards regression models were used to evaluate the association between ALBI and long-term MACEs. Model 1 was an unadjusted crude model; Model 2 was adjusted for sex and age; and Model 3 included sex, age, hypertension, diabetes, smoking, alcohol consumption, LnCRP, fasting blood glucose, the GRACE score, BMI, LDL-C and creatinine. Because age and creatinine-related information was also incorporated into the GRACE score, Model 3 was interpreted as a conservative adjustment model, not as a clinical prediction model. A personal history of coronary artery disease was not included in the final adjusted model.

Continuous ALBI was analyzed per 1-SD increase. For categorical ALBI, T1 was used as the reference group, and P for trend was calculated. Cox models were fitted separately in each imputed dataset, and the results were pooled using Rubin's rules.

Restricted cubic spline analysis was performed to evaluate the dose–response relationship between ALBI and the risk of long-term MACEs. Four knots were placed at the 5th, 35th, 65th and 95th percentiles of the ALBI distribution, with the median ALBI value as the reference. The overall association, linear component and nonlinear component were assessed using the corresponding joint, linear-term and nonlinear-term tests, respectively.

2.8 Testing the proportional hazards assumption

The proportional hazards assumption was assessed using Schoenfeld residuals. In each of the 50 multiply imputed datasets, the correlation between Schoenfeld residuals and log(time + 1) was assessed for each covariate. Because these diagnostics produced P values rather than regression coefficients, P

values were summarized by their median, minimum, maximum and the number of datasets with $P < 0.05$; they were not pooled using Rubin's rules. Detailed results are presented in Supplementary Table S2.

When a covariate showed potential time dependence, a stratified Cox regression model was used as a sensitivity analysis. Patients were stratified by age (≤ 65 years vs > 65 years), allowing age-specific baseline hazards while estimating a common ALBI coefficient across strata. This approach evaluated the potential effect of age-related time dependence on the estimated association between ALBI and long-term MACEs.

2.9 Subgroup analysis

Prespecified subgroups included age, BMI, sex, smoking status, hypertension and diabetes. Age was categorized as ≤ 65 years or > 65 years, and BMI as < 28 kg/m² or ≥ 28 kg/m². Within each subgroup, multivariable Cox models were used to assess the association between each 1-SD increase in ALBI and long-term MACEs. The stratification variable was removed from the corresponding adjusted model to avoid duplicate adjustment.

Interaction P values were calculated by including ALBI-by-subgroup interaction terms in the Cox models. These exploratory analyses evaluated the consistency of the association between ALBI and long-term MACEs across clinical subgroups.

2.10 Model discrimination and ROC analysis

To evaluate the incremental discriminatory value of ALBI, we first constructed a baseline model incorporating the admission GRACE score. ALBI was then added to this model. Harrell's C-index and the 365-day time-dependent AUC were compared between the two models. Differences and 95% confidence intervals were estimated using 1,000 patient-level bootstrap resamples, and two-sided bootstrap P values were calculated for the increments.

Baseline and time-dependent ROC curves at 30, 180 and 365 days were plotted, with AUCs and 95% confidence intervals calculated. Baseline ROC analysis treated the occurrence of any MACE during available follow-up as a binary outcome, whereas time-dependent ROC analysis evaluated event status at each prespecified horizon using inverse probability of censoring weighting (IPCW). AUC confidence intervals were obtained from 1,000 bootstrap resamples. Time-dependent AUC curves illustrated changes in discrimination over follow-up; detailed results are presented in Supplementary Figure S1. This analysis was exploratory and should not be interpreted as confirmatory evidence that ALBI improves clinical prediction-model performance.

2.11 Sensitivity analysis

To assess the potential impact of substantial BMI and CRP missingness on the primary results, the complete Model 3, which included BMI and LnCRP, was compared with a sensitivity model that excluded BMI and LnCRP but retained the other prespecified covariates. Both models used the same multiply imputed datasets.

Both models assessed the association of each 1-SD increase in ALBI and of ALBI tertiles with long-term MACEs. HRs, 95% confidence intervals, P values and P for trend were compared.

In addition, a complete-case sensitivity analysis included only patients with no missing data for ALBI, follow-up time, MACEs or Model 3 covariates. This analysis evaluated the stability of the primary results under an alternative missing-data strategy. Changes in effect size, direction or statistical significance were reported in the Results and Discussion sections.

2.12 Assessment of multicollinearity

The variance inflation factor (VIF) was used to assess multicollinearity among the covariates in Model 3. VIFs were calculated using the Model 3 covariates from the first imputed dataset as a prespecified diagnostic. Detailed results are presented in Supplementary Table S3.

2.13 Statistical software and significance criteria

Statistical analyses were performed using Python. The pandas, NumPy, SciPy and statsmodels packages were used for data processing and statistical modeling, and Matplotlib was used to generate statistical figures. All tests were two-sided, with $P < 0.05$ considered statistically significant. Cox regression results are presented as hazard ratios (HRs) and 95% confidence intervals. The effect of continuous ALBI is reported per 1-SD increase.

3 Results

3.1 Study participants and baseline characteristics

A total of 681 patients with NSTEMI who underwent PCI were ultimately included in this study. Based on tertiles of the ALBI score at admission, patients were divided into the T1, T2 and T3 groups, with 227 patients in each group. The ALBI ranges for the T1, T2 and T3 groups were − 3.65 to − 2.81, − 2.81 to − 2.54 and − 2.53 to − 1.33, respectively. Follow-up was calculated from the date of discharge until the first MACE, last follow-up or the administrative study cutoff date of September 6, 2026. Patients who experienced an endpoint event were followed until the first event, whereas those without an endpoint event were followed until the last follow-up or the administrative study cutoff date. The median follow-up duration for the overall cohort was 585 days, with an interquartile range of 389–839 days. During follow-up, 186 MACEs occurred, corresponding to 27.3% of the cohort. The five first-recorded MACE components occurred in 52 patients with all-cause death, 15 with acute MI, 12 with HF readmission, 106 with angina requiring PCI and 1 with an acute cerebrovascular event, totaling 186 events. The detailed patient inclusion and exclusion process is shown in Fig. 1.

Note

Study participants were screened according to the predefined inclusion and exclusion criteria, and 681 patients with NSTEMI who underwent PCI were ultimately included.

There were no statistically significant differences among the three groups in sex distribution or the prevalence of hypertension and diabetes. As the ALBI score increased, patient age progressively increased, with median ages of 60, 65 and 71 years in the T1, T2 and T3 groups, respectively ($P < 0.001$); BMI progressively decreased to 24.52, 23.26 and 22.58 kg/m², respectively ($P < 0.001$). Patients in the T3 group had lower systolic and diastolic blood pressure, and the proportions of smokers and alcohol consumers also differed among the three groups.

Regarding clinical severity, patients in the T3 group had a lower LVEF, a larger LVEDD, a higher Killip class and a markedly elevated GRACE score. The median GRACE scores in the three groups were 140, 146 and 171, respectively ($P < 0.001$). Laboratory tests showed that CRP and LnCRP levels were significantly higher in the T3 group than in the T1 and T2 groups, with median LnCRP values of 1.64, 1.75 and 2.54, respectively ($P < 0.001$). As the ALBI score increased, lymphocyte count, hemoglobin, platelet count, albumin and eGFR generally decreased, whereas total bilirubin, BNP and hs-cTnT levels generally increased.

The T3 group had higher rates of furosemide and spironolactone use, as well as a higher incidence of HF during hospitalization. During long-term follow-up, the cumulative proportions of MACEs in the T1, T2 and T3 groups were 18.06%, 29.07%, and 34.80%, respectively, showing an increasing trend with higher ALBI scores ($P < 0.001$). There was no statistically significant difference in follow-up duration among the three groups ($P = 0.620$). See Table 1.

Table 1
Baseline characteristics according to ALBI tertiles.

Variable	Overall (n = 681)	T1 (-3.65 to -2.81, n = 227)	T2 (-2.81 to -2.54, n = 227)	T3 (-2.53 to -1.33, n = 227)	P value
Demographic characteristics					
Sex, male	520 (76.36)	177 (77.97)	178 (78.41)	165 (72.69)	0.279
Age (years)	66.00 (57.00, 74.00)	60.00 (52.00, 69.50)	65.00 (57.00, 73.00)	71.00 (63.00, 78.50)	< 0.001
Vital signs and anthropometric measurements					
BMI	23.45 (21.18, 25.87)	24.52 (22.41, 26.62)	23.26 (21.11, 25.71)	22.58 (20.33, 25.02)	< 0.001
Medical history					
Hypertension, yes	345 (50.70%)	124 (54.74%)	108 (47.77%)	113 (49.58%)	0.312
Diabetes, yes	171 (25.11%)	63 (27.95%)	45 (19.89%)	62 (27.51%)	0.086
Smoking, yes	317 (46.55%)	108 (47.58%)	120 (52.86%)	89 (39.21%)	0.013
Alcohol consumption, yes	135 (19.82%)	56 (24.67%)	48 (21.15%)	31 (13.66%)	0.011
Echocardiography					
LVEF (%)	56.00 (50.00, 60.00)	56.00 (53.00, 60.00)	57.00 (51.00, 60.00)	55.00 (46.00, 59.00)	< 0.001
Clinical severity					
Killip class	I: 382 (56.09%); II: 227 (33.33%); III: 39 (5.73%); IV: 33 (4.85%)	I: 152 (66.96%); II: 59 (25.99%); III: 11 (4.85%); IV: 5 (2.20%)	I: 139 (61.23%); II: 75 (33.04%); III: 5 (2.20%); IV: 8 (3.52%)	I: 91 (40.09%); II: 93 (40.97%); III: 23 (10.13%); IV: 20 (8.81%)	< 0.001

Note: Values were presented as n (%) or median (interquartile range), unless otherwise indicated. Continuous variables were compared using analysis of variance or Kruskal–Wallis tests, and categorical variables using χ^2 or Fisher's exact tests. BMI, body mass index; LVEF, left ventricular ejection fraction; GRACE, global registry of acute coronary events; CRP, C-reactive protein; LDL-C, low-density lipoprotein cholesterol; eGFR, estimated glomerular filtration rate; ALBI, albumin–bilirubin; LnCRP, natural logarithm of CRP; PCI, percutaneous coronary intervention; HF, heart failure; MACEs, major adverse cardiovascular events; ALT, alanine aminotransferase. A complete table of all collected variables is provided in Supplementary Table S5; variables shown there are not necessarily included in the primary model.

Variable	Overall (n = 681)	T1 (-3.65 to -2.81, n = 227)	T2 (-2.81 to -2.54, n = 227)	T3 (-2.53 to -1.33, n = 227)	P value
Demographic characteristics					
GRACE score	152.00(129.00, 178.00)	140.00(117.00, 160.00)	146.00(127.00, 168.00)	171.00(150.00, 189.50)	< 0.001
Laboratory tests					
CRP (mg/L)	7.11 (2.48, 28.12)	5.32 (2.30, 12.04)	5.72 (1.88, 15.41)	14.80 (5.00, 67.28)	< 0.001
Total bilirubin (μmol/L)	12.20 (8.90, 16.80)	10.70 (7.40, 14.10)	12.60 (9.40, 16.55)	14.20 (10.40, 19.00)	< 0.001
Albumin (g/L)	39.90 (37.30, 42.10)	43.00 (41.60, 44.50)	39.80 (38.80, 40.85)	36.30 (34.00, 37.70)	< 0.001
Fasting glucose (mmol/L)	5.60 (4.80, 7.47)	5.64 (4.78, 7.46)	5.44 (4.61, 6.89)	5.68 (4.91, 7.61)	0.203
LDL-C (mmol/L)	3.25 (2.48, 4.03)	3.38 (2.47, 4.16)	3.35 (2.73, 4.05)	2.93 (2.30, 3.78)	0.003
eGFR	85.78 (67.81, 96.78)	90.49 (71.75, 99.79)	86.16 (70.72, 97.66)	77.56 (59.93, 92.91)	< 0.001
ALBI	-2.67 (-2.90, -2.47)	-2.98 (-3.08, -2.90)	-2.67 (-2.73, -2.60)	-2.35 (-2.47, -2.18)	< 0.001
LnCRP	1.91 (0.88, 3.18)	1.64 (0.73, 2.53)	1.75 (0.70, 2.76)	2.54 (1.38, 4.09)	< 0.001
Medications during hospitalization					
Antiplatelet therapy, yes	677 (99.41%)	226 (99.56%)	226 (99.56%)	225 (99.12%)	0.778
Statin therapy, yes	680 (99.85%)	227 (100.00%)	227 (100.00%)	226 (99.56%)	0.367
Anticoagulant therapy, yes	627 (92.07%)	205 (90.31%)	209 (92.07%)	213 (93.83%)	0.381
Interventional treatment and					

Note: Values were presented as n (%) or median (interquartile range), unless otherwise indicated. Continuous variables were compared using analysis of variance or Kruskal–Wallis tests, and categorical variables using χ^2 or Fisher's exact tests. BMI, body mass index; LVEF, left ventricular ejection fraction; GRACE, global registry of acute coronary events; CRP, C-reactive protein; LDL-C, low-density lipoprotein cholesterol; eGFR, estimated glomerular filtration rate; ALBI, albumin–bilirubin; LnCRP, natural logarithm of CRP; PCI, percutaneous coronary intervention; HF, heart failure; MACEs, major adverse cardiovascular events; ALT, alanine aminotransferase. A complete table of all collected variables is provided in Supplementary Table S5; variables shown there are not necessarily included in the primary model.

Variable	Overall (n = 681)	T1 (-3.65 to -2.81, n = 227)	T2 (-2.81 to -2.54, n = 227)	T3 (-2.53 to -1.33, n = 227)	P value
Demographic characteristics					
coronary anatomy					
In-hospital PCI, yes	681 (100.00%)	227 (100.00%)	227 (100.00%)	227 (100.00%)	-
Single-vessel disease, yes	226 (33.19%)	88 (38.77%)	75 (33.04%)	63 (27.75%)	0.045
Two-vessel disease, yes	242 (35.54%)	73 (32.16%)	83 (36.56%)	86 (37.89%)	0.410
Three-vessel disease, yes	211 (30.98%)	66 (29.07%)	68 (29.96%)	77 (33.92%)	0.493
Left main disease, yes	42 (6.17%)	11 (4.85%)	11 (4.85%)	20 (8.81%)	0.128
In-hospital outcomes					
In-hospital HF, yes	85 (12.48%)	13 (5.73%)	23 (10.13%)	49 (21.59%)	< 0.001
In-hospital malignant arrhythmia, yes	24 (3.52%)	1 (0.44%)	12 (5.29%)	11 (4.85%)	0.008
Follow-up outcomes					
Any MACEs, yes	186 (27.31%)	41 (18.06%)	66 (29.07%)	79 (34.80%)	< 0.001
Follow-up days	585.00 (389.00, 839.00)	575.00 (413.00, 865.00)	596.00(397.00, 818.50)	550.00 (376.50, 842.00)	0.620
Other variables					
Creatinine (mg/dL)	0.94 (0.80, 1.13)	0.94 (0.80, 1.10)	0.93 (0.79, 1.10)	0.96 (0.82, 1.16)	0.148

Note: Values were presented as n (%) or median (interquartile range), unless otherwise indicated. Continuous variables were compared using analysis of variance or Kruskal–Wallis tests, and categorical variables using χ^2 or Fisher's exact tests. BMI, body mass index; LVEF, left ventricular ejection fraction; GRACE, global registry of acute coronary events; CRP, C-reactive protein; LDL-C, low-density lipoprotein cholesterol; eGFR, estimated glomerular filtration rate; ALBI, albumin–bilirubin; LnCRP, natural logarithm of CRP; PCI, percutaneous coronary intervention; HF, heart failure; MACEs, major adverse cardiovascular events; ALT, alanine aminotransferase. A complete table of all collected variables is provided in Supplementary Table S5; variables shown there are not necessarily included in the primary model.

Variable	Overall (n = 681)	T1 (-3.65 to -2.81, n = 227)	T2 (-2.81 to -2.54, n = 227)	T3 (-2.53 to -1.33, n = 227)	P value
Demographic characteristics					
ALT (U/L)	25.90 (17.30, 38.00)	26.50 (18.45, 36.45)	24.60 (16.60, 35.50)	26.60 (16.75, 41.70)	0.290

Note: Values were presented as n (%) or median (interquartile range), unless otherwise indicated. Continuous variables were compared using analysis of variance or Kruskal–Wallis tests, and categorical variables using χ^2 or Fisher's exact tests. BMI, body mass index; LVEF, left ventricular ejection fraction; GRACE, global registry of acute coronary events; CRP, C-reactive protein; LDL-C, low-density lipoprotein cholesterol; eGFR, estimated glomerular filtration rate; ALBI, albumin–bilirubin; LnCRP, natural logarithm of CRP; PCI, percutaneous coronary intervention; HF, heart failure; MACEs, major adverse cardiovascular events; ALT, alanine aminotransferase. A complete table of all collected variables is provided in Supplementary Table S5; variables shown there are not necessarily included in the primary model.

3.2 Kaplan–Meier analysis

Kaplan–Meier analysis showed that higher ALBI scores were associated with a higher cumulative incidence of MACEs. Compared with T1, patients in T3 had a higher risk of MACEs during follow-up, whereas T2 had an intermediate risk. The curves for the three groups gradually diverged over time. Log-rank tests showed significant differences among the groups during the entire follow-up period and at 30, 180 and 365 days (all $P < 0.001$). See Fig. 2.

Note

The curves showed the cumulative incidence of MACEs among patients in different ALBI tertiles. Between-group differences were assessed using the log-rank test, presenting results for the entire follow-up period, as well as at 30, 180 and 365 days.

3.3 Cox regression analysis

The median follow-up duration was 585 days, during which 186 MACEs occurred. After fasting glucose was included as an imputation target, all 681 patients and 186 events contributed to the multiply imputed Model 3 analyses. In the crude model, each 1-SD increase in ALBI was associated with a 32% higher risk of MACEs (HR = 1.32, 95% CI: 1.15–1.51, $P < 0.001$). The association remained significant after adjustment for sex and age (HR = 1.25, 95% CI: 1.08–1.46, $P = 0.003$) and after full adjustment in Model 3 (HR = 1.25, 95% CI: 1.06–1.46, $P = 0.007$). Compared with T1, the fully adjusted HRs were 1.59 (95% CI: 1.07–2.38, $P = 0.023$) for T2 and 1.60 (95% CI: 1.05–2.42, $P = 0.028$) for T3, with a significant trend across tertiles (P for trend = 0.034). See Table 2.

Table 2
Cox proportional hazards regression analysis of ALBI and long-term MACEs.

Exposure	Events, n (%)	Model 1 HR (95% CI); P value	Model 2 HR (95% CI); P value	Model 3 HR (95% CI); P value
ALBI (per 1-SD increase)	186 (27.3%)	1.32 (1.15–1.51); <0.001	1.25 (1.08–1.46); 0.003	1.25 (1.06–1.46); 0.007
ALBI tertiles				
T1 (reference)	41 (18.1%)	Reference	Reference	Reference
T2	66 (29.1%)	1.60 (1.09–2.37); 0.018	1.53 (1.03–2.27); 0.034	1.59 (1.07–2.38); 0.023
T3	79 (34.8%)	1.89 (1.29–2.76); <0.001	1.63 (1.10–2.43); 0.015	1.60 (1.05–2.42); 0.028
P for trend		0.001	0.019	0.034

Note: Model 1, crude, Model 2, adjusted for sex and age, Model 3, additionally adjusted for hypertension, diabetes, smoking, alcohol consumption, LnCRP, fasting glucose, GRACE score, BMI, LDL-C and creatinine. ALBI was standardized and analyzed per 1-SD increase. After multiple imputation, all 681 patients and 186 events contributed to Model 3.

3.4 Restricted cubic spline analysis

Restricted cubic spline analysis showed no significant nonlinear association between ALBI and long-term MACEs (P for nonlinearity = 0.528). The linear component was statistically significant (P for linearity = 0.007), whereas the overall joint test was borderline (P = 0.054). Thus, the findings provide no evidence of nonlinearity and are compatible with an approximately linear association within the observed ALBI range, but should not be interpreted as evidence of a validated threshold. See Fig. 3.

Note

The solid line represented the HR estimate and the shaded area the 95% CI. The median ALBI was used as the reference. P for nonlinearity = 0.528, P for linearity = 0.007.

3.5 Subgroup and sensitivity analyses

3.5.1 Subgroup analysis

In the overall cohort, each 1-SD increase in ALBI remained associated with a higher risk of MACEs (HR = 1.25, 95% CI: 1.06–1.46, P = 0.007). The direction of association was generally consistent across age, BMI, gender, smoking, hypertension and diabetes subgroups. No subgroup interaction reached statistical significance. See Fig. 4.

Note

HRs were estimated per 1-SD increase in ALBI. The P values for interaction were used to assess whether the effects differ across subgroups.

3.5.2 Sensitivity analysis of BMI and LnCRP adjustment

In the sensitivity model excluding BMI and LnCRP, each 1-SD increase in ALBI remained associated with a higher risk of long-term MACEs (HR = 1.21, 95% CI: 1.04–1.41, P = 0.015). Compared with T1, the HRs were 1.57 for T2 (95% CI: 1.06–2.34, P = 0.025) and 1.51 for T3 (95% CI: 1.00–2.28, P = 0.047), with P for trend = 0.060. The direction of the primary association therefore remained consistent after BMI and LnCRP were excluded. See Table 3.

Table 3
Sensitivity analysis results excluding BMI and LnCRP.

Exposure	**Events, n (%)**	**Model 3 including BMI and LnCRP**	**Sensitivity model excluding BMI and LnCRP**
ALBI (per 1-SD increase)	186 (27.3%)	1.25 (1.06–1.46); 0.007	1.21 (1.04–1.41); 0.015
ALBI tertiles			
T1 (reference)	41 (18.1%)	Reference	Reference
T2	66 (29.1%)	1.59 (1.07–2.38); 0.023	1.57 (1.06–2.34); 0.025
T3	79 (34.8%)	1.60 (1.05–2.42); 0.028	1.51 (1.00–2.28); 0.047
P for trend		0.034	0.060

Note: The results were based on 50 multiply imputed datasets and were combined using Rubin's rules. Model 3 included BMI and LnCRP, whereas the sensitivity model excluded BMI and LnCRP.

3.5.3 Sensitivity analysis in complete-cases

The complete-case analysis included 216 patients with no missing data for ALBI, BMI, LnCRP or the other Model 3 covariates; 78 experienced MACEs. In Model 3, each 1-SD increase in ALBI was not significantly associated with long-term MACEs (HR = 1.11, 95% CI: 0.85–1.45, P = 0.453). The effect direction remained positive, but statistical significance was attenuated, possibly because of the substantial reduction in sample size and number of events. See Table 4.

Table 4
Complete-case sensitivity analysis.

Exposure	Sample size/events	HR (95% CI); P value
ALBI (per 1-SD increase)	216/78	1.11 (0.85–1.45); 0.453
T1 (reference)	216/78	Reference
T2	216/78	1.42 (0.75–2.70); 0.287
T3	216/78	1.53 (0.77–3.06); 0.229
P for trend	216/78	0.243

Note: The complete-case analysis included patients with no missing values for ALBI, follow-up time, MACEs and Model 3 covariates.

3.5.4 Age-stratified sensitivity analysis and proportional hazards assumption testing

The proportional hazards assumption testing indicated that, in all 50 multiple-imputation datasets, no consistent violation of the proportional hazards assumption was found for ALBI. However, age may exhibit time dependence. After conducting stratified Cox analyses by age ≤ 65 years and > 65 years, each 1-SD increase in ALBI remained associated with an increased risk of long-term MACEs (HR = 1.21, 95% CI: 1.04–1.41, P = 0.015). The HRs for the T2 and T3 groups were 1.56 (95% CI: 1.05–2.32, P = 0.029) and 1.54 (95% CI: 1.02–2.32, P = 0.041), respectively, with a trend test P value of 0.049. This result is consistent with the direction of the main analysis. See Table 5.

Table 5
Age-stratified sensitivity analysis.

Exposure	Sample size/events	HR (95% CI); P value
ALBI (per 1-SD increase)	681/186	1.21 (1.04–1.41); 0.015
T1 (reference)	681/186	Reference
T2	681/186	1.56 (1.05–2.32); 0.029
T3	681/186	1.54 (1.02–2.32); 0.041
P for trend	681/186	0.049

Note: A stratified Cox model was fitted with age (≤ 65 years vs > 65 years) as the stratification variable. The model allowed age-specific baseline hazards and estimated a common ALBI coefficient across strata; other covariates were adjusted according to Model 3. The analysis included 681 patients and 186 events.

3.6 Model discrimination and ROC analyses

3.6.1 The influence of ALBI on the model discrimination

The GRACE-based model had a Harrell's C-index of 0.590 (95% CI: 0.548–0.632), which increased to 0.598 (95% CI: 0.556–0.643) after ALBI was added. The increment was 0.008 (95% CI: −0.011–0.028, P = 0.370). The 365-day IPCW time-dependent AUC increased from 0.602 (95% CI: 0.547–0.654) to 0.609 (95% CI: 0.555–0.662), with an increment of 0.007 (95% CI: −0.019–0.031, P = 0.582). See Table 6.

Table 6
Discrimination after adding ALBI to the admission GRACE-based model.

Metric	Admission GRACE-based model	Admission model + ALBI	Increment (95% CI)	P value
Harrell's C-index	0.590 (0.548–0.632)	0.598 (0.556–0.643)	0.008 (− 0.011 to 0.028)	0.370
365-day IPCW time-dependent AUC	0.602 (0.547–0.654)	0.609 (0.555–0.662)	0.007 (− 0.019 to 0.031)	0.582

Note: The C-index and time-dependent AUC are reported with 95% confidence intervals (95% CI); IPCW denotes inverse probability of censoring weighting. Increment refers to the change after adding ALBI relative to the GRACE-based model. Differences and 95% confidence intervals were estimated using 1,000 patient-level bootstrap resamples.

3.6.2 ROC and time-dependent ROC analysis

Baseline ROC analysis showed that the GRACE model predicted long-term MACEs with an AUC of 0.633 (95% CI: 0.581–0.682). After adding ALBI, the AUC was 0.643 (95% CI: 0.595–0.692). In the 30-day time-dependent ROC analysis, the AUCs for the GRACE model and the GRACE+ALBI model were 0.740 (95% CI: 0.653–0.834) and 0.693 (95% CI: 0.584–0.794), respectively. At 180 days, the AUCs were 0.616 (95% CI: 0.552–0.682) and 0.620 (95% CI: 0.554–0.685), respectively. At 365 days, they were 0.605 (95% CI: 0.551–0.658) and 0.608 (95% CI: 0.554–0.661), respectively. Overall, after adding ALBI, the model AUC changed only slightly; therefore, it is still not possible to conclude that ALBI can consistently improve the predictive performance of the GRACE model. The time-dependent ROC curves are shown in Fig. 5.

Note

The figure showed ROC curves for baseline, 30 days, 180 days and 365 days; the area under the curve (AUC) and its 95% CI were used to assess model discrimination.

4 Discussion

4.1 Main research findings

This study included 681 patients with NSTEMI who underwent PCI, with a median follow-up duration of 585 days (interquartile range: 389–839 days). During follow-up, 186 patients experienced a MACE, corresponding to 27.3% of the cohort. Higher admission ALBI scores were associated with a higher incidence of long-term MACEs. The cumulative proportions of MACEs in T1, T2 and T3 were 18.1%,

29.1% and 34.8%, respectively. Kaplan–Meier curves and log-rank tests showed significant differences among the groups during the entire follow-up period and at 30, 180 and 365 days.

In Cox regression analysis, ALBI remained associated with long-term MACEs after full adjustment for hypertension, diabetes, smoking, alcohol consumption, LnCRP, fasting blood glucose, GRACE, BMI, LDL-C and creatinine. Each 1-SD increase in ALBI was associated with a higher risk of MACEs (HR = 1.25, 95% CI: 1.06–1.46, P = 0.007). Compared with T1, the Model 3 HRs were 1.59 for T2 (95% CI: 1.07–2.38, P = 0.023) and 1.60 for T3 (95% CI: 1.05–2.42, P = 0.028), with P for trend = 0.034. Restricted cubic spline analysis showed no evidence of nonlinearity (P for nonlinearity = 0.528), whereas the linearity test was significant (P for linearity = 0.007). These results were compatible with an approximately linear association within the observed ALBI range.

In subgroup analyses, the direction of the association between ALBI and long-term MACEs was generally consistent across age, BMI, sex, smoking, hypertension and diabetes, and no interaction test reached statistical significance. After BMI and LnCRP were excluded, the ALBI effect remained significant (HR = 1.21, 95% CI: 1.04–1.41, P = 0.015). In the complete-case analysis, the effect direction remained positive, but statistical significance was lost after the sample size and event count were substantially reduced. These findings support consistency in the direction of the association while indicating that substantial covariate missingness may reduce estimate precision. Adding ALBI to the GRACE-based model produced only small, statistically nonsignificant increases in Harrell's C-index and 365-day time-dependent AUC. ALBI is therefore better interpreted as a risk marker independently associated with long-term MACEs, rather than as a demonstrated improvement to GRACE-based prediction.

4.2 Comparison with domestic and international research results

The ALBI score was developed as a simple index based on albumin and bilirubin and has subsequently been studied in liver disease and cardiovascular populations [7, 9, 16, 17, 22]. In AHF, Kawata et al. reported an independent association between admission ALBI and in-hospital mortality[10]. Matsue et al. found that ALBI was associated with adverse outcomes in a cohort of patients with AHF[11], and Han et al. reported a similar association with in-hospital death in a large HF cohort[12]. Yildirim et al. further linked ALBI to no-reflow in patients with non-ST-segment elevation ACS undergoing PCI[18]. Together, these studies support the biological plausibility of ALBI as a marker of systemic illness, but they do not directly establish its relationship with long-term composite MACEs in PCI-treated NSTEMI discharge survivors.

Recent studies make the remaining evidence gap more explicit. Chen et al. assessed bilirubin fractions and in-hospital adverse events in Chinese patients with STEMI after primary PCI [19] ; this differs from the present study in both the MI phenotype and the endpoint, and the exposure was not the ALBI score. Zhao et al. examined ALBI in an ICU-based MIMIC-IV PCI cohort, with ICU and short-term post-discharge mortality as the principal outcomes[20]; the critically ill setting and short outcome horizon limit direct comparability with a discharge-survivor cohort. Chen et al. evaluated 982 patients with NSTEMI in Hubei

and reported an association between ALBI and post-discharge all-cause mortality over a median of 27 months[21]. This is the closest comparator, but the present study specifically focused on patients treated with PCI who survived to discharge and used a composite long-term MACE endpoint. The current findings therefore complement, rather than duplicate, prior work. A comparison of study populations, exposures, endpoints and follow-up periods is presented in Supplementary Table S4.

The present study should be interpreted in this context. Its contribution is not the general observation that ALBI is associated with cardiovascular prognosis, which has been reported in several settings, but the assessment of a prespecified long-term composite endpoint in a relatively homogeneous group of NSTEMI patients treated with PCI and surviving to discharge. The direction of the association was consistent with the Hubei NSTEMI mortality study [21], while the absence of a statistically significant improvement in the C-index or 365-day AUC after adding ALBI to GRACE indicates that prognostic association should not be equated with validated incremental prediction. Differences in endpoint definition, treatment setting, sample size, follow-up, covariate specification and external validation may account for the different findings across studies.

Evidence concerning the individual components of ALBI also provides biological context. Prior studies have shown that low albumin levels are associated with an increased risk of early cardiovascular events and cardiac death [23]. Total bilirubin, direct bilirubin or bilirubin-related indices have also been reported to be associated with long-term adverse outcomes after PCI[24]. These findings indirectly support the association observed in the present study, while also emphasizing that ALBI combines two laboratory measures and should not be interpreted as a direct measure of a single causal pathway. Its potential advantage over individual components requires formal external validation and head-to-head model comparison.

4.3 Possible mechanisms linking ALBI to long-term MACEs

The ALBI score combines serum albumin and total bilirubin. A higher ALBI score indicates a lower albumin level, a higher total bilirubin level, or both. These changes may be associated with adverse outcomes in NSTEMI, although ALBI is more likely to represent an integrated marker of several pathological processes than a direct measure of a single causal pathway.

First, hypoalbuminemia may reflect limited nutritional reserves, chronic inflammation and disease severity [25]. Albumin is a negative acute-phase protein synthesized by the liver, and inflammation can alter its synthesis, distribution and metabolism[26]. Hypoalbuminemia may also reduce intravascular colloid osmotic pressure, alter drug binding and promote tissue edema[27]. Inflammation and immune activation are related to coronary atherosclerosis, plaque instability and impaired myocardial repair[28]. Lower albumin levels may therefore indicate reduced physiological reserves for withstanding subsequent cardiovascular events. The association between ALBI and MACEs persisted after adjustment for LnCRP, suggesting that ALBI may contain information not fully reflected by CRP.

Second, an elevated bilirubin level may reflect acute hepatic congestion, low perfusion, tissue hypoxia or altered bilirubin metabolism. Studies in HF have linked abnormal liver tests to poor prognosis, often in the context of venous congestion and reduced cardiac output rather than primary liver disease [29]. In NSTEMI, myocardial ischemia, impaired left ventricular function and changes in volume loading may affect hepatic perfusion and venous return. Bilirubin may therefore signal deterioration in overall circulatory status. Although bilirubin has antioxidant and potential vascular-protective properties, higher levels during acute illness may also accompany oxidative stress, inflammation and endothelial dysfunction[30]. Its cardiovascular implications should therefore be interpreted in the context of the patient's overall condition.

Furthermore, ALBI may be related to coronary microvascular dysfunction and myocardial repair. Inflammation, oxidative stress, endothelial dysfunction and inadequate microcirculatory perfusion can affect myocardial perfusion after PCI, left ventricular remodeling and subsequent HF risk [31]. ALBI may capture several of these processes simultaneously because it combines albumin and bilirubin. However, this observational study did not measure hepatic venous pressure, endothelial function, oxidative stress or microcirculatory perfusion. These mechanisms are therefore pathophysiological inferences and do not establish that higher ALBI directly causes MACEs.

In the RCS analysis, we found no significant nonlinear relationship. Within the ALBI distribution observed in this cohort, risk generally increased as ALBI rose, without a clear threshold or inflection point. This supports analyzing ALBI as a continuous variable in the primary analysis. However, the borderline overall joint test warrants caution. The tertiles were used mainly to facilitate clinical presentation and group comparisons; their cutoffs should not be interpreted as externally validated clinical thresholds.

4.4 Potential clinical value of ALBI and the boundaries of outcomes

Clinically, ALBI requires only albumin and total bilirubin from routine admission testing, making it inexpensive, reproducible and readily available. In patients with NSTEMI undergoing PCI, ALBI may provide supplementary information beyond the GRACE score by identifying patients with reduced nutritional reserves, hepatic congestion or a greater systemic pathophysiological burden. It may also help prompt closer post-discharge follow-up, risk-factor management and monitoring for HF symptoms.

However, adding ALBI did not significantly improve the GRACE model's C-index or 365-day time-dependent AUC. ALBI should therefore not yet be regarded as a validated independent prediction model, and it should not be used alone to determine PCI strategy, pharmacotherapy or follow-up intensity. The present findings support interpreting ALBI as a marker independently associated with long-term MACEs and as a potential adjunct for risk stratification. Its incremental predictive and clinical value requires further assessment through calibration, decision-curve analysis and external validation in larger, multicenter prospective cohorts. The GRACE score should remain the foundation of risk stratification and prognostic assessment in NSTEMI [32] .

4.5 Strengths and limitations of the study

This study has several strengths. First, the cohort was relatively homogeneous, consisting of patients with NSTEMI who underwent PCI, which reduced heterogeneity related to treatment strategy and disease spectrum. Second, the median post-discharge follow-up was 585 days, and outcomes were assessed at 30, 180 and 365 days as well as over the entire follow-up period. Third, ALBI was analyzed both continuously and by tertiles, and its robustness was examined using Kaplan–Meier analysis, Cox regression, restricted cubic splines, subgroup analysis, sensitivity analysis and model discrimination. Fourth, PMM multiple imputation retained clinically important covariates with substantial missingness, including BMI and LnCRP, while complete-case and covariate-exclusion analyses assessed the stability of the findings.

Several limitations should be acknowledged. First, the single-center retrospective observational design cannot fully eliminate selection bias, information bias or residual confounding; the observed association cannot therefore be interpreted as causal. Second, BMI and LnCRP had relatively high proportions of missing data, and multiple imputation relied on the MAR assumption. Although sensitivity analyses showed a consistent direction of effect, the complete-case confidence intervals were wider, and the influence of the missing-data mechanism cannot be excluded. Third, ALBI was measured only at admission, so the incremental prognostic value of changes during hospitalization or follow-up could not be assessed. Fourth, MACEs were analyzed as a composite endpoint, and the component events may differ in mechanism and clinical severity. Because component-specific models were not performed, heterogeneity across components could not be evaluated. Fifth, age showed potential time dependence in the proportional hazards assessment. Although the age-stratified analysis showed the same overall direction, a single conventional HR may not fully describe effects across all time periods. Sixth, adding ALBI did not significantly improve model discrimination, and external validation, calibration assessment and decision-curve analysis were not performed. Clinical implications should therefore be interpreted cautiously.

5 Conclusion

Among patients with NSTEMI who underwent PCI, a higher admission ALBI score was independently associated with a higher risk of long-term MACEs after discharge. The association was approximately linear within the observed ALBI range, and its direction remained positive in sensitivity analyses, although the complete-case estimate was less precise and not statistically significant. Adding ALBI to GRACE did not produce a statistically significant improvement in discrimination. ALBI is therefore best viewed as a simple, readily available marker that may assist long-term risk stratification, rather than as a substitute for GRACE or a validated independent prediction tool. Multicenter prospective studies with external validation, calibration and assessment of clinical benefit are needed, to further clarify its value in the long-term management of patients with NSTEMI.

Abbreviations

ALBI	admission albumin–bilirubin
MACE	major adverse cardiovascular event
PCI	percutaneous coronary intervention
NSTEMI	non-ST-segment elevation myocardial infarction
ACS	acute coronary syndrome
GRACE	Global Registry of Acute Coronary Events
MI	Myocardial Infarction
1-SD	1-standard-deviation
HF	heart failure
AHF	acute heart failure
eGFR	estimated glomerular filtration rate
BMI	body mass index
CKD	chronic kidney disease
COPD	chronic obstructive pulmonary disease
AF	atrial fibrillation
LVEF	left ventricular ejection fraction
LVEDD	left ventricular end-diastolic diameter
CRP	C-reactive protein
CK-MB	creatine kinase-MB
hs-cTnT	high-sensitivity cardiac troponin T
NT-proBNP	N-terminal pro–B-type natriuretic peptide
HDL-C	high-density lipoprotein cholesterol
LDL-C	low-density lipoprotein cholesterol
ALT	alanine aminotransferase

IPCW	inverse probability of censoring weighting
VIF	variance inflation factor
HRs	hazard ratios
BUN/Cr	blood urea nitrogen-to-creatinine ratio
MAR	missing-at-random
PMM	predictive mean matching

Declarations

Ethics statement

This study was reviewed and approved by the Medical Ethics Committee of the Affiliated Hospital of Guangdong Medical University (Ethics Approval Number: PJKT2026-279). This study is a retrospective observational study. The clinical data used have been de-identified prior to analysis, and no additional interventions or treatments are involved during the course of the study. According to the review comments of the ethics committee, this study was approved for waiver of written informed consent from patients or their legally authorized representatives. This study is conducted in accordance with the Declaration of Helsinki and relevant ethical standards.

Conflict of interest

The authors declared that this study was conducted in the absence of any commercial or financial relationships that could be perceived as a potential conflict of interest.

Author Contribution

YL: Data collection and organization, Statistical analysis, Drafting the initial manuscript. JY: Research conception and design, Methodology, Statistical analysis. CL: Data verification, Interpretation of results. JW: Research guidance, Supervision, Manuscript revision. SL: Research supervision, Manuscript revision, Finalization.

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Data Availability

The individual-level data underlying this study were obtained from the electronic medical record system of the Affiliated Hospital of Guangdong Medical University and cannot be made publicly available because of patient confidentiality and institutional data-governance requirements. De-identified data may be obtained from the corresponding author upon reasonable request, subject to approval by the Ethics Committee of the Affiliated Hospital of Guangdong Medical University and compliance with the conditions of the original ethical approval and applicable institutional regulations. The analysis code is available from the corresponding author upon reasonable request.

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Figures

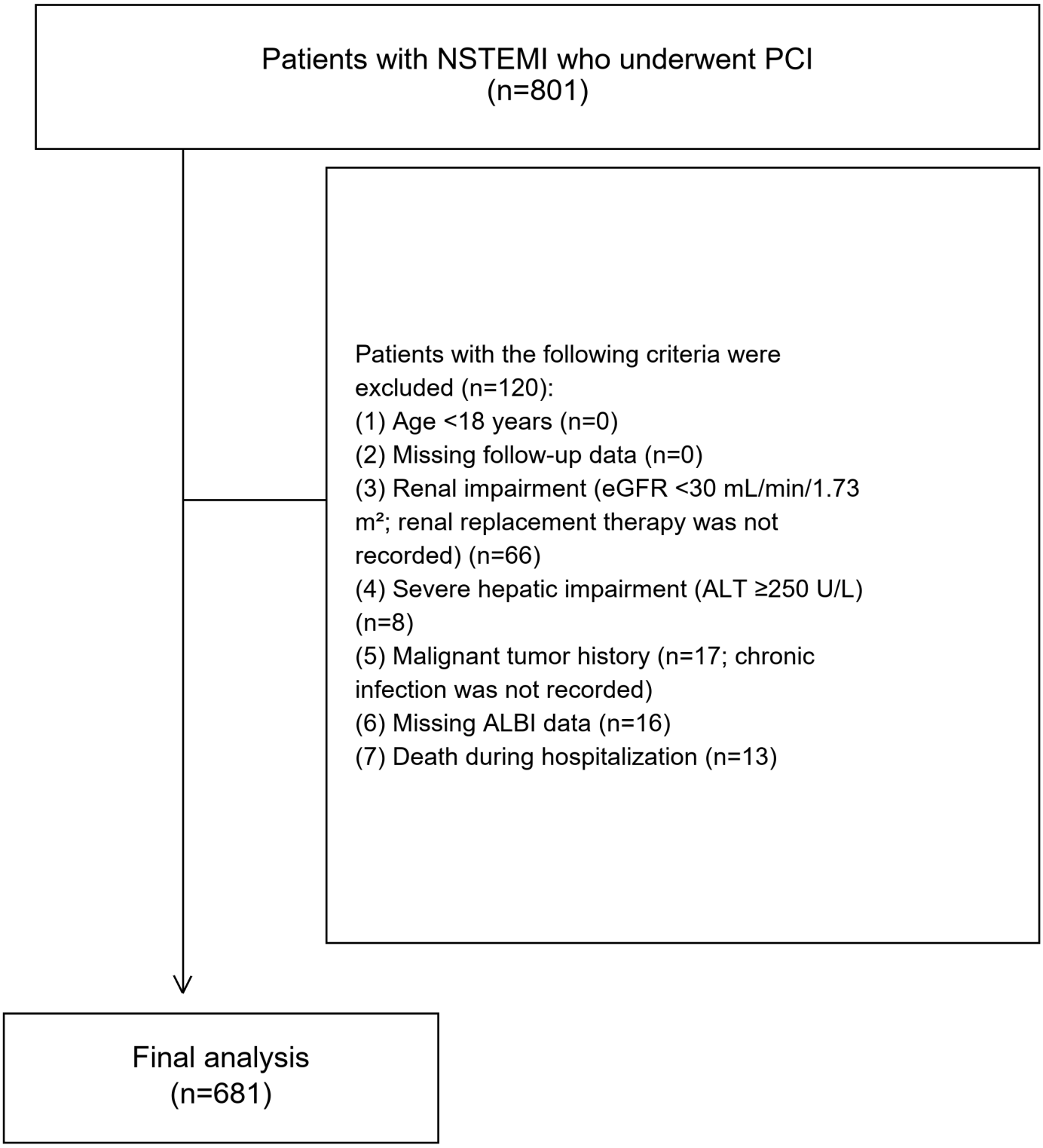


Figure 1

Flowchart of study participant selection.

Note: Study participants were screened according to the predefined inclusion and exclusion criteria, and 681 patients with NSTEMI who underwent PCI were ultimately included.

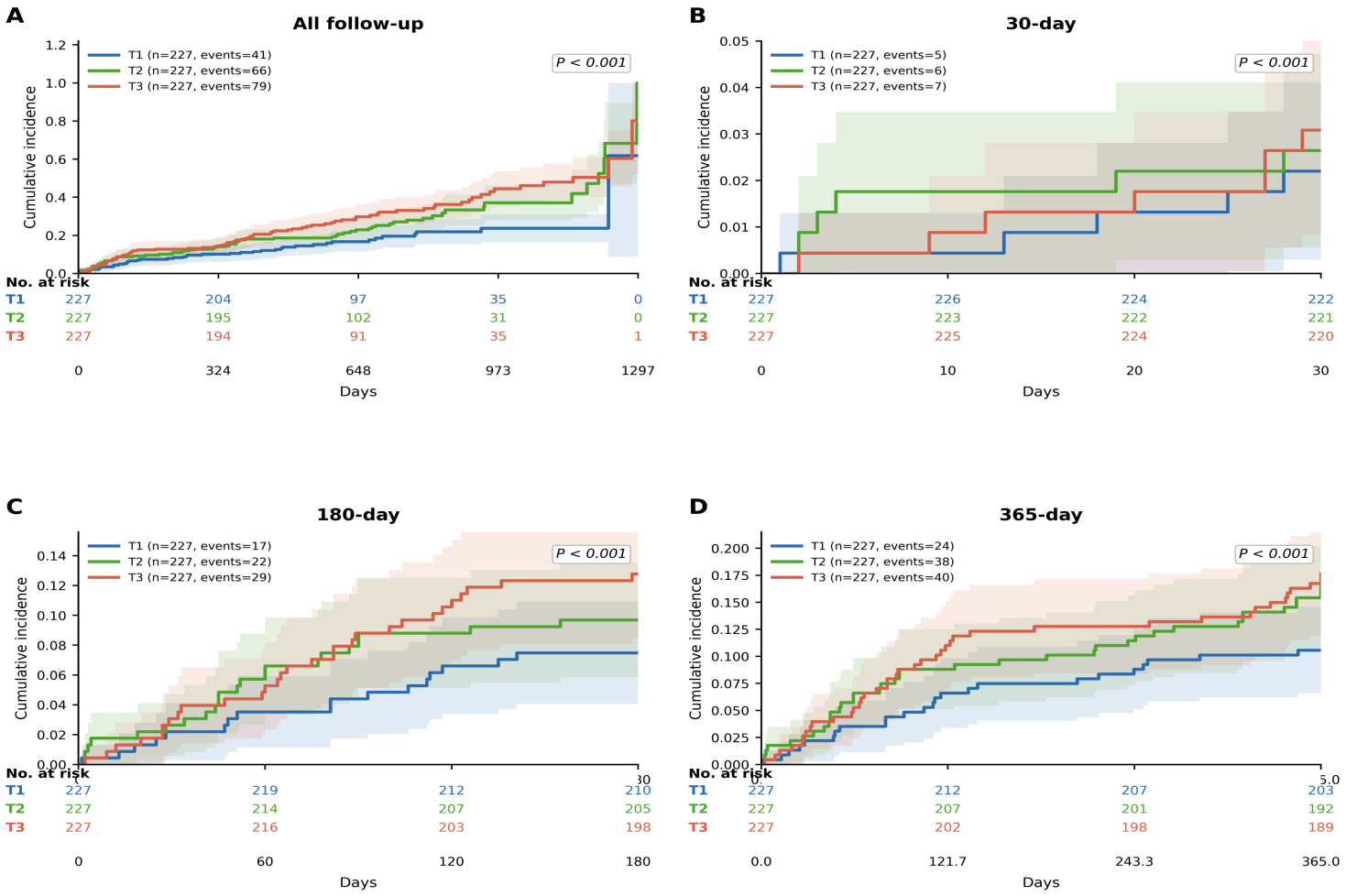


Figure 2

Kaplan–Meier curves of patients in ALBI tertiles.

Note: The curves showed the cumulative incidence of MACEs among patients in different ALBI tertiles. Between-group differences were assessed using the log-rank test, presenting results for the entire follow-up period, as well as at 30, 180 and 365 days.

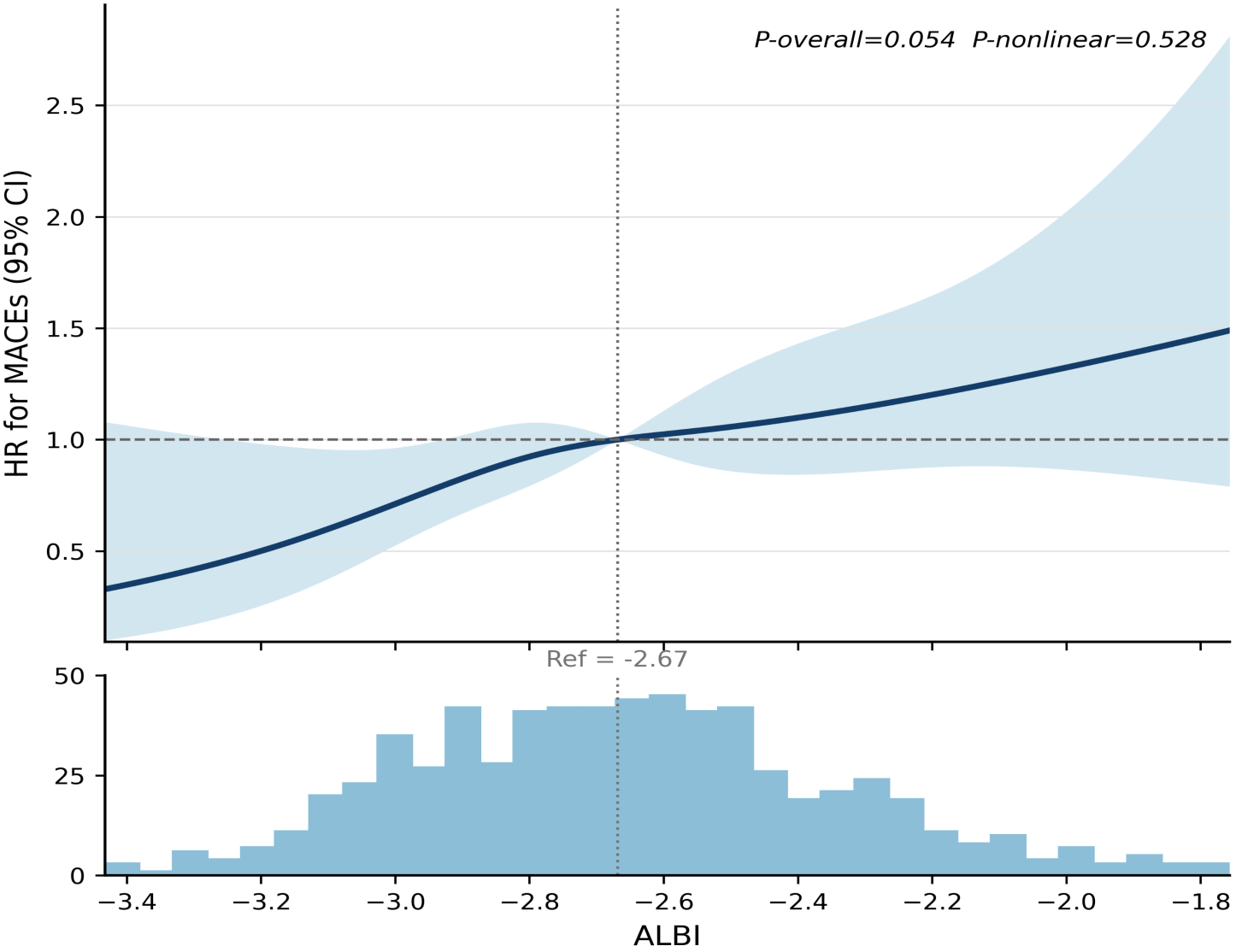


Figure 3

Restricted cubic spline association between ALBI and long-term MACEs.

Note: The solid line represented the HR estimate and the shaded area the 95% CI. The median ALBI was used as the reference. P for nonlinearity=0.528, P for linearity=0.007.

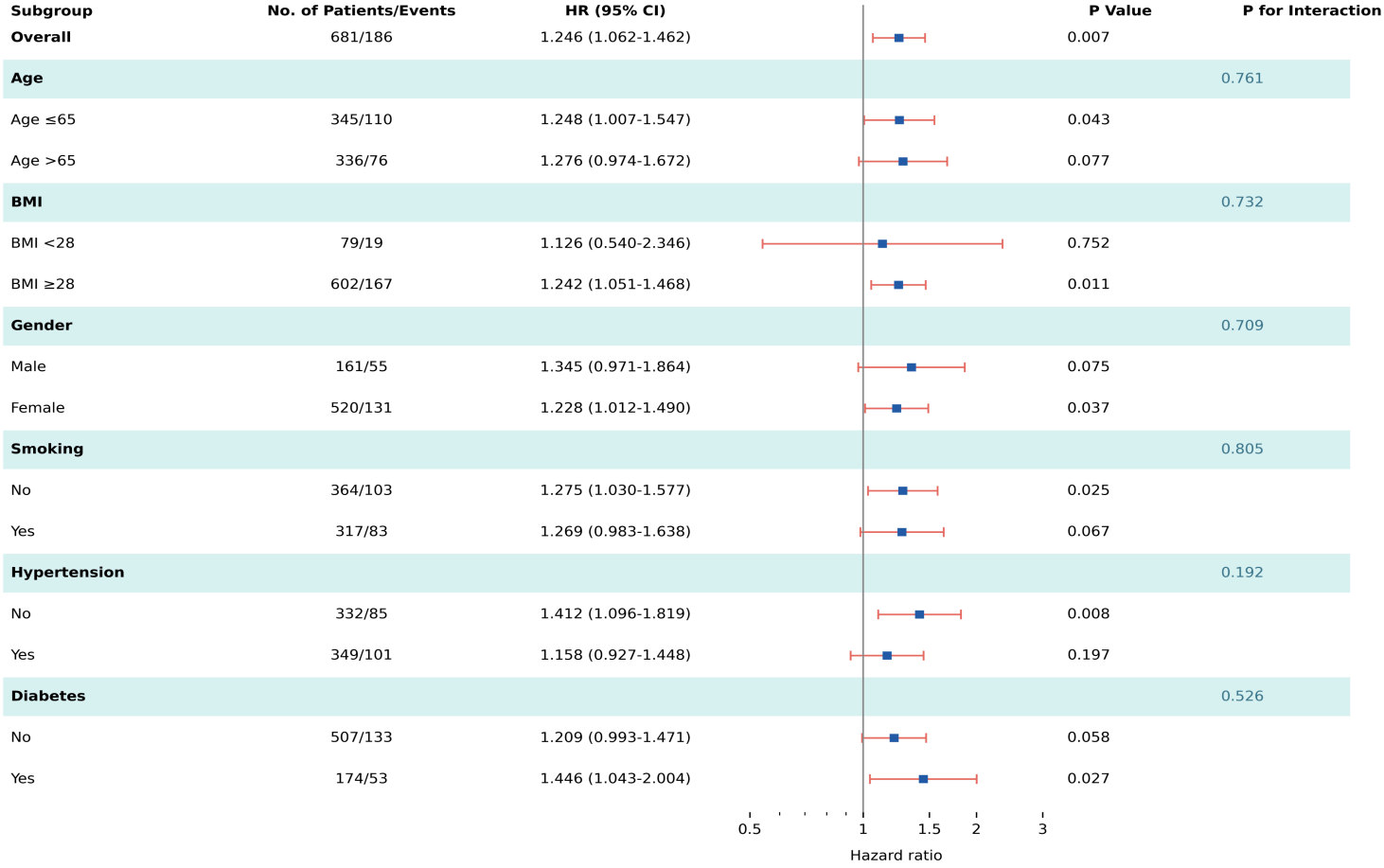


Figure 4

Subgroup analysis of the association between ALBI and long-term MACEs.

Note: HRs were estimated per 1-SD increase in ALBI. The P values for interaction were used to assess whether the effects differ across subgroups.

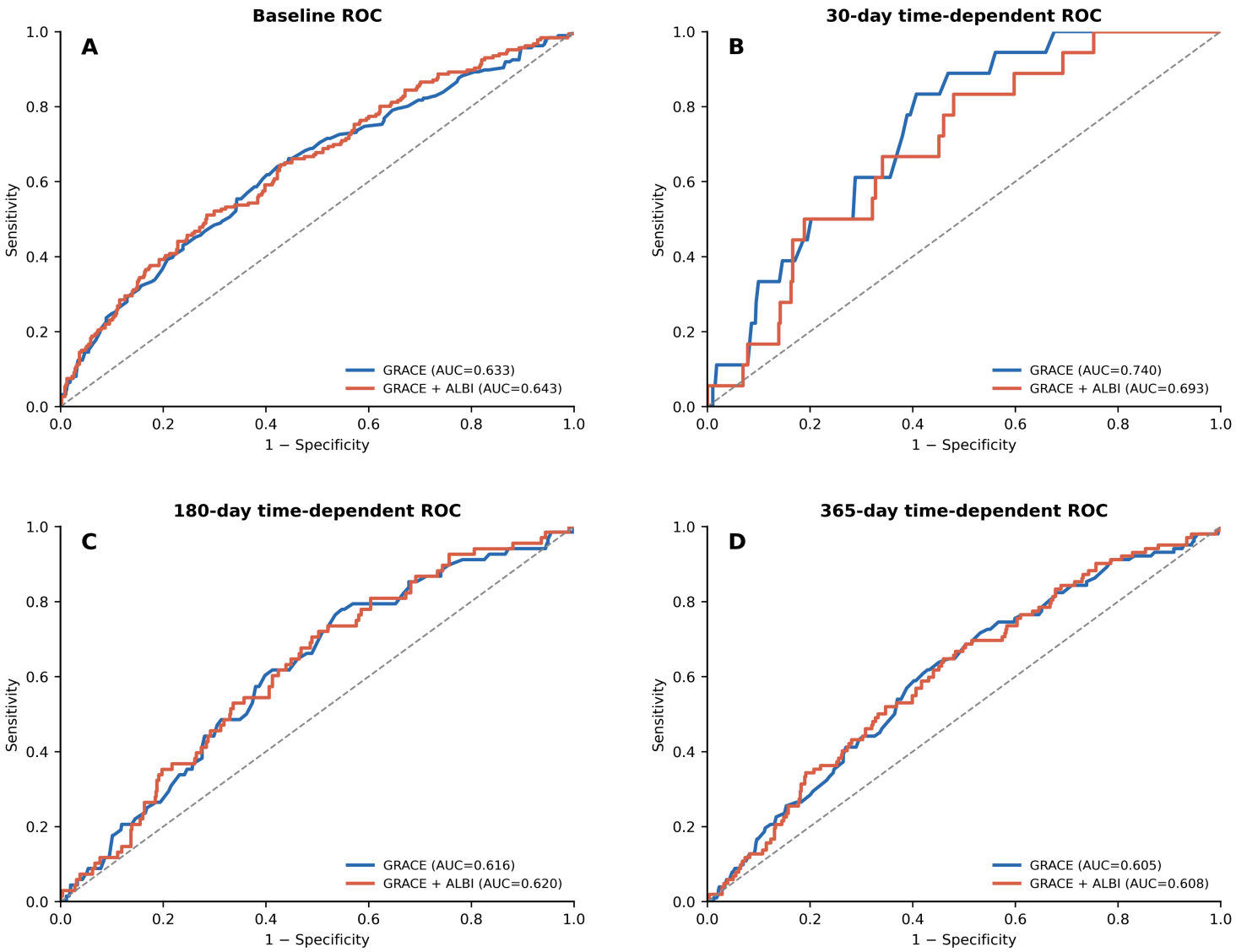


Figure 5

Baseline and time-dependent ROC curves.

Note: The figure showed ROC curves for baseline, 30 days, 180 days and 365 days; the area under the curve (AUC) and its 95% CI were used to assess model discrimination.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMaterial1.docx