

Article

Predictive Value of the Baseline Tricuspid Annular Plane Systolic Excursion/Pulmonary Artery Systolic Pressure Ratio for Low Cardiac Output Syndrome After Coronary Artery Bypass Grafting in Patients With Coronary Artery Disease and Reduced Ejection Fraction

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Abstract

Background: Patients with coronary artery disease and reduced ejection fraction, defined as a left ventricular ejection fraction (LVEF) <50%, have a high incidence of low cardiac output syndrome (LCOS) after coronary artery bypass grafting (CABG). Preoperative risk assessment remains largely based on left ventricular parameters, such as LVEF, whereas the predictive value of right ventricular–pulmonary arterial (RV-PA) coupling has not been systematically evaluated. Thus, this study aimed to investigate the predictive value of the preoperative tricuspid annular plane systolic excursion-to-pulmonary artery systolic pressure ratio (TAPSE/PASP) for LCOS after CABG in this population. **Methods:** We retrospectively included 307 patients with coronary artery disease who underwent isolated CABG between February 2021 and February 2025 and had a preoperative LVEF <50%. The primary endpoint was LCOS within 72 h after surgery. Multiple logistic regression was used to assess the independent association between TAPSE/PASP and LCOS. Receiver operating characteristic (ROC) curves were used to compare the discriminative performance of echocardiographic parameters, and the DeLong test was used to evaluate the incremental predictive value of adding TAPSE/PASP to the baseline clinical model. Internal validation was performed using 1000 bootstrap resamples. **Results:** Among the 307 patients, 101 (32.9%) developed postoperative LCOS. TAPSE/PASP was lower in the LCOS group than in the non-LCOS group: 0.28 (0.22–0.36) vs 0.47 (0.38–0.57) mm/mmHg; $p < 0.001$. Multiple logistic regression showed that each 0.1-unit increase in TAPSE/PASP was associated with a lower risk of LCOS after adjustment for age, sex, body mass index (BMI), New York Heart Association (NYHA) functional class, LVEF, chronic kidney disease, recent acute coronary syndrome, and coronary lesion characteristics (odds ratio (OR) = 0.62; 95% confidence interval (CI), (0.50–0.77); $p < 0.001$). This association remained stable in sensitivity analyses incorporating surgical strategy, mitral regurgitation (MR) severity, and ischemic/functional MR; in the MR-adjusted model, the OR was 0.64 (95% CI, 0.51–0.80); $p < 0.001$. Quartile-based analysis showed a stepwise decrease in LCOS incidence with increasing TAPSE/PASP, from 59.7% in the first quartile (Q1) to 11.7% in the fourth quartile (Q4) (trend test $p < 0.001$). Among individual echocardiographic parameters, TAPSE/PASP had an area under the receiver operating characteristic curve (AUC) of 0.810 (95% CI, 0.758–0.861), which was higher than that of PASP (AUC, 0.734; 95% CI, 0.675–0.793; $p = 0.041$), and LVEF (AUC, 0.699; 95% CI, 0.638–0.761; $p = 0.008$). After TAPSE/PASP was added to the baseline clinical model, the AUC increased from 0.781 (95% CI, 0.730–0.832) to 0.851 (95% CI, 0.809–0.893; DeLong test $p = 0.002$). The bootstrap-corrected AUC was 0.838 (95% bootstrap CI, 0.803–0.881), and the Hosmer–Lemeshow test indicated good calibration ($\chi^2 = 6.48$, $p = 0.593$). **Conclusions:** Preoperative TAPSE/PASP is an independent predictor of LCOS after CABG in patients with coronary artery disease and reduced ejection fraction. As part of routine preoperative echocardiographic assessment, this parameter may provide valuable incremental information for risk stratification in this high-risk population. Future prospective studies should further evaluate whether dynamic or exercise-derived RV-PA coupling can improve the prediction of functional outcomes and perioperative events beyond resting TAPSE/PASP in high-risk CABG patients.

Keywords: right ventricular–pulmonary arterial coupling; low cardiac output syndrome; coronary artery bypass grafting; left ventricular ejection fraction; tricuspid annular plane systolic excursion-to-pulmonary artery systolic pressure ratio

1. Introduction

Coronary artery bypass grafting (CABG) is an important revascularization strategy for multivessel coronary artery disease and left main coronary artery disease. However, in patients with impaired preoperative left ventricular systolic function, operationally defined in this study as left ventricular ejection fraction (LVEF) $<50\%$, perioperative risk is markedly increased, and postoperative low cardiac output syndrome (LCOS) is one of the key complications leading to early mortality and adverse outcomes [1,2,3]. Previous studies have shown that this population has a high incidence of postoperative LCOS; once LCOS occurs, it not only prolongs intensive care unit stay and increases the need for mechanical circulatory support but is also closely associated with substantially increased in-hospital mortality [2,3]. Therefore, accurate preoperative identification of high-risk patients and precise risk stratification are essential prerequisites for optimizing perioperative management.

Traditional risk assessment has focused mainly on left ventricular function, with LVEF remaining the core parameter. However, increasing attention is being paid to the role of right ventricular function and the mechanical matching relationship between the right ventricle and pulmonary artery in perioperative risk assessment for cardiac surgery [4,5]. Right ventricular–pulmonary arterial (RV-PA) coupling reflects the adaptive relationship between right ventricular contractile reserve and pulmonary arterial afterload. Impaired coupling suggests that the right ventricle can no longer maintain effective forward output under afterload stress and is an important signal of global cardiac decompensation [5]. The tricuspid annular plane systolic excursion to pulmonary artery systolic pressure ratio (TAPSE/PASP), measured by transthoracic echocardiography, is a noninvasive surrogate of RV-PA coupling and has been shown to have prognostic value in heart failure, pulmonary hypertension, and structural cardiac interventions [5,6,7,8].

However, the value of TAPSE/PASP for predicting LCOS after CABG in patients with coronary artery disease and reduced ejection fraction has not been systematically evaluated [4]. Existing studies are often limited by small sample sizes and single-endpoint designs and have paid insufficient attention to this specific population with impaired left ventricular systolic function [9]. In addition, whether TAPSE/PASP can provide incremental predictive value beyond traditional echocardiographic parameters such as LVEF and TAPSE alone within a multiple logistic regression framework remains insufficiently validated [10]. Against this background, this retrospective study systematically evaluated the predictive value of preoperative TAPSE/PASP for LCOS after CABG in patients with reduced ejection fraction, aiming to provide evidence for precise perioperative risk assessment in this high-risk population.

2. Materials and Methods

2.1 Study Population

This retrospective study included patients with atherosclerotic coronary artery disease who underwent CABG at our hospitals from February 1, 2021, to February 1, 2025. After screening according to prespecified criteria, 307 patients were ultimately included. The study complied with the Declaration of Helsinki and was approved by the Medical Ethics Committee of our hospitals. The requirement for written informed consent was waived because of the retrospective study design.

Preoperative LVEF $<50\%$ was used as the operational inclusion criterion for “reduced ejection fraction” to identify patients with impaired preoperative left ventricular systolic function.

The inclusion criteria were as follows: (1) age ≥ 18 years; (2) atherosclerotic coronary artery disease confirmed by coronary angiography and treated with isolated CABG; (3) preoperative transthoracic echocardiography showing LVEF $<50\%$; (4) standardized transthoracic echocardiography completed within 7 days before surgery, with no cardiogenic shock on the examination day, no intra-aortic balloon pump (IABP) or venoarterial extracorporeal membrane oxygenation (VA-ECMO), no continuous intravenous inotropic or vasopressor support, systolic blood pressure ≥ 90 mmHg, and mean arterial pressure ≥ 65 mmHg; and (5) availability of data on the main exposure, primary outcome, and key clinical covariates.

The exclusion criteria were as follows: (1) concomitant valve surgery, aortic surgery, ventricular aneurysm resection, congenital heart disease repair, or other cardiac/great vessel surgery, or a clearly established preoperative need for concomitant mitral intervention; (2) previous cardiac surgery; (3) preoperative cardiogenic shock or preoperative mechanical circulatory support, including IABP or VA-ECMO; (4) primary pulmonary hypertension, chronic thromboembolic pulmonary hypertension, or severe acute exacerbation of chronic lung disease within 14 days before surgery requiring high-flow oxygen therapy, noninvasive ventilation, or invasive mechanical ventilation, all of which could clearly increase pulmonary circulatory afterload; (5) moderate or greater tricuspid regurgitation, obvious congenital right-heart structural abnormalities, significant right ventricular outflow tract obstruction, or severe pulmonary valve stenosis; (6) poor-quality preoperative echocardiographic images preventing reliable measurement of TAPSE and PASP; and (7) missing data for the main exposure, primary outcome, or prespecified key covariates.

Patients not included because TAPSE or PASP could not be obtained were defined as technical exclusions caused by uncertainty in main exposure assessment. Case screening was performed consecutively according to the prespecified criteria.

2.2 Clinical Data Collection

Clinical data were obtained from the hospital electronic medical record system, anesthesia system, surgical record system, echocardiography database, and intensive care unit records. Data collected included baseline demographic characteristics, comorbidities, preoperative cardiac function and coronary lesion characteristics, laboratory parameters, and perioperative surgical variables.

Demographic and comorbidity variables included age, sex, body mass index (BMI), smoking history, hypertension, diabetes mellitus, chronic kidney disease, previous myocardial infarction, atrial fibrillation, and history of stroke. Smoking history was categorized as never, former, or current smoking. Hypertension was defined according to the 2024 European Society of Cardiology (ESC) hypertension guideline criteria or a previous documented diagnosis/regular antihypertensive treatment [11]. Diabetes mellitus was defined according to the 2025 American Diabetes Association (ADA) diagnostic and classification standards or a previous documented diagnosis/regular glucose-lowering treatment [12]. Chronic kidney disease was defined according to the 2024 Kidney Disease: Improving Global Outcomes (KDIGO) guideline as abnormalities of kidney structure or function present for at least 3 months; operationally, this study defined chronic kidney disease as a documented previous diagnosis or a traceable preoperative estimated glomerular filtration rate (eGFR) $<60 \text{ mL} \cdot \text{min}^{-1} \cdot 1.73 \text{ m}^{-2}$ for at least 3 months [13]. Previous myocardial infarction, atrial fibrillation, and stroke history were determined comprehensively from previous diagnoses, discharge diagnoses, electrocardiographic evidence, or imaging evidence. New York Heart Association (NYHA) functional class was determined according to exercise tolerance and symptom grading recorded by the attending physician in the admission record.

Preoperative cardiac function and coronary lesion characteristics included NYHA functional class, LVEF, left ventricular end-diastolic diameter, left main coronary artery disease, three-vessel disease, and recent acute coronary syndrome. Left main disease was defined as $\geq 50\%$ stenosis of the left main coronary artery [14]. Three-vessel disease was defined as diameter stenosis $\geq 70\%$ in all three major epicardial coronary artery systems: the left anterior descending artery system, left circumflex artery system, and right coronary artery system [15]. Recent acute coronary syndrome was defined within the framework of the 2025 American College of Cardiology/American Heart Association/American College of Emergency Physicians/National Association of EMS Physicians/Society for Cardiovascular Angiography and Interventions acute coronary syndrome guideline as unstable angina, non-ST-segment elevation myocardial infarction, or ST-segment elevation myocardial infarction occurring within 30 days before surgery [16]. Left main disease and three-vessel disease were determined from the formal preoperative coronary angiography report

and, when necessary, reviewed by two qualified cardiovascular specialists.

Laboratory parameters included hemoglobin, serum creatinine, eGFR, albumin, and N-terminal pro-B-type natriuretic peptide (NT-proBNP). In principle, the most recent test result within 72 h before surgery was used. If multiple measurements of the same variable were available within this window, the value closest to the time of surgery was included in the analysis. eGFR was calculated using the 2021 Chronic Kidney Disease Epidemiology Collaboration (CKD-EPI) creatinine equation [17].

Baseline mitral regurgitation (MR) severity and MR etiology were collected. MR severity was graded as none/trace, mild, moderate, or severe. Ischemic/functional MR was defined as MR occurring in the context of coronary artery disease and left ventricular remodeling without evidence of primary organic leaflet disease. Patients with severe MR or those requiring concomitant mitral surgery were not included in this study; patients with moderate or less MR who were not judged by the heart team to require concomitant mitral intervention were retained in the cohort.

Perioperative variables included surgical strategy (on-pump CABG or off-pump CABG), graft type, number of distal anastomoses, cardiopulmonary bypass time, aortic cross-clamp time, and intraoperative transfusion. Cardiopulmonary bypass time and aortic cross-clamp time were applicable only to patients undergoing on-pump CABG and were used for descriptive statistics and related subgroup analyses, but not as general covariates in the main model for the entire cohort. Intraoperative transfusion was defined as transfusion of any red blood cell, plasma, or platelet product from the start of surgery to leaving the operating room. Postoperative hemodynamic support variables were used only for adjudicating the postoperative LCOS endpoint and were not included in the main analysis model as baseline predictors.

Surgical strategy was determined by the preoperative heart team and the attending surgeon according to coronary target-vessel anatomy, the degree of ascending aortic calcification, hemodynamic stability, heart size, and anticipated technical difficulty of anastomosis. Off-pump CABG was preferentially considered for patients with marked ascending aortic calcification, those in whom major target-vessel revascularization could be completed on a beating heart, and those in whom intraoperative hemodynamic stability could be maintained. On-pump CABG was more commonly used for patients with difficult target-vessel exposure, the need for more complete revascularization, marked cardiac enlargement, or anticipated difficulty maintaining stable circulation during off-pump surgery. This choice was considered a clinical decision variable; therefore, cardiopulmonary bypass time and aortic cross-clamp time were not included as baseline predictors in the main model, and only surgical strategy was included in sensitivity analyses.

To preserve the temporal sequence between exposure and outcome, preoperative variables were regarded as the main set of predictors. Intraoperative variables were used mainly for descriptive analyses and sensitivity analyses. Except for surgical strategy, perioperative variables that clearly occurred after the main exposure were not included in the main adjusted model in principle, to reduce mediation bias. Specifically, preoperative clinical, laboratory, and echocardiographic variables were defined as the most recent preoperative measurements within the prespecified time window; intraoperative variables were derived from anesthesia and surgical records; and postoperative variables were used only for endpoint adjudication and outcome description and were not included in adjusted models assessing the association between the main exposure and outcome.

2.3 Echocardiographic Examination and RV-PA Coupling Assessment

All preoperative transthoracic echocardiographic examinations were performed by qualified sonographers according to a standardized protocol using standard parasternal and apical views. Acquisition and reporting of right ventricular function and pulmonary arterial pressure-related parameters followed the American Society of Echocardiography guideline recommendations for adult right-heart echocardiographic assessment [5]. Left ventricular systolic function was assessed using the biplane Simpson method to obtain LVEF [18]. MR severity was determined according to the principles of comprehensive echocardiographic assessment of valvular regurgitation [19].

Preoperative transthoracic echocardiography in this study was not performed by a single operator. Routine image acquisition and initial measurements were completed by multiple qualified sonographers in our echocardiography laboratory according to a standardized protocol, and formal reports were reviewed by senior physicians certified in cardiovascular ultrasound. The main echocardiographic variables were obtained from preoperative formal echocardiographic reports and the structured database to ensure that exposure variables had been recorded before postoperative outcomes occurred and to reduce measurement bias caused by knowledge of outcomes in this retrospective study.

If multiple preoperative echocardiographic examinations were available during the same hospitalization, the examination closest to surgery that also met the above hemodynamic stability criteria was preferentially selected. Blood pressure, heart rate, mechanical circulatory support, and intravenous inotropic/vasopressor use were recorded at the time of examination. For patients with atrial fibrillation or other arrhythmias, TAPSE and peak tricuspid regurgitation velocity were averaged over 3–5 consecutive cardiac cycles. Patients without a reliable tricuspid regurgitation signal or in whom right atrial pressure could not be reasonably estimated were excluded during screening and did not enter the subsequent exposure analysis.

RV-PA coupling was expressed as the TAPSE/PASP ratio. TAPSE was measured by M-mode echocardiography in the apical four-chamber view and was defined as the systolic longitudinal displacement of the lateral tricuspid annulus, expressed in millimeters [20]. PASP was calculated from the peak tricuspid regurgitation velocity using the modified Bernoulli equation: $\text{PASP} = 4 \times (\text{peak tricuspid regurgitation velocity})^2 + \text{right atrial pressure}$ [5]. Right atrial pressure was estimated from inferior vena cava diameter and inspiratory collapse according to guideline-recommended echocardiographic criteria [5].

To verify the reproducibility of the main exposure variables, the study team performed an interobserver agreement analysis on archived preoperative transthoracic echocardiographic images from 50 randomly selected patients among the 307 included patients, without altering the main analysis database. Sampling was approximately representative of the LCOS outcome proportion, including 16 patients with LCOS and 34 without LCOS. Two physicians with more than 5 years of cardiovascular ultrasound experience independently remeasured TAPSE and PASP while blinded to patient clinical data, surgical outcomes, original report values, and each other's measurements. PASP remeasurement included assessment of peak tricuspid regurgitation velocity and right atrial pressure estimation; TAPSE/PASP was calculated directly from each observer's own TAPSE and PASP measurements. Neither observer participated in LCOS endpoint adjudication, and both were blinded to surgical strategy and perioperative treatment.

If the two observers differed by more than 2 mm for TAPSE or more than 10 mmHg for PASP, or if there was disagreement regarding the measurability of the tricuspid regurgitation spectrum or inferior vena cava images, a third senior echocardiographer performed a quality-control review. This review was used only for the agreement analysis and image-quality confirmation and did not change the pre-extracted exposure variables used in the main analysis.

The prespecified echocardiographic parameters included TAPSE, PASP, TAPSE/PASP, LVEF, and left ventricular end-diastolic diameter, with TAPSE/PASP as the main exposure. In the main analysis, TAPSE/PASP was entered into the multiple logistic regression model as a continuous variable. Because no pathological threshold sufficiently validated externally for this study population was available, this study did not prespecify a fixed diagnostic cut-off for RV-PA uncoupling. Instead, lower TAPSE/PASP was treated as a continuous phenotype of impaired RV-PA coupling. To enhance clinical interpretability, patients were additionally stratified by TAPSE/PASP quartiles to assess the trend in LCOS risk across different TAPSE/PASP levels. Any study-specific reference cut-off reported in the Results should be regarded as exploratory and statistical in nature; it was not used for main model construction and should not be directly equated with a clinical diagnostic threshold.

2.4 Study Endpoints and Related Definitions

The primary endpoint was LCOS within 72 h after CABG. LCOS was defined as a persistent hypoperfusion state dominated by inadequate cardiac pump function after volume status was judged clinically adequate and after active major bleeding, cardiac tamponade, predominantly vasoplegic distributive hypotension, severe infection or sepsis, and uncorrected rapid malignant arrhythmias had been excluded. During the study period, the intensive care unit (ICU) used a standardized postoperative circulatory support pathway [21]: when mean arterial pressure was <65 mmHg or systolic blood pressure was <90 mmHg for at least 30 min and was accompanied by lactate >2.0 mmol/L or progressively increasing lactate, urine output <0.5 mL $\cdot$ kg $^{-1}\cdot$ h $^{-1}$ for more than 4 h, central venous oxygen saturation $<60\%$, poor peripheral perfusion, or altered mental status, volume status, rhythm, bleeding volume, and mechanical ventilation parameters were first reassessed. When inadequate volume responsiveness and cardiac pump failure were considered the main mechanism, circulatory support drugs such as dobutamine, milrinone, epinephrine, or norepinephrine were initiated or increased according to the departmental standard protocol. If persistent hypoperfusion, failure to maintain target perfusion pressure, or progressively rising lactate remained despite adequate pharmacologic support, cardiovascular surgeons, anesthesiologists, and ICU physicians jointly evaluated the need for IABP, VA-ECMO, or other mechanical circulatory support.

LCOS met either of the following criteria [21]: (1) cardiac index <2.2 L $\cdot$ min $^{-1}\cdot$ m $^{-2}$; or, when cardiac index was not routinely available, systolic blood pressure persistently <90 mmHg or mean arterial pressure <65 mmHg for at least 30 min, or the need for continuous escalation of circulatory support to maintain these blood pressure targets, together with at least one sign of hypoperfusion, including arterial lactate >2.0 mmol/L or progressively increasing lactate, urine output <0.5 mL $\cdot$ kg $^{-1}\cdot$ h $^{-1}$ for more than 4 h, cold and clammy peripheral skin, altered mental status, or central venous oxygen saturation $<60\%$, leading to initiation of at least one additional inotrope or continuous increase in the dose of an existing agent; or (2) new initiation of IABP, VA-ECMO, or other mechanical circulatory support because of postoperative cardiac pump failure. Planned preoperative or intraoperative mechanical circulatory support was not counted as an endpoint event.

Endpoint events were independently reviewed by two investigators blinded to preoperative TAPSE/PASP results using a prespecified event adjudication form. They reviewed ICU progress notes, hemodynamic monitoring results, laboratory changes, echocardiographic/imaging data, and treatment decisions. If the two investigators disagreed, a third senior cardiovascular surgeon made the final adjudication under the same blinded conditions.

Perioperative LCOS, initiation of mechanical circulatory support, and intraoperative transfusion were extracted

from ICU, anesthesia, and surgical records according to a prespecified data dictionary.

2.5 Statistical Analysis

Statistical analyses were performed using R version 4.3.2 (Vienna, Austria). Before between-group comparisons, continuous variables underwent distribution diagnostics, including histograms, quantile-quantile (Q-Q) plots, box plots, and the Shapiro-Wilk test; skewness, kurtosis, sample size, and clinical interpretability were also considered when determining approximate normality. Normally distributed variables are presented as mean $\pm$ standard deviation (SD) and were compared between groups using the independent-samples t test, with the conventional t test or Welch-corrected t test selected according to the variance homogeneity test. Non-normally distributed variables are presented as median and interquartile range (IQR) and were compared using the Mann-Whitney U test. Categorical variables are presented as numbers and percentages and were compared using the Pearson χ^2 test, continuity-corrected χ^2 test, or Fisher exact test. All statistical tests were two-sided, and $p < 0.05$ was considered statistically significant.

Baseline characteristics were first compared between the LCOS and non-LCOS groups. Univariable analysis results were used mainly to describe between-group differences and to assist in identifying potential risk factors, but they were not the sole criterion for entry into multiple logistic regression models. Multiple logistic regression models were prespecified according to clinical relevance, previous evidence, and variable temporal sequence, aiming to establish a minimally sufficient adjustment set. Prespecified adjustment factors included age, sex, BMI, NYHA functional class, LVEF, chronic kidney disease, recent acute coronary syndrome, left main disease, and three-vessel disease. Because surgical strategy could affect postoperative LCOS, an extended model incorporating surgical strategy was additionally constructed as a sensitivity analysis. Because MR could affect PASP and TAPSE/PASP, another sensitivity model further incorporated MR severity and ischemic/functional MR on the basis of the main model, with MR severity handled as moderate MR versus none/trace or mild MR. In principle, intraoperative variables that clearly occurred after the main exposure were not included in the main model to reduce overadjustment and mediation bias. The number of variables included in the final model was controlled according to the number of endpoint events, following the principle of no more than one degree of freedom per 10 endpoint events to minimize the risk of overfitting.

The main exposure variable, TAPSE/PASP, was first entered into the model as a continuous variable, and results are reported as odds ratios (ORs) with 95% confidence intervals (CIs). The functional relationship between continuous predictors and the logit was initially tested under the linearity assumption. If obvious departure from linearity was identified, appropriate transformation or restricted cubic

Table 1. Baseline clinical characteristics by group.

Variable	Overall (n = 307)	LCOS group (n = 101)	Non-LCOS group (n = 206)	Statistic	p value
Age (years, mean $\pm$ SD)	64.6 $\pm$ 8.7	66.8 $\pm$ 8.4	63.6 $\pm$ 8.6	$t = 3.11$	0.002
Male sex, n (%)	246 (80.1)	80 (79.2)	166 (80.6)	$\chi^2 = 0.08$	0.777
BMI (kg/m ² , mean $\pm$ SD)	25.0 $\pm$ 3.3	24.5 $\pm$ 3.1	25.2 $\pm$ 3.4	$t = -1.80$	0.073
Smoking history, n (%)				$\chi^2 = 8.65$	0.013
Never smoker	118 (38.4)	31 (30.7)	87 (42.2)		
Former smoker	121 (39.4)	38 (37.6)	83 (40.3)		
Current smoker	68 (22.1)	32 (31.7)	36 (17.5)		
Hypertension, n (%)	193 (62.9)	69 (68.3)	124 (60.2)	$\chi^2 = 1.92$	0.166
Diabetes mellitus, n (%)	129 (42.0)	53 (52.5)	76 (36.9)	$\chi^2 = 6.75$	0.009
Chronic kidney disease, n (%)	59 (19.2)	32 (31.7)	27 (13.1)	$\chi^2 = 15.06$	<0.001
Previous myocardial infarction, n (%)	142 (46.3)	58 (57.4)	84 (40.8)	$\chi^2 = 7.56$	0.006
Atrial fibrillation, n (%)	31 (10.1)	17 (16.8)	14 (6.8)	$\chi^2 = 7.52$	0.006
History of stroke, n (%)	38 (12.4)	16 (15.8)	22 (10.7)	$\chi^2 = 1.67$	0.197
NYHA functional class, n (%)				$\chi^2 = 24.23$	<0.001
Class II	90 (29.3)	16 (15.8)	74 (35.9)		
Class III	161 (52.4)	53 (52.5)	108 (52.4)		
Class IV	56 (18.2)	32 (31.7)	24 (11.7)		
Recent acute coronary syndrome, n (%)	97 (31.6)	53 (52.5)	44 (21.4)	$\chi^2 = 30.36$	<0.001
Left main disease, n (%)	134 (43.6)	57 (56.4)	77 (37.4)	$\chi^2 = 10.01$	0.002
Three-vessel disease, n (%)	256 (83.4)	89 (88.1)	167 (81.1)	$\chi^2 = 2.43$	0.119

Note: SD, standard deviation; BMI, body mass index; NYHA, New York Heart Association; LCOS, low cardiac output syndrome. Continuous variables are presented as mean $\pm$ SD and compared using the independent-samples t test; categorical variables are presented as n (%) and compared using the Pearson χ^2 test, continuity-corrected χ^2 test, or Fisher exact test. In the Statistic column, t denotes the independent-samples t test statistic and χ^2 denotes the χ^2 test statistic; Fisher exact test was used for categorical variables with low expected frequencies. p values are two-sided.

splines were prioritized; stratified analysis based on clinical meaning was considered only when necessary. Collinearity diagnostics were performed for multiple logistic regression models, and a variance inflation factor (VIF) >5 was considered to indicate significant collinearity.

Receiver operating characteristic (ROC) curves were used to evaluate the discriminative performance of pre-specified echocardiographic parameters (TAPSE/PASP, TAPSE, PASP, and LVEF) for postoperative LCOS, and areas under the receiver operating characteristic curves (AUCs) with 95% CIs were calculated. The 95% CIs for sensitivity and specificity were calculated using the Wilson method. To evaluate the incremental predictive value of TAPSE/PASP, the baseline clinical model and an extended model consisting of the baseline clinical model plus TAPSE/PASP were further constructed, and AUCs were compared between models using the DeLong test. Model calibration was assessed using the Hosmer–Lemeshow goodness-of-fit test, calibration curve, and calibration slope. These calibration and internal validation procedures were performed for the final prediction model. Bootstrap resampling with 1000 iterations was used for internal validation to assess the stability of model performance.

Interobserver agreement for TAPSE, PASP, and TAPSE/PASP was assessed using the intraclass correlation coefficient (ICC); a two-way random-effects, absolute-

agreement, single-measure model, namely ICC (2,1), was used, and the ICC, 95% CI, and p value were reported. Before Bland-Altman analysis, the distributions of paired differences between the two observers were assessed using difference histograms, Q-Q plots, box plots, and the Shapiro-Wilk test. If paired differences were approximately normally distributed, the mean difference, standard deviation of the differences, and 95% limits of agreement based on mean $\pm 1.96 \times$ SD were reported. If paired differences did not satisfy the normality assumption, the median difference (IQR) and empirical 2.5th and 97.5th percentile limits of agreement were reported. The uncertainty of the limits of agreement was estimated using 1000 bootstrap resamples.

3. Results

3.1 Overall Study Population and Primary Endpoint

A total of 468 patients met the screening condition of atherosclerotic coronary artery disease treated with CABG and preoperative LVEF $<50\%$. According to the pre-specified criteria, 161 patients were excluded: 39 underwent concomitant other cardiac/great vessel surgery or had a clearly established preoperative need for concomitant mitral intervention; 14 had previous cardiac surgery; 22 had preoperative cardiogenic shock or preoperative mechanical circulatory support; 11 had conditions clearly increasing pulmonary circulatory afterload; 16 had moder-

Table 2. Preoperative laboratory and echocardiographic parameters by group.

Variable	Overall (n = 307)	LCOS group (n = 101)	Non-LCOS group (n = 206)	Statistic	p value
Hemoglobin (g/L, mean $\pm$ SD)	130.7 $\pm$ 18.3	126.0 $\pm$ 20.0	133.0 $\pm$ 17.0	$t = -3.02$	0.003
Serum creatinine (μ mol/L, median (IQR))	93 (79, 115)	103 (86, 129)	88 (76, 107)	$Z = -4.18$	<0.001
eGFR ($\text{mL} \cdot \text{min}^{-1} \cdot 1.73 \text{ m}^{-2}$, mean $\pm$ SD)	73.7 $\pm$ 19.3	68.1 $\pm$ 20.4	76.4 $\pm$ 18.2	$t = -3.47$	<0.001
Albumin (g/L, mean $\pm$ SD)	39.0 $\pm$ 4.2	37.8 $\pm$ 4.6	39.6 $\pm$ 3.9	$t = -3.38$	0.001
NT-proBNP (pg/mL, median (IQR))	1420 (780, 2960)	2580 (1460, 4310)	1040 (610, 2050)	$Z = -6.57$	<0.001
LVEF (% , mean $\pm$ SD)	40.3 $\pm$ 5.3	37.9 $\pm$ 5.5	41.5 $\pm$ 4.8	$t = -5.412$	<0.001
Left ventricular end-diastolic diameter (mm, mean $\pm$ SD)	59.2 $\pm$ 6.8	61.5 $\pm$ 7.0	58.0 $\pm$ 6.4	$t = 4.23$	<0.001
TAPSE (mm, mean $\pm$ SD)	15.4 $\pm$ 3.2	13.3 $\pm$ 2.8	16.4 $\pm$ 2.9	$t = -9.01$	<0.001
PASP (mmHg, median (IQR))	39 (31, 47)	46 (39, 55)	35 (29, 42)	$Z = -7.08$	<0.001
TAPSE/PASP (mm/mmHg, median (IQR))	0.40 (0.30, 0.52)	0.28 (0.22, 0.36)	0.47 (0.38, 0.57)	$Z = -9.41$	<0.001
Mitral regurgitation severity, n (%)				$\chi^2 = 10.21$	0.006
None/trace	104 (33.9)	26 (25.7)	78 (37.9)		
Mild	168 (54.7)	56 (55.4)	112 (54.4)		
Moderate	35 (11.4)	19 (18.8)	16 (7.8)		
Severe	0 (0.0)	0 (0.0)	0 (0.0)		
Ischemic/functional mitral regurgitation, n (%)	83 (27.0)	36 (35.6)	47 (22.8)	$\chi^2 = 5.02$	0.025

Note: SD, standard deviation; IQR, interquartile range; eGFR, estimated glomerular filtration rate; NT-proBNP, N-terminal pro-B-type natriuretic peptide; LVEF, left ventricular ejection fraction; TAPSE, tricuspid annular plane systolic excursion; PASP, pulmonary artery systolic pressure; TAPSE/PASP, tricuspid annular plane systolic excursion to pulmonary artery systolic pressure ratio; MR, mitral regurgitation; LCOS, low cardiac output syndrome. Normally distributed continuous variables are presented as mean $\pm$ SD and compared using the independent-samples t test; non-normally distributed variables are presented as median (IQR) and compared using the Mann-Whitney U test; categorical variables are presented as n (%) and compared using the χ^2 test, continuity-corrected χ^2 test, or Fisher exact test. In the Statistic column, t denotes the independent-samples t test statistic, Z denotes the standardized statistic for the Mann-Whitney U test, and χ^2 denotes the χ^2 test statistic. Because severe MR occurred in 0 patients, the overall χ^2 test for MR severity was performed across three levels: none/trace, mild, and moderate. p values are two-sided.

ate or greater tricuspid regurgitation or obvious right-heart structural/outflow tract abnormalities; 33 had poor-quality preoperative echocardiographic images preventing reliable measurement of TAPSE or PASP; and 26 had missing data for the main exposure, primary outcome, or key covariates. Ultimately, 307 patients were included.

The median interval between preoperative echocardiography and surgery was 3 (2, 5) days; 291 patients (94.8%) completed echocardiography within 5 days before surgery, and all patients completed echocardiography within 7 days before surgery. At the time of measurement, mean arterial pressure was 78 ± 10 mmHg and heart rate was 76 ± 12 beats/min; no patient received IABP, VA-ECMO, or continuous intravenous inotropic/vasopressor support during measurement. Among the 307 patients, 101 developed LCOS within 72 h after surgery, for an incidence of 32.9%; 206 patients did not develop LCOS, accounting for 67.1%. Among the 101 patients with LCOS, 74 (73.3%) were adjudicated mainly on the basis of persistent hypoperfusion requiring initiation or continuous escalation of inotropic/circulatory support; 27 (26.7%) required new initiation of mechanical circulatory support because of postoperative cardiac pump failure, including 21 treated with IABP alone, 5 treated with VA-ECMO alone, and 1 treated with combined IABP and VA-ECMO. The two investigators initially agreed on LCOS endpoint adjudication in 295 of 307

patients (96.1%); Cohen $\kappa = 0.91$, 95% CI (0.86, 0.96), $p < 0.001$.

3.2 Baseline Clinical Characteristics

Compared with the non-LCOS group, the LCOS group was older; had a different distribution of smoking history; had higher proportions of diabetes mellitus, chronic kidney disease, previous myocardial infarction, atrial fibrillation, recent acute coronary syndrome, and left main disease; and had worse NYHA functional class (all $p < 0.05$). There were no statistically significant differences between the two groups in sex, BMI, hypertension, stroke history, or three-vessel disease (all $p > 0.05$) (Table 1).

3.3 Preoperative Laboratory and Echocardiographic Parameters

Compared with the non-LCOS group, the LCOS group had lower preoperative hemoglobin, eGFR, albumin, LVEF, TAPSE, and TAPSE/PASP, and higher serum creatinine, NT-proBNP, left ventricular end-diastolic diameter, and PASP (all $p < 0.05$). MR severity and ischemic/functional MR differed between groups, with higher proportions of moderate MR and ischemic/functional MR in the LCOS group (both $p < 0.05$) (Table 2).

Table 3. Perioperative surgical variables by group.

Variable	Overall (n = 307)	LCOS group (n = 101)	Non-LCOS group (n = 206)	Statistic	p value
Surgical strategy, n (%)				$\chi^2 = 4.56$	0.033
On-pump CABG	219 (71.3)	80 (79.2)	139 (67.5)		
Off-pump CABG	88 (28.7)	21 (20.8)	67 (32.5)		
Graft type, n (%)				$\chi^2 = 1.07$	0.586
Left internal mammary artery only	62 (20.2)	17 (16.8)	45 (21.8)		
Left internal mammary artery + saphenous vein	218 (71.0)	75 (74.3)	143 (69.4)		
Bilateral internal mammary arteries + other grafts (radial artery/saphenous vein)	27 (8.8)	9 (8.9)	18 (8.7)		
Number of distal anastomoses, median (IQR)	3 (3, 4)	3 (3, 4)	3 (3, 4)	$Z = -0.92$	0.357
Cardiopulmonary bypass time (min, on-pump CABG only)	109 (90, 128)	119 (99, 140)	103 (86, 122)	$Z = -4.11$	<0.001
Aortic cross-clamp time (min, on-pump CABG only)	63.0 $\pm$ 18.9	69.0 $\pm$ 21.0	60.0 $\pm$ 17.0	$t = 3.46$	<0.001
Intraoperative transfusion, n (%)	93 (30.3)	50 (49.5)	43 (20.9)	$\chi^2 = 26.31$	<0.001

Note: CABG, coronary artery bypass grafting; SD, standard deviation; IQR, interquartile range; LCOS, low cardiac output syndrome. Cardiopulmonary bypass time and aortic cross-clamp time were calculated only among patients undergoing on-pump CABG. The number of distal anastomoses and cardiopulmonary bypass time are presented as median (IQR) and compared using the Mann-Whitney U test; aortic cross-clamp time is presented as mean $\pm$ SD and compared using the independent-samples t test; categorical variables are presented as n (%) and compared using the Pearson χ^2 test, continuity-corrected χ^2 test, or Fisher exact test. In the Statistic column, t denotes the independent-samples t test statistic, Z denotes the standardized statistic for the Mann-Whitney U test, and χ^2 denotes the χ^2 test statistic. p values are two-sided.

Interobserver agreement analysis was performed in 50 randomly selected patients, including 16 with LCOS (32.0%), which was close to the overall cohort LCOS incidence of 32.9%. The interobserver ICCs for TAPSE, PASP, and TAPSE/PASP were 0.92, 95% CI (0.87, 0.95), $p < 0.001$; 0.89, 95% CI (0.82, 0.93), $p < 0.001$; and 0.91, 95% CI (0.85, 0.94), $p < 0.001$, respectively. Q-Q plots and Shapiro-Wilk tests indicated that the paired differences between the two observers deviated from normality: TAPSE $W = 0.947$, $p = 0.025$; PASP $W = 0.938$, $p = 0.012$; and TAPSE/PASP $W = 0.950$, $p = 0.032$ (**Supplementary Fig. 1, Supplementary Table 1**). Therefore, Bland-Altman agreement was summarized using a nonparametric approach. The median difference for TAPSE was 0.1 mm, IQR (−0.6, 0.8), with empirical 95% limits of agreement (−2.1, 2.5) mm; the median difference for PASP was 0.8 mmHg, IQR (−2.4, 4.5), with empirical 95% limits of agreement (−9.5, 11.6) mmHg; and the median difference for TAPSE/PASP was −0.004 mm/mmHg, IQR (−0.025, 0.019), with empirical 95% limits of agreement (−0.083, 0.072) mm/mmHg. Four cases (8.0%) triggered third-party quality-control review because the measurement difference between the two observers reached the prespecified threshold; after review, all images were confirmed to be usable for the agreement analysis.

3.4 Perioperative Surgical Variables

Compared with the non-LCOS group, the LCOS group had a different distribution of surgical strategy, a higher proportion of on-pump CABG, and a higher intraoperative transfusion rate; among patients undergoing on-pump CABG, cardiopulmonary bypass time and aortic

cross-clamp time were longer (all $p < 0.05$). There were no statistically significant differences between groups in graft-type distribution or number of distal anastomoses (both $p > 0.05$) (Table 3).

3.5 Multiple Logistic Regression Analysis of TAPSE/PASP and Postoperative LCOS

Testing of the relationship between continuous variables and the logit showed no clear deviation from linearity for TAPSE/PASP, with nonlinearity test $p = 0.214$; no clear deviation from linearity was observed for age, BMI, or LVEF. Variance inflation factors for variables in the main model ranged from 1.09 to 1.87, indicating no significant collinearity. Multiple logistic regression showed that TAPSE/PASP remained independently associated with postoperative LCOS after adjustment using the prespecified minimally sufficient adjustment set. In addition to TAPSE/PASP, NYHA class III–IV, lower LVEF, chronic kidney disease, and recent acute coronary syndrome were associated with LCOS; left main disease reached statistical significance in the main model (Table 4). In the sensitivity model incorporating surgical strategy, the association between TAPSE/PASP and LCOS remained stable; per 0.1-unit increase OR = 0.59, 95% CI (0.47, 0.75), $p < 0.001$. On-pump CABG was associated with increased LCOS risk; OR = 1.87, 95% CI (1.03, 3.41), $p = 0.039$. After further adjustment for MR severity and ischemic/functional MR, TAPSE/PASP remained independently associated with postoperative LCOS; per 0.1-unit increase OR = 0.64, 95% CI (0.51, 0.80), $p < 0.001$. In this sensitivity model, moderate MR relative to none/trace or mild MR did not reach statistical significance for association with LCOS; OR = 1.59,

Table 4. Multiple logistic regression analysis of TAPSE/PASP and postoperative LCOS.

Variable	Main-model OR, 95% CI	<i>p</i> value
TAPSE/PASP (per 0.1-unit increase)	0.62; 95% CI (0.50, 0.77)	<0.001
Age (per 10-year increase)	1.21; 95% CI (0.89, 1.65)	0.223
Male sex	0.86; 95% CI (0.45, 1.64)	0.641
BMI (per 1 kg/m ² increase)	0.96; 95% CI (0.89, 1.04)	0.319
NYHA class III–IV (vs class II)	1.92; 95% CI (1.07, 3.45)	0.029
LVEF (per 5% increase)	0.78; 95% CI (0.65, 0.93)	0.007
Chronic kidney disease	2.18; 95% CI (1.25, 3.82)	0.006
Recent acute coronary syndrome	1.98; 95% CI (1.17, 3.36)	0.011
Left main disease	1.71; 95% CI (1.02, 2.88)	0.042
Three-vessel disease	1.46; 95% CI (0.71, 3.03)	0.307

Note: OR, odds ratio; CI, confidence interval; BMI, body mass index; NYHA, New York Heart Association; LVEF, left ventricular ejection fraction; TAPSE/PASP, tricuspid annular plane systolic excursion to pulmonary artery systolic pressure ratio; LCOS, low cardiac output syndrome. The main model included age, sex, BMI, NYHA functional class, LVEF, chronic kidney disease, recent acute coronary syndrome, left main disease, and three-vessel disease. *p* values are two-sided Wald test *p* values; the Wald test evaluates whether the logistic regression coefficient differs from 0. NYHA functional class was modeled as class III–IV versus class II; age was modeled per 10-year increase, LVEF per 5% increase, and TAPSE/PASP per 0.1-unit increase. Sensitivity model results are reported in the text. OR <1 indicates that an increase in the variable value or the presence of the exposure is associated with lower LCOS risk.

Table 5. TAPSE/PASP quartiles and postoperative LCOS occurrence.

TAPSE/PASP quartile	Definition	No. of patients	LCOS events, n (%)
Q1	≤first quartile cutoff	77	46 (59.7)
Q2	>first quartile cutoff and ≤second quartile cutoff	77	29 (37.7)
Q3	>second quartile cutoff and ≤third quartile cutoff	76	17 (22.4)
Q4	>third quartile cutoff	77	9 (11.7)

Note: Q, quartile; TAPSE/PASP, tricuspid annular plane systolic excursion to pulmonary artery systolic pressure ratio; LCOS, low cardiac output syndrome. Stratification was based on quartiles of the original TAPSE/PASP distribution. The χ^2 trend test was used to evaluate the linear trend in LCOS incidence with increasing TAPSE/PASP quartile; χ^2 denotes the linear trend test statistic. *p* value is two-sided.

95% CI (0.76, 3.35), *p* = 0.219. Ischemic/functional MR also did not reach statistical significance; OR = 1.28, 95% CI (0.70, 2.35), *p* = 0.424. To enhance clinical interpretability, a quartile-based stratified analysis of TAPSE/PASP was further performed. With increasing TAPSE/PASP, LCOS incidence decreased in a stepwise manner, with a χ^2 trend test value of 44.29 across quartiles, *p* < 0.001 (Table 5).

3.6 Predictive Performance, Calibration, and Internal Validation

Among individual echocardiographic parameters, TAPSE/PASP had the highest AUC for postoperative LCOS, at 0.810, 95% CI (0.758, 0.861). The exploratory optimal cutoff in this study was 0.34, corresponding to sensitivity of 75.2%, 95% CI (66.0, 82.6), and specificity of 73.8%, 95% CI (67.4, 79.3). Compared with TAPSE, the AUC difference for TAPSE/PASP did not reach statistical significance, *p* = 0.093. Compared with PASP and LVEF,

TAPSE/PASP had higher AUCs, *p* = 0.041 and *p* = 0.008, respectively (Table 6, Fig. 1). After TAPSE/PASP was added to the baseline clinical model, the AUC increased from 0.781 to 0.851, with DeLong test *p* = 0.002 (Table 6, Fig. 1). The baseline clinical model plus TAPSE/PASP was used as the main prediction model for calibration and internal validation. The Hosmer-Lemeshow goodness-of-fit test yielded χ^2 = 6.48, *p* = 0.593; the calibration slope was 0.94, 95% CI (0.82, 1.08). After 1000 bootstrap resamples, the corrected AUC was 0.838, 95% bootstrap CI (0.803, 0.881), indicating stable model performance (Fig. 2).

4. Discussion

This retrospective study evaluated the predictive value of preoperative TAPSE/PASP for LCOS after CABG in patients with coronary artery disease and reduced ejection fraction. The results showed that lower TAPSE/PASP

Table 6. Discriminative performance of preoperative echocardiographic parameters and prediction models for postoperative LCOS.

Parameter/model	AUC, 95% CI	Exploratory optimal cutoff	Sensitivity, 95% CI	Specificity, 95% CI	DeLong test <i>p</i> value
TAPSE/PASP	0.810; 95% CI (0.758, 0.861)	0.34	75.2%; 95% CI (66.0, 82.6)	73.8%; 95% CI (67.4, 79.3)	Reference
TAPSE	0.756; 95% CI (0.700, 0.812)	14.3 mm	70.3%; 95% CI (60.8, 78.3)	69.4%; 95% CI (62.8, 75.3)	0.093†
PASP	0.734; 95% CI (0.675, 0.793)	40.5 mmHg	67.3%; 95% CI (57.7, 75.7)	68.0%; 95% CI (61.3, 74.0)	0.041†
LVEF	0.699; 95% CI (0.638, 0.761)	40.5%	63.4%; 95% CI (53.6, 72.1)	66.0%; 95% CI (59.3, 72.1)	0.008†
Baseline clinical model	0.781; 95% CI (0.730, 0.832)	-	-	-	Reference
Baseline clinical model + TAPSE/PASP	0.851; 95% CI (0.809, 0.893)	-	-	-	0.002‡

Note: AUC, area under the receiver operating characteristic curve; CI, confidence interval; TAPSE/PASP, tricuspid annular plane systolic excursion to pulmonary artery systolic pressure ratio; TAPSE, tricuspid annular plane systolic excursion; PASP, pulmonary artery systolic pressure; LVEF, left ventricular ejection fraction; LCOS, low cardiac output syndrome. The 95% CIs for sensitivity and specificity were calculated using the Wilson method; † indicates comparison with TAPSE/PASP, and ‡ indicates comparison with the baseline clinical model. AUC comparisons used the DeLong test. “Reference” indicates the reference row for DeLong comparison; “-” indicates not applicable or not calculated. *p* values are two-sided.

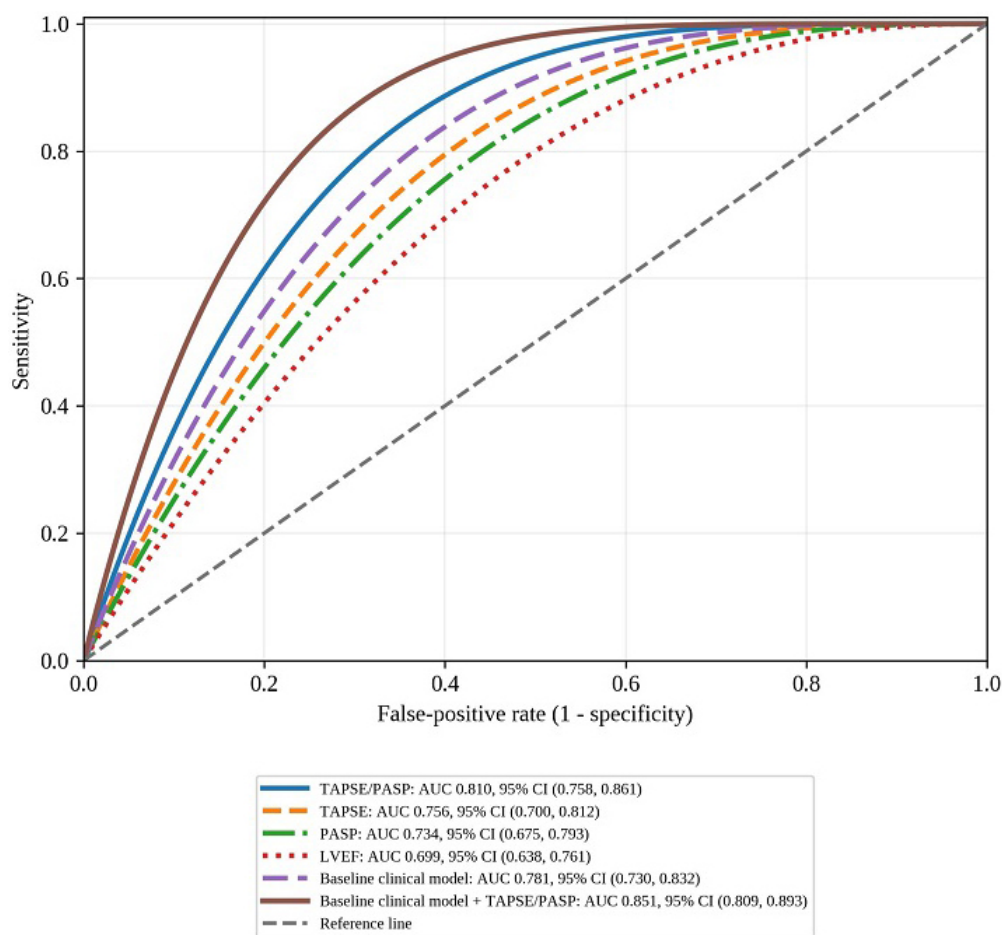


Fig. 1. Receiver operating characteristic curves for preoperative echocardiographic parameters and prediction models for postoperative low cardiac output syndrome (LCOS). AUC, area under the receiver operating characteristic curve; CI, confidence interval; TAPSE/PASP, tricuspid annular plane systolic excursion to pulmonary artery systolic pressure ratio; TAPSE, tricuspid annular plane systolic excursion; PASP, pulmonary artery systolic pressure; LVEF, left ventricular ejection fraction. Figure legend: TAPSE/PASP: AUC 0.810, 95% CI (0.758, 0.861); TAPSE: AUC 0.756, 95% CI (0.700, 0.812); PASP: AUC 0.734, 95% CI (0.675, 0.793); LVEF: AUC 0.699, 95% CI (0.638, 0.761); baseline clinical model: AUC 0.781, 95% CI (0.730, 0.832); baseline clinical model + TAPSE/PASP: AUC 0.851, 95% CI (0.809, 0.893).

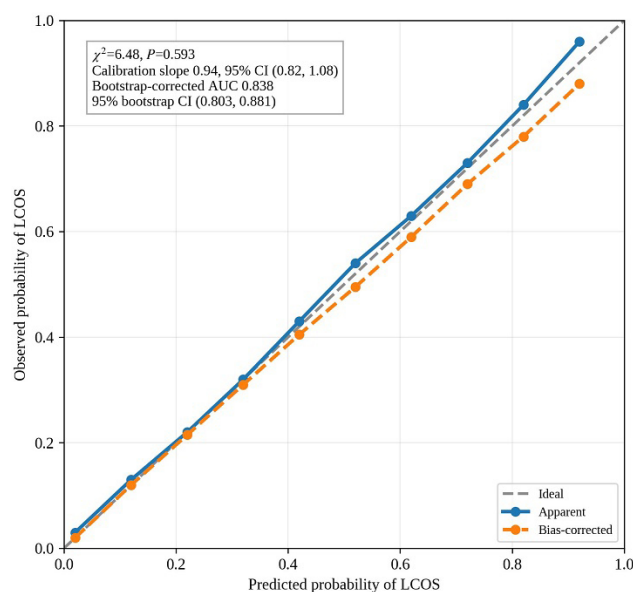


Fig. 2. Calibration curve for the main prediction model comprising the baseline clinical model plus TAPSE/PASP. TAPSE/PASP, tricuspid annular plane systolic excursion to pulmonary artery systolic pressure ratio; LCOS, low cardiac output syndrome; AUC, area under the receiver operating characteristic curve; CI, confidence interval. Figure annotation: Hosmer-Lemeshow $\chi^2 = 6.48$, $p = 0.593$; calibration slope 0.94, 95% CI (0.82, 1.08); bootstrap-corrected AUC 0.838, 95% bootstrap CI (0.803, 0.881).

was independently associated with a higher risk of LCOS; among individual echocardiographic parameters, TAPSE/PASP had the best discriminative performance; and adding TAPSE/PASP to the baseline clinical model significantly improved predictive performance.

The incidence of LCOS in this study was 32.9%, which is broadly consistent with the range reported previously in patients with impaired preoperative left ventricular systolic function [22]. This relatively high incidence suggests clear limitations in assessing surgical risk based solely on LVEF and highlights the clinical need for more sensitive predictive markers. Preoperative left ventricular systolic dysfunction itself reflects reduced baseline myocardial reserve; however, right ventricular functional status and its adaptive matching with the pulmonary circulation also play an important role in perioperative hemodynamic outcomes after cardiac surgery [23,24]. The right ventricle is sensitive to the combined insults of cardiopulmonary bypass and myocardial ischemia–reperfusion injury. Once RV-PA coupling is already impaired preoperatively, inadequate intraoperative myocardial protection, cardiopulmonary bypass-related inflammatory responses, fluctuations in pulmonary vascular resistance, and changes in volume/pressure loading may induce acute right ventricular decompensation, thereby precipitating or aggravating a low cardiac output state [25].

As a noninvasive surrogate of RV-PA coupling, TAPSE/PASP has clear physiological meaning because it integrates right ventricular longitudinal systolic function and pulmonary arterial afterload into a single ratio. Previous heart failure studies have shown that this ratio has stronger prognostic value than TAPSE or PASP alone [26,27]. Data from patients with pulmonary hypertension have similarly demonstrated that RV-PA coupling can independently predict clinical worsening and death [28]. In cardiac surgical patients, impaired preoperative RV-PA coupling has been associated with major complications and operative mortality [29]. The present study focused the application of this parameter on perioperative evaluation for CABG in patients with coronary artery disease and reduced ejection fraction.

Impaired RV-PA coupling reflected by TAPSE/PASP is not limited to cardiac surgical risk assessment. Recent prospective perioperative studies have shown that lower preoperative TAPSE/PASP is associated with hypotension after induction of general anesthesia, suggesting that even in noncardiac surgical settings, imbalance between right ventricular contractile reserve and pulmonary circulatory afterload may reduce the patient's compensatory capacity in response to anesthesia induction, vasodilation, and changes in venous return [30,31,32]. This prospective perioperative evidence supports interpreting TAPSE/PASP as a noninvasive marker of hemodynamic vulnerability. In the present study, the increased risk of LCOS after CABG among patients with low TAPSE/PASP is consistent with this physiological framework: when RV-PA coupling is already in a low-reserve state preoperatively, cardiopulmonary bypass, myocardial ischemia–reperfusion, fluctuations in pulmonary vascular resistance, and anesthesia-related changes in preload and afterload are more likely to trigger perioperative circulatory decompensation [24].

In the multiple logistic regression analysis, each 0.1-unit increase in TAPSE/PASP was associated with an approximately 38% lower risk of LCOS; OR = 0.62, 95% CI (0.50, 0.77), $p < 0.001$. The result remained stable after adjustment for LVEF and other clinical confounders, suggesting that TAPSE/PASP captures independent information beyond LVEF. This finding is consistent with the independent prognostic role of right ventricular function in cardiac surgical populations: the right ventricle is an important driver of early postoperative low cardiac output, whereas LVEF reflects only left ventricular function and has inherent limitations in evaluating the overall biventricular circulatory state [23,24]. Notably, in this study, the AUC for TAPSE alone was 0.756, whereas the AUC for TAPSE/PASP was 0.810; although the difference between them did not reach statistical significance, $p = 0.093$, TAPSE/PASP was superior to PASP and LVEF, and the differences were statistically significant. This observation is consistent with some heart failure studies and suggests that, when pulmonary artery pressure is elevated, assessment of right ventricular longitudinal motion alone without consid-

eration of afterload may underestimate the degree of RV-PA uncoupling [26,27].

TAPSE is one of the most commonly used and most readily obtainable echocardiographic parameters for assessing right ventricular longitudinal systolic function, with advantages of reproducibility, rapid acquisition, and bedside feasibility in preoperative cardiac surgical assessment. Recent cardiac surgery studies have shown that RV-PA coupling parameters are associated with major complications and operative mortality, supporting the value of right-heart functional parameters in perioperative risk assessment for CABG and valve surgery [29]. However, TAPSE mainly reflects right ventricular longitudinal motion and may be affected by global cardiac translation, regional wall motion, sternotomy, and perioperative loading conditions; therefore, it cannot by itself represent complete right ventricular systolic function. Right-heart echocardiographic assessment guidelines also emphasize that TAPSE should be interpreted in combination with other right-heart functional and pulmonary circulatory afterload parameters [5,32]. Therefore, this study used TAPSE/PASP to integrate right ventricular longitudinal contractile capacity with pulmonary arterial afterload and thereby reduce interpretive limitations caused by the loading-condition dependence of TAPSE alone.

Regarding incremental predictive value, adding TAPSE/PASP to the baseline clinical model increased the AUC from 0.781 to 0.851, DeLong test $p = 0.002$; the bootstrap-corrected AUC was 0.838, 95% bootstrap CI (0.803, 0.881); and the Hosmer-Lemeshow test showed good calibration, $p = 0.593$. These results indicate that TAPSE/PASP provides substantial additional predictive information beyond the existing clinical framework. From a practical standpoint, the parameters required to calculate TAPSE/PASP, namely TAPSE and tricuspid regurgitation velocity, can both be obtained during routine echocardiographic examination without additional testing, improving the clinical feasibility of this marker [24].

Quartile-based analysis further supported a dose-response relationship: LCOS incidence was 59.7% in the lowest TAPSE/PASP quartile (Q1) and decreased to 11.7% in the fourth quartile (Q4), with a highly significant trend ($p < 0.001$). The study-specific exploratory cut-off of 0.34 mm/mmHg is close to reference ranges used in some pulmonary hypertension and heart failure studies to indicate a risk of RV-PA uncoupling [27,28]. However, the study design does not support directly recommending this cut-off as a clinical diagnostic threshold, and its external applicability requires validation in prospective cohorts.

MR may affect TAPSE/PASP by increasing left atrial pressure, pulmonary venous pressure, and consequently PASP. Although this study excluded patients with severe MR or those requiring concomitant mitral intervention, moderate ischemic/functional MR may still constitute residual confounding. Additional sensitivity analysis showed that, after adjustment for MR sever-

ity and ischemic/functional MR, the association between TAPSE/PASP and LCOS remained stable, suggesting that the main findings were not fully explained by MR.

This study also found that NYHA class III–IV, lower LVEF, chronic kidney disease, and recent acute coronary syndrome were independently associated with LCOS, consistent with risk factors suggested in previous cardiac surgery and CABG population studies [22]. Surgical strategy (on-pump versus off-pump CABG) was also associated with LCOS in sensitivity analysis, suggesting that the adverse impact of cardiopulmonary bypass itself on perioperative myocardial function should not be overlooked. This finding is consistent with mechanisms related to cardiopulmonary bypass-associated systemic inflammatory response, myocardial edema, and ischemia–reperfusion injury [25].

This study used resting TAPSE/PASP as a surrogate of RV-PA coupling, which has advantages of clinical availability and ease of perioperative risk screening. However, RV-PA coupling is fundamentally a dynamic physiological relationship, and resting measurements may not fully reflect right ventricular contractile reserve or adaptability to exercise-related or perioperative afterload changes. A recent Journal of the American Heart Association study in patients undergoing surgery for secondary ischemic MR showed that exercise-derived TAPSE/PASP was closely related to 6-min walk distance and long-term functional outcomes, suggesting that dynamic RV-PA coupling may provide additional information on functional reserve beyond resting measurements [33]. For patients with reduced LVEF undergoing CABG, future studies may integrate resting TAPSE/PASP, exercise- or pharmacologic stress-derived RV-PA coupling, right-heart strain, and hemodynamic parameters to construct more comprehensive perioperative risk stratification models.

Limitations

This study has several limitations. First, the retrospective design inevitably carries risks of selection bias and information bias. Although strict inclusion and exclusion criteria were prespecified, the influence of unmeasured confounders cannot be fully excluded. Second, PASP was indirectly estimated from tricuspid regurgitation velocity and may therefore be subject to measurement error; reliability decreases when the tricuspid regurgitation signal is suboptimal. Patients in whom reliable measurement was not possible were excluded during screening, but residual measurement error may still have attenuated the true predictive value of TAPSE/PASP. Independent blinded remeasurement showed good interobserver agreement for TAPSE/PASP. The interobserver paired differences showed mild non-normality, and the Bland-Altman results were reported using median differences and empirical percentile limits of agreement to reduce bias caused by the normal-approximation assumption. PASP still depends on tricuspid regurgitation spectral quality and right atrial pressure

estimation, and TAPSE may also be affected by global cardiac translation and imaging-plane angle. Therefore, the results should be interpreted as risk prediction findings under standardized preoperative transthoracic echocardiographic conditions, and future multicenter studies are still needed to validate the consistency of TAPSE/PASP measurement across different echocardiography laboratories. Third, although TAPSE/PASP reflects RV-PA coupling better than TAPSE alone, it cannot replace more comprehensive assessments of right ventricular function, such as three-dimensional right ventricular ejection fraction, right-heart strain, or invasive pressure-volume loops. Fourth, this was a two-center study, and the external generalizability of the findings requires validation in multicenter studies.

5. Conclusions

Preoperative TAPSE/PASP is an independent predictor of LCOS after CABG in patients with coronary artery disease and reduced ejection fraction. Its predictive performance is superior to PASP alone and LVEF, and it has the highest AUC among individual echocardiographic parameters. Adding TAPSE/PASP to the baseline clinical model further improves predictive performance. As a noninvasive and readily available surrogate of RV-PA coupling, TAPSE/PASP may provide valuable supplementary information for preoperative risk stratification in this high-risk population and may help optimize perioperative management. Future prospective multicenter studies should further evaluate whether dynamic or exercise-derived RV-PA coupling can improve prediction of functional outcomes and perioperative events beyond resting TAPSE/PASP in high-risk CABG patients and further validate its optimal reference range and value in guiding clinical interventions.

Availability of Data and Materials

The dataset analyzed in this study can be obtained from the corresponding author upon reasonable request.

Author Contributions

YJ, HYL and YL designed the research study. YHL, YJ, HL and XXZ performed the research. YL analyzed the data and drafted the manuscript. All authors contributed to critical revision of the manuscript for important intellectual content. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

The study was carried out in accordance with the guidelines of the Declaration of Helsinki and approved by the Ethics Committee of our hospitals (SIR RUN RUN SHAW HOSPITAL 2026 investigator initiated trial NO.2350). The requirement for written informed consent was waived because of the retrospective study design.

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Conflicts of Interest

The authors declare no conflicts of interest.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at <https://doi.org/10.31083/HSF53167>.

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