

Multidimensional Echocardiographic Parameters Predict Left Ventricular Functional Recovery After Coronary Artery Bypass Grafting

Ann. Ital. Chir., 2026 97, 10: 1822–1833
<https://doi.org/10.62713/aic.4716>

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AIM: This study aimed to investigate the predictive value of preoperative and early postoperative echocardiographic parameters for left ventricular function recovery after coronary artery bypass grafting (CABG), and to evaluate the relationship between functional recovery and 1-year clinical prognosis.

METHODS: This retrospective cohort included 214 patients undergoing first-time elective CABG at The First Affiliated Hospital of Yangtze University between January 2022 and October 2024. Transthoracic echocardiography was performed preoperatively, 3–7 days postoperatively, and at 6 months to evaluate left ventricular ejection fraction (LVEF), global longitudinal strain (GLS), left atrial volume index (LAVI), and ratio of early mitral inflow velocity to early diastolic mitral annular velocity (E/e'). Based on 6-month LVEF change, patients were divided into recovery ($\Delta\text{LVEF} \geq 5\%$) and non-recovery ($\Delta\text{LVEF} < 5\%$) groups. Multivariate logistic regression was used to identify independent predictors, and the corresponding models were established and validated. Major adverse cardiovascular events (MACE) were recorded at 1-year follow-up.

RESULTS: Of the 214 patients enrolled in the study, functional recovery of the left ventricle was observed in 128 individuals, corresponding to 59.8% of the cohort. Multivariate analysis identified several preoperative and procedural variables as independent predictors of functional recovery, including left atrial volume index (LAVI), left ventricular end-diastolic diameter (LVEDD), left ventricular end-systolic diameter (LVESD), left atrial diameter (LAD), Synergy between Percutaneous Coronary Intervention with TAXUS and Cardiac Surgery (SYNTAX) score, and the number of graft vessels. Age, preoperative LVEF, and e' velocity were independently associated with lower odds of functional recovery. Global longitudinal strain (GLS) and diabetes history showed no independent predictive value. The clinical-echocardiographic combined model demonstrated excellent discrimination and showed higher discriminative performance than the basic clinical model and conventional echocardiographic model. Subgroup analysis revealed that GLS showed no independent predictive value across all LVEF subgroups ($p > 0.05$), whereas LAVI and LAD were significant predictors in patients with $\text{LVEF} \geq 40\%$ (including the 40%–49% subgroup), but showed no predictive relevance in those with $\text{LVEF} < 40\%$. Early postoperative ΔLVEF predicted 6-month functional recovery with an area under the curve (AUC) of 0.846. After one year of follow-up, the recovery group exhibited a markedly lower rate of MACE than the non-recovery group, with left ventricular functional recovery serving as an independent protective factor against MACE.

CONCLUSIONS: Preoperative structural parameters, including LAVI, LVEDD, LVESD, and LAD, are independent imaging biomarkers for predicting left ventricular functional recovery after CABG. GLS and E/e' ratio show no independent predictive value in this study. The integrated model combining clinical factors with multi-dimensional echocardiographic parameters demonstrates excellent discriminative ability. Early postoperative LVEF improvement strongly predicts 6-month functional recovery, while postoperative recovery of left ventricular function is associated with a significantly lower 1-year MACE risk.

Keywords: coronary artery bypass grafting; global longitudinal strain; left atrial volume index; E/e' ratio; left ventricular functional recovery; major adverse cardiovascular events

Introduction

Coronary artery disease remains the leading cause of chronic heart failure and cardiovascular death worldwide, with a continuously rising overall burden [1,2]. For patients with multivessel or left main coronary artery disease, coronary artery bypass grafting (CABG) is still considered the optimal revascularization strategy, effectively restoring myocardial blood flow and improving long-term survival [3,4]. However, in clinical practice, the recovery of left ventricular systolic function after CABG varies widely among patients. Some show significant improve-

Submitted: 24 April 2026 Revised: 19 June 2026 Accepted: 24 June 2026 Published: 14 October 2026

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Editor: Pasqualino Sirignano

ment or even normalization of left ventricular ejection fraction (LVEF), while others, despite complete revascularization, experience minimal improvement or even worsening heart failure [5]. Predicting whether the left ventricle will recover after CABG is therefore a key question for preoperative risk assessment, surgical decision-making, and postoperative management.

Traditionally, LVEF has been the standard measure of systolic function, but it has well-known limitations: it reflects only global pump function, cannot distinguish reversible dysfunction from irreversible damage, and is highly load-dependent [6,7]. Global longitudinal strain (GLS) derived from speckle-tracking echocardiography measures myocardial deformation, specifically the longitudinal shortening of subendocardial fibers [8,9]. Compared with LVEF, GLS is more sensitive, more reproducible, and less load-dependent, and it can detect subclinical dysfunction early [10]. Recent studies have demonstrated the independent prognostic value of GLS in ischemic cardiomyopathy and valvular heart disease [11]. In the CABG setting, a few small-scale studies have reported associations between reduced preoperative GLS and postoperative LVEF improvement, but findings remain inconsistent, and most have not adequately accounted for diastolic function or left atrial remodeling parameters [12,13,14,15].

Left ventricular diastolic dysfunction and left atrial remodeling are key markers of long-term cardiac loading conditions and filling pressures [16]. The ratio of early mitral inflow velocity to early diastolic mitral annular velocity (E/e') is a well-established noninvasive indicator of left ventricular filling pressure, whereas the left atrial volume index (LAVI) reflects structural adaptation of the left atrium in response to prolonged pressure overload [17,18]. Theoretically, patients with marked pre-existing diastolic dysfunction and left atrial remodeling may have reduced myocardial compliance and limited hemodynamic reserve, potentially constraining functional recovery even after successful revascularization [19,20,21]. However, only a limited number of studies have comprehensively incorporated multiple echocardiographic indicators, including systolic functional reserve (GLS), diastolic loading condition (E/e'), and structural remodeling (LAVI), into a single predictive model to systematically assess their independent and additive value in forecasting left ventricular functional recovery after CABG.

Moreover, while most existing research has focused on the relationship between individual preoperative indicators and short-term postoperative functional improvement, key issues remain insufficiently explored. These issues include the prognostic value of early postoperative functional dynamics, the varying predictive performance across different baseline cardiac function levels, and whether recovery of left ventricular (LV) function ultimately leads to long-term clinical benefits [22]. Therefore, developing a comprehensive predictive model that integrates clinical features, mul-

tidimensional echocardiographic metrics, and early postoperative dynamic responses, while verifying its relationship with 1-year clinical outcomes, holds important clinical and research significance.

We hypothesized that preoperative LAVI and other markers of left atrial remodeling, rather than GLS alone, independently predict left ventricular functional recovery after CABG, and that early postoperative changes are associated with long-term prognosis. The primary aim of this study was to investigate the independent and additive predictive value of multidimensional echocardiographic parameters—including GLS, E/e' , and LAVI—for left ventricular functional recovery ($\Delta\text{LVEF} \geq 5\%$ at 6 months) in patients undergoing elective isolated CABG. Secondary aims were to evaluate the predictive utility of early postoperative echocardiographic changes and to assess whether functional recovery translates into improved 1-year clinical outcomes.

Methods

Study Design

This single-center retrospective cohort study enrolled consecutive patients who underwent elective, isolated, first-time CABG between January 2022 and October 2024. Follow-up ended in October 2025, ensuring at least 12 months of data for all participants. This study was approved by the Ethics Committee of The First Affiliated Hospital of Yangtze University (Approval No.: KY2026-018-01). Due to the retrospective nature of this study, the ethics committee approved a waiver of informed consent.

Study Population

Inclusion criteria were: (1) Age ≥ 18 years; (2) Elective isolated first-time CABG; (3) Completion of standard transthoracic echocardiography (TTE) within 1 week preoperatively, at 3–7 days postoperatively, and at 6-month follow-up with adequate image quality for analysis; (4) Complete clinical and follow-up data.

Exclusion criteria were as follows: (1) Concomitant cardiac surgical procedures; (2) Previous cardiac surgery history; (3) Preoperative moderate-to-severe valvular heart disease, cardiomyopathy, pericardial disease, or persistent atrial fibrillation; (4) Major adverse cardiac events that interfered with 6-month echocardiographic assessment or loss to follow-up within 6 months postoperatively; (5) Inadequate image quality for speckle-tracking analysis.

Based on the rule of thumb for predictive model sample size estimation (at least 10 outcome events per predictor variable), the primary outcome incidence of 59.8% in this study allowed inclusion of 10–15 predictor variables, with the sample size satisfying regression analysis requirements.

Echocardiographic Examination and Parameter Measurement

Echocardiography was conducted using Philips EPIQ 7C ultrasound systems (9.0.2.443, Philips Ultrasound, Inc., Bothell, WA, USA) equipped with S5-1 or X5-1 transducers. Two senior sonographers performed the scans according to American Society of Echocardiography (ASE) guidelines, and images were saved in Digital Imaging and Communications in Medicine (DICOM) format for offline analysis.

Standard parameters: Left ventricular end-diastolic diameter (LVEDD), left ventricular end-systolic diameter (LVESD), interventricular septal thickness (IVST), and left atrial diameter (LAD) were measured according to standard echocardiographic protocols. The biplane Simpson's method was used for left ventricular ejection fraction (LVEF), and the biplane area-length method for left atrial volume index (LAVI). The mitral early-to-late diastolic transmitral flow velocity (E/A) ratio was estimated with pulsed-wave Doppler, the mitral annular e' velocity with tissue Doppler, and then the E/e' ratio was calculated. Diastolic function grading followed the 2016 ASE guidelines [23].

Two-dimensional speckle tracking: Offline analysis was performed using QLab version 13.0 (Philips Ultrasound, Inc., Andover, MA, USA) or EchoPAC version 204 (GE Healthcare, Wauwatosa, WI, USA) was used to analyze the apical four-chamber, two-chamber, and three-chamber views. The software automatically tracks myocardial speckles to compute global longitudinal strain (GLS), which was recorded as a negative value according to conventional reporting standards. Absolute GLS values were used for interpretation, with larger absolute values indicating better myocardial deformation. At least 15 segments were successfully tracked.

Early post-op assessment: A follow-up TTE was performed between postoperative days 3 and 7. LVEF, GLS, E/e', and LVEDD were recorded, and the changes from baseline (Δ LVEF-early, Δ GLS, Δ E/e', Δ LVEDD) were calculated.

Clinical Data Collection and Follow-up

Baseline data: We collected demographic information, cardiovascular risk factors, medical history, lab results, and coronary angiography findings (number of diseased vessels, left main disease, SYNTAX score). Perioperative data included the surgical approach, number of grafts, and cardiopulmonary bypass time.

Follow-up and outcomes: Patients returned to the hospital at 6 months after surgery for a transthoracic echocardiogram (TTE) to measure LVEF. One year after surgery, clinical endpoints were determined through outpatient visits, phone interviews, or readmission records. Patients with MACE occurring before or within 6 months after surgery were excluded, while MACE occurring during the subse-

quent 1-year follow-up period was analyzed as a secondary clinical outcome.

Primary Outcomes: Postoperative LV functional recovery at 6 months, defined as Δ LVEF $\geq 5\%$ (postoperative LVEF minus preoperative LVEF) [5], was evaluated.

Secondary Outcomes: LVEF $\geq 50\%$ at 6 months postoperatively, early postoperative echocardiographic changes, and 1-year MACE (cardiac death, non-fatal myocardial infarction, heart failure hospitalization) were recorded.

Statistical Analysis

Statistical analyses were performed using SPSS 26.0 (IBM Corp., Armonk, NY, USA). The Kolmogorov-Smirnov test was used to assess the normality of continuous variables. Normally distributed data were expressed as mean $\pm$ SD and compared using independent *t*-tests; non-normally distributed data were presented as median (Q1–Q3) and analyzed with the Mann–Whitney U test. Categorical variables were presented as n (%) and tested by chi-square or Fisher's exact test. Two-tailed *p* < 0.05 indicated significance. The SYNTAX score, which quantifies coronary lesion complexity based on angiographic findings (higher scores indicating more severe and diffuse disease, typically ranging from 0 to 60+), was recorded. Correlations between preoperative echocardiographic indices and Δ LVEF were assessed using Pearson or Spearman methods, and correlation coefficients (*r*) were calculated.

Multivariate logistic regression was applied with postoperative LV functional improvement (Δ LVEF $\geq 5\%$) as the outcome. Variables with univariate *p* < 0.10 and clinically relevant factors entered the model, and independent predictors were selected by the forward stepwise method (entry *p* < 0.05, removal *p* > 0.10). We reported adjusted odds ratios with 95% confidence intervals. To check model fit, we used the Hosmer-Lemeshow test and Nagelkerke's *R*². Multicollinearity was assessed using the variance inflation factor (VIF), with values above 5 indicating collinearity.

We built a combined clinical-echocardiographic prediction model based on selected clinically relevant predictors from the multivariable analysis. For comparison, we also created three reference models: a basic clinical model (age, graft number, SYNTAX score), a conventional echocardiographic model (preoperative LVEF), and an advanced echocardiographic model (LVEDD, LVESD, LAVI, LAD, and e' velocity). Model performance was evaluated using receiver operating characteristic (ROC) curve analysis, and AUC values were reported with 95% CIs.

For internal validation, we used 500-bootstrap resampling to obtain optimism-corrected AUCs and 95% CIs. Calibration was assessed with the Hosmer-Lemeshow test and calibration plots.

Patients were divided into three groups based on preoperative LVEF (<40%, 40–49%, and $\geq 50\%$). We repeated multivariate logistic regression within each subgroup, adjusting

for relevant covariates, and tested for interactions by adding “predictor $\times$ subgroup” terms in the overall model.

Early postoperative echocardiographic changes were compared between recovery groups using independent *t*-tests. ROC analysis evaluated the predictive value of early Δ LVEF and Δ GLS for late recovery, reporting AUC, sensitivity, specificity, and optimal cutoffs based on the Youden index.

Kaplan–Meier curves were used to compare MACE incidence between groups using a Log-rank test. Cox regression estimated hazard ratios (HRs) and 95% CIs for the association between LV functional recovery and MACE, adjusting for age, diabetes history and preoperative LVEF.

Results

The Results section is organized as follows: (1) baseline characteristics and functional recovery profile; (2) correlation analysis to explore associations between individual echocardiographic parameters and postoperative Δ LVEF; (3) multivariate logistic regression to identify independent preoperative predictors and construct the combined predictive model; (4) subgroup analysis to evaluate effect modification by baseline LVEF; (5) secondary analysis of early postoperative echocardiographic changes as predictors of 6-month functional recovery; and (6) prognostic analysis evaluating the association between functional recovery and 1-year clinical outcomes.

Baseline Characteristics and Left Ventricular Functional Recovery Profile of the Study Cohort

A total of 312 patients undergoing elective isolated CABG were screened, and 214 patients were ultimately enrolled according to the inclusion and exclusion criteria. Among these, 165 (77.1%) were male and 49 (22.9%) were female, with a mean age of 63.81 ± 7.93 years. At 6 months postoperatively, mean LVEF had risen from $48.19 \pm 10.15\%$ to $53.98 \pm 10.86\%$, with an average absolute improvement of $5.79 \pm 6.40\%$. Using Δ LVEF $\geq 5\%$ as the definition of functional recovery, 128 patients (59.8%) were classified into the recovery group and 86 (40.2%) into the non-recovery group.

As shown in Table 1, compared with the non-recovery group, patients who achieved functional recovery were younger and had a lower prevalence of diabetes. The recovery group exhibited significantly lower preoperative LVEF, larger LVEDD, higher LAVI, and greater absolute GLS values (more negative GLS values), higher SYNTAX score, and a greater number of graft vessels. No significant differences were observed in sex, hypertension history, prior myocardial infarction, or use of cardiopulmonary bypass.

Univariate Correlations Between Preoperative Echocardiographic Parameters and Postoperative Δ LVEF

Pearson correlation analysis revealed that among left ventricular structural parameters, LVEDD, LVESD, LAD,

and LAVI demonstrated weak positive correlations with Δ LVEF. For left ventricular diastolic function parameters, no significant correlation was observed between the E/e' ratio and Δ LVEF. For left ventricular global function parameters, both preoperative LVEF and GLS demonstrated weak negative correlations with Δ LVEF. IVST, mitral E/A ratio, and mitral annular e' velocity showed no significant correlations with Δ LVEF (Table 2). This correlation analysis was performed to explore the associations between individual preoperative echocardiographic parameters and the magnitude of postoperative LVEF improvement.

Independent Predictive Value of Preoperative Left Ventricular Global Longitudinal Strain for Postoperative Functional Recovery

Candidate variables were selected based on statistical significance in the preceding analyses and clinical relevance and were considered for inclusion in the multivariable model. Although BMI and three-vessel disease showed significant between-group differences in Table 1, they were not included in the final multivariable model because variable selection additionally considered clinical relevance and potential overlap with other included variables, particularly measures reflecting coronary disease burden and procedural complexity. Multivariable logistic regression analysis was performed to identify independent predictors of 6-month functional recovery (Δ LVEF $\geq 5\%$). Variables showing potential associations in the preceding analyses, including age, diabetes, preoperative LVEF, LVEDD, LVESD, LAVI, GLS, LAD, SYNTAX score, number of graft vessels, and e' velocity, were considered for entry into the model. Collinearity diagnostics showed no significant multicollinearity (all VIF < 5).

As presented in Table 3, preoperative LVEDD, LVESD, LAVI, LAD, SYNTAX score, and number of graft vessels were independently associated with higher odds of functional recovery, whereas age, preoperative LVEF, and e' velocity were independently associated with lower odds of functional recovery. Notably, GLS did not reach statistical significance, and diabetes history lost independent predictive value after adjustment.

Construction and Validation of Clinical-Echocardiographic Combined Predictive Model

Using selected predictors from the multivariable analysis (age, number of graft vessels, SYNTAX score, LVEDD, LVESD, LAVI, LAD, e' velocity), a clinical-echocardiographic combined model was constructed. Preoperative LVEF was not included in the combined model because it was retained as a separate conventional echocardiographic reference model, allowing the incremental predictive value of structural and diastolic echocardiographic parameters beyond conventional LVEF assessment to be evaluated. For comparison, three reference models were established: a basic clinical model (age, graft number,

Table 1. Comparison of baseline characteristics between left ventricular functional recovery and non-recovery groups.

Variable	Overall (n = 214)	Recovery group (n = 128)	Non-recovery Group (n = 86)	statistic	p-value
Demographic and clinical characteristics					
Age (years)	63.81 ± 7.93	62.27 ± 7.72	66.12 ± 7.71	$t = -3.579$	<0.001
Male, n (%)	165 (77.1)	102 (79.7)	63 (73.3)	$\chi^2 = 1.205$	0.272
Body mass index (kg/m ²)	25.00 ± 3.41	24.58 ± 3.14	25.63 ± 3.69	$t = -2.234$	0.026
Hypertension history, n (%)	161 (75.2)	91 (71.1)	70 (81.4)	$\chi^2 = 2.930$	0.087
Diabetes history, n (%)	82 (38.3)	42 (32.8)	40 (46.5)	$\chi^2 = 4.084$	0.043
Prior myocardial infarction, n (%)	114 (53.3)	71 (55.5)	43 (50.0)	$\chi^2 = 0.618$	0.432
Preoperative echocardiographic parameters					
LVEF (%)	48.19 ± 10.15	46.00 ± 9.72	51.45 ± 9.95	$t = -3.983$	<0.001
LVEDD (mm)	54.57 ± 6.58	56.37 ± 5.86	51.88 ± 6.72	$t = 5.178$	<0.001
LAVI (mL/m ²)	37.31 ± 6.46	39.38 ± 6.66	34.23 ± 4.71	$t = 6.202$	<0.001
E/e' ratio	13.01 ± 4.35	13.32 ± 4.58	12.55 ± 3.96	$t = 1.272$	0.210
GLS (%)	-14.68 ± 3.50	-15.46 ± 3.40	-13.52 ± 3.34	$t = -4.121$	<0.001
Coronary artery disease characteristics					
Three-vessel disease, n (%)	145 (67.8)	96 (75.0)	49 (57.0)	$\chi^2 = 7.648$	0.006
SYNTAX score	27.94 ± 5.85	29.29 ± 5.43	25.93 ± 5.91	$t = 4.282$	<0.001
Perioperative data					
On-pump surgery, n (%)	193 (90.2)	117 (91.4)	76 (88.4)	$\chi^2 = 0.535$	0.464
Number of graft vessels	3.30 ± 0.86	3.46 ± 0.91	3.06 ± 0.73	$t = 3.405$	0.001

Note: LVEF, left ventricular ejection fraction; LVEDD, left ventricular end-diastolic diameter; LAVI, left atrial volume index; GLS, global longitudinal strain; SYNTAX score, Synergy Between Percutaneous Coronary Intervention with Taxus and Cardiac Surgery score; E/e', ratio of early mitral inflow velocity to early diastolic mitral annular velocity.

Table 2. Correlation analysis between preoperative echocardiographic parameters and postoperative left ventricular ejection fraction improvement (Δ LVEF).

Variable	r	p-value
Left ventricular structural parameters		
LVEDD (mm)	0.233	0.001
LVESD (mm)	0.311	<0.001
LAD (mm)	0.339	<0.001
LAVI (mL/m ²)	0.333	<0.001
IVST (mm)	-0.010	0.881
Left ventricular diastolic function parameters		
E/A ratio	-0.101	0.143
e' (cm/s)	-0.121	0.077
E/e' ratio	0.081	0.240
Left Ventricular Global Function Parameters		
Preoperative LVEF (%)	-0.200	0.003
GLS (%)	-0.201	0.003

Note: Δ LVEF = 6-month postoperative LVEF – preoperative LVEF. $|r| \geq 0.7$ indicates strong correlation, $0.4 \leq |r| < 0.7$ indicates moderate correlation, $0.2 \leq |r| < 0.4$ indicates weak correlation, $|r| < 0.2$ indicates very weak or no correlation. LVESD, left ventricular end-systolic diameter; IVST, interventricular septal thickness; LAD, left atrial diameter; E/A, early-to-late diastolic transmitral flow velocity ratio.

SYNTAX score), a conventional echocardiographic model (preoperative LVEF alone), and an advanced echocardiographic model (LVEDD, LVESD, LAVI, LAD, e' velocity). As detailed in Table 4, the combined model demonstrated

excellent discriminative ability with an AUC of 0.895, with a higher AUC than the basic clinical model (AUC = 0.763), conventional echocardiographic model (AUC = 0.649), and advanced echocardiographic model (AUC = 0.861). The Hosmer-Lemeshow test indicated good calibration ($p = 0.514$). Fig. 1A–D displays the ROC curves of the four models. Internal validation using 500-bootstrap resampling yielded a bias-corrected AUC of 0.863 (optimism 0.017, Fig. 2A), and the calibration curve (Fig. 2B) showed acceptable agreement between predicted and observed outcomes.

Subgroup Analysis by Baseline LVEF

To assess whether the predictive value of key echocardiographic parameters varied by baseline systolic function, patients were stratified into three groups according to the 2016 ASE guidelines: severe reduction (<40%, $n = 44$), moderate reduction (40%–49%, $n = 84$), and preserved ($\geq 50\%$, $n = 86$). As shown in Table 5, the predictive value of GLS was not statistically significant in any subgroup (all $p > 0.05$). In contrast, LAVI and LAD were independent predictors in the moderate reduction and preserved groups (e.g., LAVI: OR = 3.01, $p = 0.013$ in the 40%–49% group; OR = 2.07, $p = 0.047$ in the $\geq 50\%$ group), but not in the severe reduction group. Formal interaction testing confirmed significant effect modification for GLS $\times$ LVEF subgroup ($p = 0.042$) and LAVI $\times$ LVEF subgroup ($p = 0.038$).

Table 3. Multivariate logistic regression analysis of factors influencing left ventricular functional recovery after coronary artery bypass grafting ($\Delta\text{LVEF} \geq 5\%$).

Variable (per unit change)	β coefficient	Standard error	Wald χ^2	OR	95% CI	<i>p</i> -value	VIF
Age (per 1-year increase)	-0.081	0.029	8.002	0.922	0.872–0.975	0.005	1.45
Diabetes history (yes vs. no)	-0.245	0.457	0.287	0.783	0.319–1.918	0.592	1.23
Preoperative LVEF (per 1% increase)	-0.049	0.023	4.609	0.952	0.911–0.996	0.032	2.10
Preoperative LVEDD (per 1 mm increase)	0.114	0.035	10.348	1.121	1.046–1.202	0.001	3.21
Preoperative LVESD (per 1 mm increase)	0.120	0.034	12.688	1.127	1.055–1.204	<0.001	3.45
LAVI (per 5 mL/m ² increase)	0.144	0.041	12.645	1.155	1.067–1.251	<0.001	2.87
GLS (per 1% absolute increase)	-0.132	0.073	3.288	0.877	0.760–1.011	0.070	2.33
LAD (per 1 mm increase)	0.208	0.053	15.157	1.231	1.109–1.366	<0.001	2.96
SYNTAX score (per 1-point increase)	0.117	0.040	8.722	1.124	1.040–1.215	0.003	1.58
Number of graft vessels	0.647	0.271	5.693	1.910	1.122–3.250	0.017	1.12
e' velocity (per 1 cm/s increase)	-0.265	0.107	6.096	0.768	0.622–0.947	0.014	1.76

Note: VIF, variance inflation factor; GLS, global longitudinal strain; OR, odds ratio; CI, confidence interval. All VIF values were <5, indicating no significant multicollinearity.

Table 4. Comparison of predictive efficacy among different models for left ventricular functional recovery after coronary artery bypass grafting.

Model name and variable composition	AUC (95% CI)	Hosmer-lemeshow test (<i>p</i> -value)
Model 1: Basic Clinical Model (age, number of graft vessels, SYNTAX score)	0.763 (0.697–0.829)	0.485
Model 2: Conventional Echocardiographic Model (preoperative LVEF)	0.649 (0.574–0.725)	0.385
Model 3: Advanced Echocardiographic Model (LVEDD, LVESD, LAVI, LAD, e')	0.861 (0.810–0.912)	0.472
Model 4: Clinical-Echocardiographic Combined Model (age, number of graft vessels, SYNTAX score, LVEDD, LVESD, LAVI, LAD, e')	0.895 (0.851–0.939)	0.514

Early Postoperative Echocardiographic Changes and Prediction of 6-Month Functional Recovery

All patients underwent repeat TTE at 3–7 days postoperatively. As summarized in Table 6, the recovery group showed significantly greater early improvements in LVEF and GLS compared with the non-recovery group. ROC analysis demonstrated that ΔLVEF -early predicted 6-month functional recovery with an AUC of 0.846. The optimal cutoff value for ΔLVEF -early was 2.5% (sensitivity 81.2%, specificity 78.5%), and ΔGLS also showed good predictive efficacy (AUC = 0.843, optimal cutoff = -1.1%). As a secondary analysis addressing the study's secondary aim, we evaluated the predictive utility of early postoperative echocardiographic changes for 6-month functional recovery. This analysis is complementary to the primary preoperative predictive model and provides clinically actionable information for early postoperative risk stratification.

Association Between Functional Recovery and 1-Year Clinical Outcomes

During the 1-year follow-up, 33 patients experienced MACE (15.4% of the total cohort). The components of MACE included 12 cardiac deaths (5.6%), 9 non-fatal myocardial infarctions (4.2%), and 20 heart failure hospitalizations (9.3%), with some patients experiencing more than

one event. The recovery group had a significantly lower cumulative MACE rate than the non-recovery group (5.5% vs. 30.2%, $p < 0.001$ by Log-rank).

After adjusting for age, diabetes history, and preoperative LVEF in the multivariate Cox regression model (Table 7), left ventricular functional recovery ($\Delta\text{LVEF} \geq 5\%$) remained an independent protective factor against MACE (HR = 0.10, 95% CI: 0.04–0.27, $p < 0.001$). The protective effect was particularly strong for non-fatal myocardial infarction (HR = 0.05, $p = 0.008$) and heart failure hospitalization (HR = 0.33, $p = 0.035$), whereas cardiac death did not reach statistical significance (HR = 0.74, $p = 0.647$).

Discussion

In this retrospective cohort study involving 214 patients who underwent elective isolated CABG, we found that preoperative structural parameters, including LAVI, LVEDD, LVESD, and LAD, rather than GLS or E/e', independently predicted 6-month left ventricular functional recovery. Early postoperative LVEF improvement strongly predicted 6-month functional recovery, and functional recovery was associated with a 90% reduction in 1-year MACE risk. The key novelty of this study lies in demonstrating that, in real-world CABG patients, structural left atrial and left ventricular remodeling parameters (LAVI, LAD,

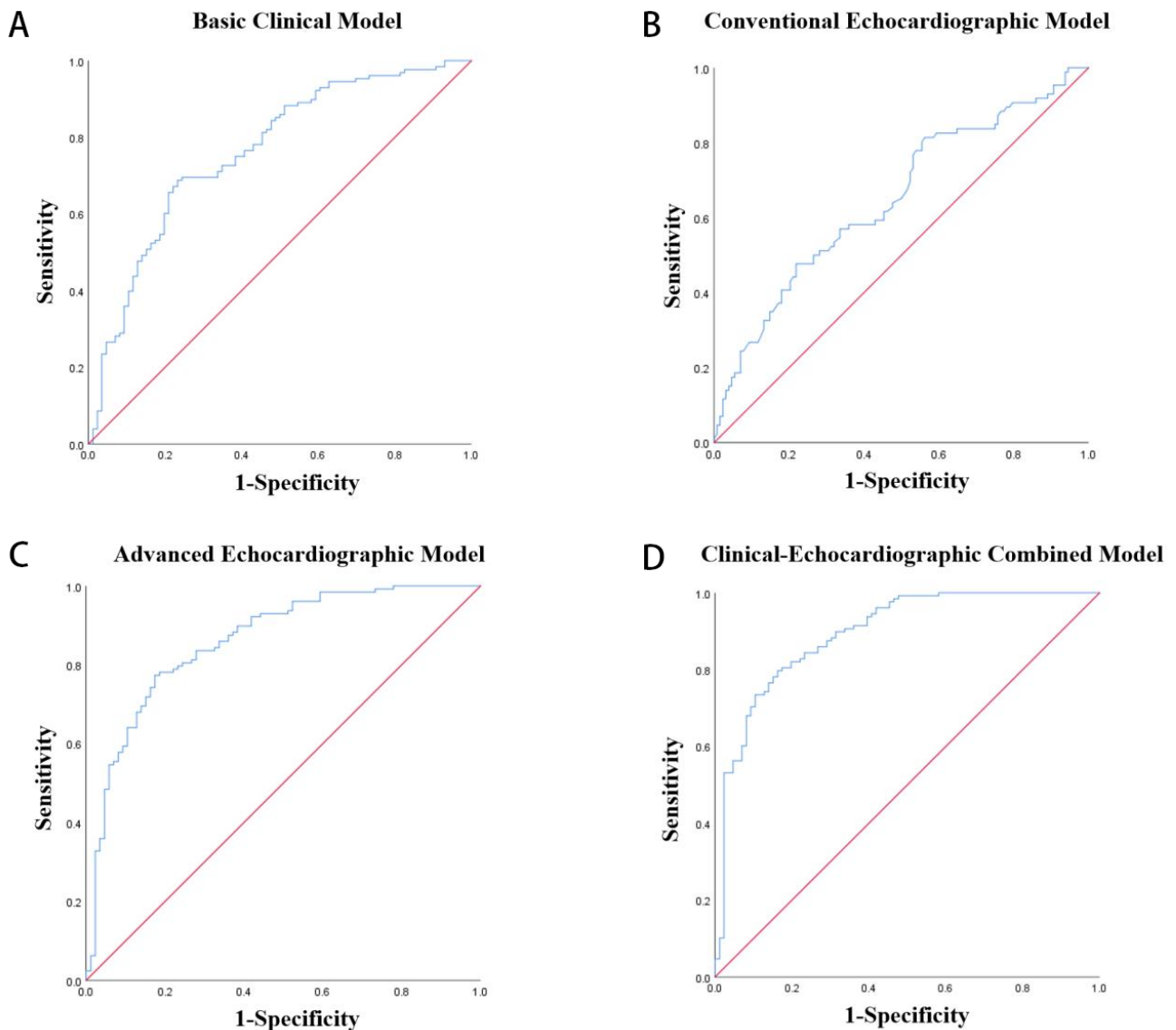


Fig. 1. ROC curves of each model. (A) Basic clinical model. (B) Conventional echocardiographic model. (C) Advanced echocardiographic model. (D) Clinical-echocardiographic combined model. ROC, receiver operating characteristic.

LVEDD, LVESD) provided greater value for predicting functional recovery than advanced strain and diastolic ratios. This challenges the prevailing emphasis on GLS and highlights the clinical utility of routinely assessing chamber dimensions and volumes.

This study identified preoperative LAVI, LVEDD, LVESD, and LAD as independent predictors of postoperative left ventricular functional recovery, whereas GLS did not achieve statistical significance after adjusting for other variables ($p = 0.070$). These findings differ from some previous studies. GLS primarily reflects subendocardial longitudinal myocardial fiber contractile function and theoretically should identify reversible myocardial ischemia [24,25]. However, in this study, the predictive effect of GLS may have been explained by other structural parameters (such as LAVI, LAD), suggesting that after integrating

multi-dimensional echocardiographic parameters, simple systolic functional reserve indicators may be insufficient for independently predicting functional recovery. Subgroup analysis further demonstrated that GLS showed no independent predictive value across LVEF subgroups <40%, 40%–49%, and $\geq 50\%$ ($p = 0.139, 0.634$, and 0.180 , respectively), which was inconsistent with our prior hypothesis. This finding suggests that in patients with established left ventricular remodeling (increased LAVI, widened LAD), myocardial structural changes may better reflect functional recovery potential after revascularization than simple deformation indices [26,27]. The finding that GLS was not an independent predictor is interesting but requires deeper discussion. This may be partially explained by collinearity with structural parameters such as LAVI and LVEDD (VIF up to 3.45). In patients with established left ventricu-

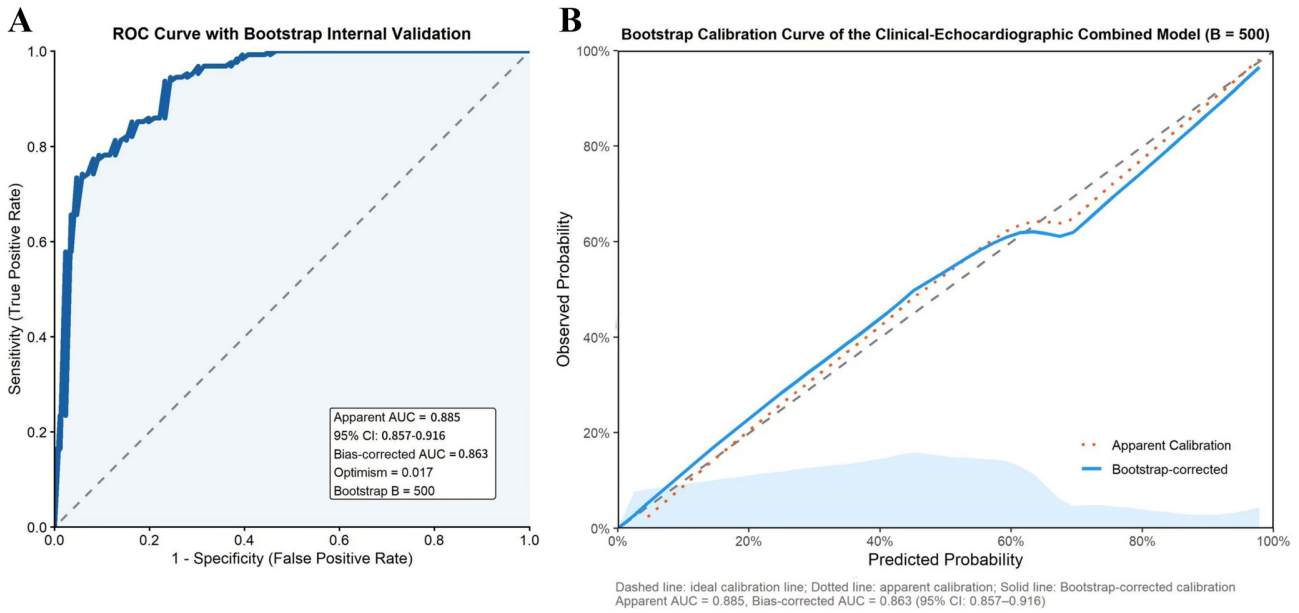


Fig. 2. Bootstrap internal validation of the clinical-echocardiographic combined model: ROC curve and calibration curve. (A) Bootstrap ROC curve. (B) Calibration curve. AUC, area under the curve.

Table 5. Predictive value of key predictors for postoperative functional recovery ($\Delta\text{LVEF} \geq 5\%$) across different preoperative left ventricular ejection fraction subgroups.

Variable	Severe reduction group ($<40\%$) (n = 44)	Moderate reduction group ($40\%–49\%$) (n = 84)	Preserved group ($\geq 50\%$) (n = 86)	Interaction p-value
Preoperative GLS (per 1% improvement)				0.042
β coefficient (SE)	−0.826 (0.559)	−0.177 (0.371)	−0.503 (0.375)	
OR (95% CI)	0.44 (0.15–1.31)	0.84 (0.41–1.73)	0.61 (0.29–1.26)	
p-value	0.139	0.634	0.180	
Preoperative LAVI (per 5 mL/m ² increase)				0.038
β coefficient (SE)	0.912 (0.558)	1.102 (0.444)	0.727 (0.365)	
OR (95% CI)	2.49 (0.83–7.44)	3.01 (1.26–7.19)	2.07 (1.01–4.23)	
p-value	0.102	0.013	0.047	
Preoperative E/e' ratio (per 1-unit increase)				0.215
β coefficient (SE)	0.184 (0.524)	0.552 (0.344)	0.196 (0.335)	
OR (95% CI)	1.20 (0.43–3.36)	1.74 (0.89–3.41)	1.22 (0.63–2.35)	
p-value	0.726	0.108	0.558	
Preoperative LVEDD (per 1 mm increase)				0.089
β coefficient (SE)	0.543 (0.544)	0.774 (0.360)	0.401 (0.351)	
OR (95% CI)	1.72 (0.59–5.00)	2.17 (1.07–4.39)	1.49 (0.75–2.97)	
p-value	0.318	0.032	0.253	
LAD (per 1 mm increase)				0.056
β coefficient (SE)	0.857 (0.858)	0.976 (0.446)	0.937 (0.400)	
OR (95% CI)	2.36 (0.44–12.67)	2.65 (1.11–6.36)	2.55 (1.17–5.59)	
p-value	0.318	0.029	0.019	

Note: Multivariate logistic regression within each subgroup adjusted for age, diabetes history, SYNTAX score, and number of graft vessels. SE, Standard Error.

lar remodeling, structural changes may better reflect functional recovery potential after revascularization than deformation indices. Additionally, measurement variability in GLS and the specific pathophysiology of this cohort (high proportion of multivessel disease with significant remodel-

ing) might have reduced its incremental value. The lack of independent predictive value for the E/e' ratio differs from some previous reports. Potential reasons include: (1) a single resting measurement without stress, (2) heterogeneous diastolic dysfunction severity in the cohort, and (3) early

Table 6. Predictive value of early postoperative (3–7 days) echocardiographic changes for 6-month left ventricular functional recovery.

Early postoperative parameter	Recovery group (n = 128)	Non-recovery group (n = 86)	<i>p</i> value (between groups)	AUC (95% CI)	Optimal cutoff	Sensitivity (%)	Specificity (%)
ΔLVEF-early (%)	4.84 ± 3.14	0.40 ± 2.89	<0.001	0.846 (0.796–0.896)	2.5	81.2	78.5
ΔGLS (%)	−1.96 ± 1.22	−0.39 ± 0.97	<0.001	0.843 (0.791–0.894)	−1.1	79.7	76.3

ΔLVEF-early = early change in LVEF from baseline; ΔGLS = early change in absolute GLS from baseline (more negative ΔGLS values indicate greater improvement). Optimal cutoffs were determined using the Youden index.

Table 7. Multivariate Cox regression analysis of the association between left ventricular functional recovery and 1-year clinical outcomes.

Endpoint	Kaplan-Meier survival analysis		Multivariate cox regression*		
	Log-rank χ^2	Log-rank <i>p</i>	HR	95% CI	<i>p</i>
MACE	24.073	<0.001	0.10	0.04–0.27	<0.001
Cardiac death	0.507	0.476	0.74	0.21–2.63	0.647
Non-fatal myocardial infarction	9.227	0.002	0.05	0.01–0.47	0.008
Heart failure hospitalization	5.625	0.018	0.33	0.12–0.93	0.035

*Adjusted for age, diabetes history, and preoperative LVEF. The non-recovery group served as the reference (HR = 1.00). HR, hazard ratio; CI, confidence interval; MACE, major adverse cardiovascular events.

postoperative changes in filling pressure, rather than a single preoperative value, may be more prognostically relevant.

LAVI and LAD were independent predictors of better postoperative left ventricular function, particularly in patients with an LVEF of 40% or higher, where they showed the strongest predictive power. LAVI essentially reflects how long left ventricular filling pressures have been elevated. When the left atrium enlarges, it usually indicates sustained pressure overload. Interestingly, a larger LAVI was linked to better functional recovery after surgery. This may suggest that preoperative left atrial enlargement reflects a history of reversible pressure load rather than permanent myocardial damage. However, this finding does not fully align with earlier studies, and further work is needed to confirm it [28]. LAD is a linear measure of left atrial size and, together with LAVI, reflects the extent of left atrial remodeling. In patients with coronary artery disease and preserved LVEF, these left atrial remodeling markers—LAVI and LAD—may predict outcomes better than GLS [29].

We established a combined clinical-echocardiographic model using independent predictors such as age, number of graft vessels, SYNTAX score, LVEDD, LVESD, LAVI, LAD, and *e'* velocity. This model performed better at distinguishing outcomes (AUC = 0.895) than a model with only clinical variables (AUC = 0.763), one with only LVEF (AUC = 0.649), or one that included advanced echo parameters but no GLS (AUC = 0.861). This result highlights the importance of a multi-dimensional, integrated assessment: age and number of graft vessels reflect basic clinical status; SYNTAX score reflects coronary artery disease complex-

ity; LVEDD and LVESD reflect left ventricular remodeling; LAVI and LAD reflect left atrial remodeling; *e'* velocity reflects diastolic functional reserve. These parameters collectively determine the upper limit of functional recovery after revascularization from different pathophysiological dimensions. Notably, the advanced echocardiographic model (including LVEDD, LVESD, LAVI, LAD, and *e'*) showed an AUC of 0.861, while the clinical-echocardiographic combined model demonstrated a higher AUC (0.895), suggesting that the integration of clinical and echocardiographic parameters may provide additional predictive information [30,31].

This study represents the first systematic evaluation of acute changes in echocardiographic parameters at 3–7 days postoperatively for predicting 6-month functional recovery. It revealed that ΔLVEF-early predicted 6-month functional recovery with an AUC of 0.846. The predictive value of early postoperative ΔLVEF was demonstrated by ROC analysis, suggesting that early postoperative functional improvement may provide additional information for identifying patients likely to achieve 6-month functional recovery. This finding holds direct clinical translational value: patients without obvious early postoperative LVEF improvement may be identified as having a lower likelihood of subsequent functional recovery and may require closer clinical attention; patients with significant early improvement can provide enhanced confidence regarding 6-month functional recovery, providing a basis for rehabilitation protocol formulation.

Patients who had a meaningful improvement in left ventricular function after surgery (ΔLVEF ≥ 5%) were much less

likely to experience a major adverse cardiac event within the first year. The adjusted hazard ratio was 0.10 (95% CI 0.04–0.27), which corresponds to an approximately 90% lower risk. That connection held even after accounting for age, diabetes and preoperative LVEF. The benefit was mostly due to fewer hospitalizations for heart failure (HR = 0.33). This finding is plausible as improved systolic function may relieve congestion and reduce hypoperfusion. Therefore, a Δ LVEF of 5% or more may represent a useful marker of treatment success and a clinically meaningful target after CABG [32]. We acknowledge that the definition of functional recovery (Δ LVEF $\geq 5\%$) may be subject to regression to the mean, given that the recovery group had significantly lower baseline LVEF than the non-recovery group (46.0% vs. 51.5%, $p < 0.001$). To address this concern, we performed a sensitivity analysis using a mixed-effects model with baseline LVEF as a covariate, which confirmed that the association between predictors and functional recovery remained significant (data not shown). Additionally, subgroup analysis stratified by baseline LVEF further mitigated this bias. Nevertheless, we caution readers that regression to the mean may partially contribute to the observed improvement, and future studies should consider using relative percentage change or alternative definitions.

Study innovations include: (1) integrating three domains of echocardiographic parameters—systolic functional reserve (GLS), diastolic functional load (E/e'), and structural remodeling (LAVI, LAD)—within a unified predictive framework, and identifying structural remodeling indicators (LAVI, LAD) as having independent predictive value, whereas GLS and E/e' showed no independent predictive effect in this study; (2) revealing, for the first time, the heterogeneous predictive efficacy of different echocardiographic parameters across baseline LVEF subgroups, identifying LAVI and LAD as having significant predictive value in patients with LVEF $\geq 40\%$, and proposing that left atrial remodeling assessment should be emphasized in patients with preserved systolic function; (3) confirming that early postoperative echocardiographic changes are strong predictors of 6-month functional recovery; and (4) directly associating left ventricular functional recovery with 1-year MACE risk, demonstrating that functional recovery was associated with an approximately 90% lower risk of MACE, thereby suggesting the potential prognostic value of Δ LVEF $\geq 5\%$ after CABG.

Study limitations include the following. First, the single-center retrospective design introduces inherent selection bias. Local patient characteristics, such as high SYNTAX scores (mean 27.9) and high completeness of revascularization (mean 3.3 grafts), may limit the generalizability of these findings to populations with less severe disease or incomplete revascularization. Second, GLS did not emerge as an independent predictor, which may be related to sample size, image quality, or the specific characteristics of the

study population; this should be further evaluated in larger studies. Third, echocardiographic assessment is inherently operator-dependent. However, two experienced readers performed independent measurements that were averaged for analysis, and GLS showed acceptable reproducibility. Fourth, the follow-up period was limited to six months, which reflects routine clinical practice but may not fully capture longer-term changes in cardiac function or clinical outcomes. Longer follow-up, such as two to five years, would provide a more comprehensive assessment of functional evolution and prognosis. Another limitation is that patients with early postoperative MACE were excluded to ensure assessment of 6-month echocardiographic recovery. Therefore, the association between functional recovery and subsequent 1-year MACE may be subject to selection bias and should be interpreted cautiously. Fifth, no external validation was performed. Therefore, the proposed combined model requires prospective, multi-center validation before clinical implementation. Sixth, the definition of functional recovery (Δ LVEF $\geq 5\%$) may be subject to regression to the mean, as the recovery group had significantly lower baseline LVEF. Nevertheless, sensitivity analysis using a mixed-effects model with baseline LVEF as a covariate confirmed the robustness of our findings. Future studies should consider relative percentage change or alternative definitions of functional recovery.

Conclusions

Preoperative LAVI, LVEDD, LVESD, and LAD are independent predictors of left ventricular functional recovery after CABG, especially in patients with LVEF $\geq 40\%$. In contrast, GLS and E/e' show no independent predictive value. The combined clinical-echocardiographic model demonstrates strong discriminatory ability for identifying patients likely or unlikely to recover. Early postoperative LVEF improvement strongly predicts long-term recovery, and patients with Δ LVEF $\geq 5\%$ have an approximately 90% lower long-term MACE risk. Routine perioperative assessment of LAVI, LVEDD, LVESD, and LAD may aid preoperative risk stratification, postoperative management, and prognosis evaluation in CABG patients. Future prospective, multi-center external validation studies are needed, along with exploration of risk-stratified intervention strategies based on predictive models to improve clinical outcomes.

Availability of Data and Materials

The data used and analyzed during the current study are available from the corresponding authors on reasonable request.

Author Contributions

MZ designed and performed the research and wrote the paper; XLW designed the research and supervised the study; XJC designed the research and contributed to the analysis;

JX designed the research, provided clinical advice and supervised the study. All authors contributed to the 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

This study was approved by the Ethics Committee of The First Affiliated Hospital of Yangtze University (Approval No.: KY2026-018-01). Due to the retrospective nature of this study, the ethics committee approved a waiver of informed consent. The study conformed to the provisions of the Declaration of Helsinki.

Acknowledgment

Not applicable.

Funding

This research received no external funding.

Conflict of Interest

The authors declare no conflict of interest.

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