Association of Preoperative Cardiac Magnetic Resonance and Echocardiography with Postoperative Left Ventricular Dysfunction in Primary Mitral Regurgitation

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Background: We evaluated the relationship between preoperative left ventricular (LV) structural and functional characteristics assessed by echocardiography (Echo) and cardiac magnetic resonance (CMR) and the risk of postoperative LV dysfunction in patients with primary mitral regurgitation (MR) undergoing mitral valve (MV) repair surgery.

Methods: We retrospectively studied 223 patients (median age, 60 years; 21% women) with chronic primary MR who underwent preoperative Echo and CMR before MV repair surgery. The primary end point was postoperative LV dysfunction, defined as LV ejection fraction (LVEF) <50% on follow-up Echo.

Results: Postoperative LV dysfunction occurred in 41 patients (18%) after a median follow-up of 8.7 (interquartile range, 6.7-12.5) months. These patients had higher absolute and indexed (ind-) LV end-systolic diameters (LVESDs) and volumes (LVESVs; all $P \leq .009$), lower CMR LV ejection fraction (LVEF; $P = .003$), and a trend toward lower Echo LVEF ($P = .072$). Individually, Echo and CMR parameters showed modest discriminative ability (areas under the curve from 0.59 [0.49-0.68] for Echo LVEF to 0.70 [0.61-0.78] for Echo-indLVESD). Strain imaging, whether assessed by Echo or CMR, did not improve risk stratification. Echo indLVESD and CMR LVEF were the most contributive LV characteristics. A 2-step approach based on Echo indLVESD < or ≥18 mm/m^2, followed by CMR LVEF > or ≤56% in patients with Echo indLVESD ≥18 mm/m^2, identified 3 subgroups with distinct rates of postoperative LV dysfunction (9%, 20%, and 41%, respectively).

Conclusion: In patients with primary MR undergoing MV surgery, preoperative LV characteristics assessed by Echo and CMR showed only moderate ability to identify those at higher risk of postoperative LV dysfunction. A stepwise approach using Echo indLVESD followed by CMR LVEF may help identify subgroups at differing risk levels. These exploratory findings require confirmation in larger prospective studies. (J Am Soc Echocardiogr 2026;39:28-40.)

Keywords: Primary mitral regurgitation, Mitral valve surgery, Cardiac magnetic resonance imaging, Left ventricular dysfunction, Prognosis

INTRODUCTION

Mitral valve (MV) surgery, preferably employing repair techniques when anatomically feasible, is the only effective intervention to achieve sustained long-term outcomes in patients with primary mitral regurgitation (MR).[1] Current guidelines recommend MV surgery for patients presenting with MR-related symptoms and/or left ventricular (LV) dysfunction or dilatation, while considering MV repair feasibility and operative risk.[2] However, the optimal timing for intervention in asymptomatic primary MR patients remains debated. Ideally, MV surgery should be performed late enough to balance procedural risks but early enough to prevent irreversible cardiac remodeling, including the

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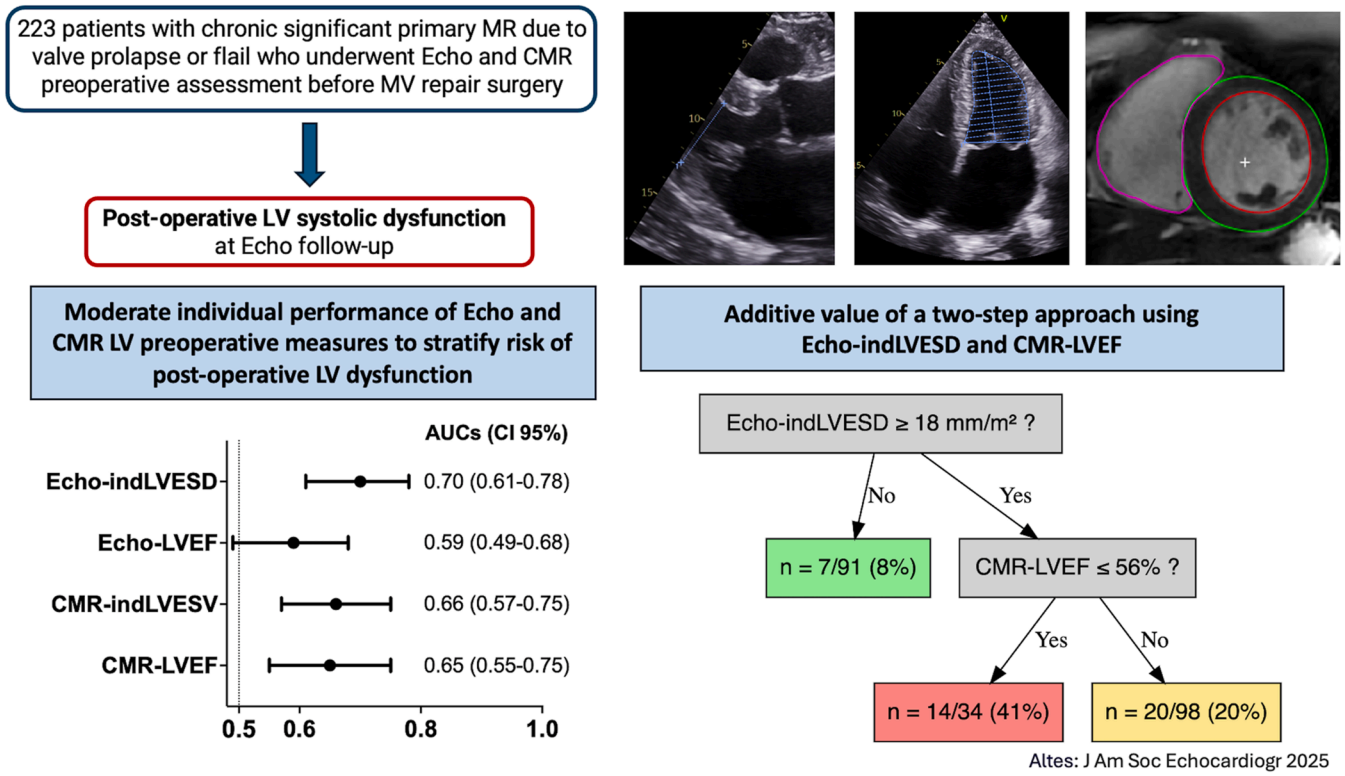

Central Illustration Association of LV Echo and CMR characteristics with risk of postoperative LV dysfunction in primary MR.

onset of LV systolic dysfunction. Indeed, postoperative LV dysfunction is not infrequent in primary MR patients undergoing MV surgery, even in those with preserved preoperative LV ejection fraction (LVEF), and, left untreated, is associated with long-term adverse clinical outcomes.[3-6] Long-standing MR increases preload and often reduces afterload, regardless of intrinsic LV contractility.[7] As a result, LVEF, which depends on loading conditions, may remain supranormal and fail to detect subtle LV systolic dysfunction. Subsequently, recent guidelines highlight the need for earlier markers of LV dysfunction, including those derived from cardiac magnetic resonance (CMR) imaging.[2,8,9]

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While transthoracic echocardiography (Echo) remains the primary imaging modality for assessing MR mechanism and severity, CMR has become increasingly important in the evaluation of with primary MR, particularly for quantifying regurgitation severity and providing tissue-level myocardial information. From a pathophysiological standpoint, LV volumes better reflect LV geometric remodeling than echocardiographic LV diameters.[7] However, echocardiographic estimation of LV volumes could be limited by geometric assumptions, variability in endocardial border delineation, suboptimal image quality, and apical foreshortening.[10] In contrast, CMR offers accurate and highly reproducible volumetric measurements. As underscored by Lachin,[11] the reproducibility of a measurement is critical, as poor reliability introduces noise and reduces statistical power, thereby weakening the association between a marker and outcomes. Imaging metrics that combine high reliability with discriminatory capacity are therefore needed for risk stratification in clinical practice. In this context, CMR-derived LV volumes and function may provide added value beyond echocardiographic measurements to better identify patients at risk of postoperative LV systolic dysfunction in primary MR.

The objective of this study was to evaluate the relationship between preoperative LV structural and functional characteristics, assessed by both CMR and Echo, and postoperative LV systolic dysfunction in patients with primary MR undergoing MV repair surgery.

METHODS

Study Population

This study involved patients with chronic significant primary MR due to valve prolapse or flail who underwent MV repair surgery in 2 tertiary centers (Brussels, Lille) between 2005 and 2022 (Figure 1). The present study is a retrospective analysis of an ongoing prospective registry, focusing on patients who had undergone Echo and CMR during the preoperative workup and in whom postoperative echocardiographic follow-up data were available. The Brussels cohort was approved by IRB (2017 07MAR123 MV-3D Doppler, 2020-01AVR 192 Valve disease, NCT02974218). The Lille cohort was part of the ongoing COHORTE-IM (NCT03962023), authorized by the French Ethic Committee (No. ID-RCB: 2019-A00869-48 Sud Méditérannée IV). Inclusion criteria were patients at least 18 years of age with significant (moderate to severe and severe according to American Society of Echocardiography/European Association of Cardiovascular Imaging guidelines) primary MR who were scheduled to undergo MV repair surgery.[2,9] Exclusion criteria were acute MR, MR from another etiology than prolapse or flail, previous cardiac surgery, more than mild another valvular heart disease, preoperative LVEF <50% whether assessed by Echo or CMR, prosthetic valve or an intracardiac shunt, pregnancy, standard

Abbreviations

AUC = Area under the curve

CMR = Cardiac magnetic resonance

CV = Coefficient of variation

Echo = Echocardiography

ECV = Extracellular volume

EDV = End-diastolic volume

EROA = Effective regurgitant orifice area

ESD = End-systolic diameter

ESV = End-systolic volume

GCS = Global circumferential strain

GLS = Global longitudinal strain

ICC = Intraclass correlation coefficient

Ind- = Indexed

IQR = Interquartile range

LV = Left ventricular, ventricle

LVEF = Left ventricular ejection fraction

LVESD = Left ventricular end-systolic diameter

LVESV = Left ventricular end-systolic volume

LVTSV = Left ventricular total stroke volume

MR = Mitral regurgitation

MV = Mitral valve

NYHA = New York Heart Association

OR = Odds ratio

RegFrac = Regurgitant fraction

RegVol = Regurgitant volume

ROC = Receiver operating characteristic

RV = Right ventricular

contraindication for CMR, poor echocardiographic image quality, missing echocardiographic follow-up data, refusal to participate in the study, and evidence of ischemic myocardial scar. We chose not to include patients with a preoperative LVEF <50%, as such patients with severe primary MR are already at an advanced stage of LV systolic dysfunction, for whom MV surgery is considered a rescue intervention. Patients who died early after MV surgery before assessment of postoperative LVEF were also not included (Supplemental Figure 1).

During the study period, CMR was performed as part of the preoperative workup in a subset of patients with significant primary MR referred for surgery at both centers, based on local clinical practice, imaging availability, and referral pathways, which evolved over time. Doppler Echo and CMR data were prospectively entered into an electronic database in each center and pooled retrospectively. Clinical data were obtained by chart review. New York Heart Association (NYHA) class was determined by the treating physician at the time of baseline evaluation. The Logistic EuroSCORE II was calculated.[12] Significant coronary artery disease was considered >50% epicardial stenosis.

Echocardiography

All patients underwent comprehensive Doppler echocardiographic examinations performed using commercially available ultrasound systems by experienced echocardiographers. Image analyses were conducted locally in each center in accordance with guidelines.[13] Mitral regurgitation severity was graded according to a multiparametric approach, as recommended by guidelines. Details regarding the echocardiographic assessment are provided in the Supplemental Methods.

Cardiac Magnetic Resonance Imaging

Details regarding the CMR assessment are provided in the Supplemental Methods. Briefly, CMR studies were performed on clinical scanners and analyzed locally by experienced operators blinded to the echocardiographic data of the patient. Left ventricular and right ventricular (RV) end-diastolic volume (EDV), end-systolic volume (ESV), and ejection fraction were assessed from consecutive short-axis cine steady-state free precession pulse images covering the entire left ventricle (LV) from the mitral plane to the apex. The LV total stroke volume (LVTSV) was obtained by subtracting the LVESV from the LVEDV. Aortic forward flow was derived from quantitative through-plane phase-contrast measurement performed at the level of the sinotubular junction perpendicular to the aorta. Mitral regurgitant volume (RegVol) was calculated by subtracting the aortic forward flow from the total LVTSV. Mitral regurgitant fraction (RegFrac) was defined as CMR RegVol divided by the LVTSV, expressed as a percentage. Left ventricular global longitudinal (GLS) and circumferential (GCS) strain were computed by feature-tracking using dedicated software (Circle CVI42, build 6.2; Supplemental Figure 2).

Clinical Decision and Follow-Up

All patients underwent MV repair surgery within 6 months following baseline evaluation based on recommendations by the respective heart teams of each institution with the approval of the patient's cardiologist in accordance with practice guidelines and patient wishes. Median time between CMR and MV surgery was 28 (2-61) days. This delay was mainly related to practical factors at both centers, including surgical scheduling constraints, time required for preoperative assessment, and patient-related considerations. Most patients were followed in our institution's outpatient clinics ($n = 172$, 77%). Others were followed in public hospitals or private practices by referring cardiologists working in coordination with our tertiary centers ($n = 51$, 23%). A follow-up echocardiogram was performed between 6 to 24 months after MV surgery. Information was obtained retrospectively. The primary end point was the occurrence of postoperative LV systolic dysfunction (defined as LVEF <50%) at echocardiographic follow-up.

Statistical Analysis

Data were analyzed with R version 4.1.1 (R Foundation for Statistical Computing) and GraphPad Prism GraphPad Software. All analyses considered a 2-tailed P value of <.05 as statistically significant.

Quantitative data are reported as median (25th-75th percentile), while qualitative data are presented as absolute numbers and percentages. Patients were stratified into normal versus postoperative LV dysfunction. Associations between the 2 groups and baseline categorical variables were examined using either Pearson chi-square statistic or Fisher's exact test. Individual differences for continuous variables were compared using Mann-Whitney U tests. Intra- and interobserver variabilities for LV characteristics were evaluated using intraclass correlation coefficient (ICC; single rater/measurement, absolute agreement, 2-way fixed-effects model) and coefficient of variation (CV).

As part of an exploratory analysis, univariate associations between preoperative Echo and CMR characteristics and postoperative LV dysfunction were assessed using receiver operating characteristic (ROC) curves, with areas under the curve (AUCs) used to quantify their individual discriminative ability.

Then 3 logistic regression models were constructed using preoperative variables selected based on both their bivariate association with

HIGHLIGHTS

- Postoperative LV systolic dysfunction is not uncommon in primary MR.
- LV measures have moderate individual value to stratify postop LV dysfunction risk.
- No relationship was found between preop MR severity and postop LV dysfunction.
- Combining LV size and function assessments improves risk stratification.
- There is additive value of indLVESD and CMR-assessed LVEF.

postoperative LV dysfunction and prior clinical knowledge. An Echo-only model included transthoracic Echo LVEF and indexed (ind-) LV end-systolic diameter (indLVESD); a CMR-only model included CMR LVEF and indexed LV end-systolic volume (indLVESV); and a combined Echo + CMR model incorporated all 4 variables. Odds ratios (OR) were standardized to allow direct comparison of effect sizes across models. Given the moderate number of events, we chose not to introduce interaction terms or model nonlinear relationships to preserve model stability and interpretability. Model performance was assessed using AUCs, compared using DeLong's test. The incremental value of the combined model was evaluated using likelihood ratio tests against Echo-only and CMR-only models. A nomogram was derived from the combined model to illustrate the relative and absolute contributions of each variable to the estimated risk of postoperative LV dysfunction. Finally, a 2-step stratification algorithm was developed using Echo indLVESD (threshold: 18 mm/m^2, prioritizing sensitivity) followed, when applicable, by CMR LVEF (threshold: 56%, prioritizing specificity), to identify and refine the risk of postoperative LV dysfunction.

RESULTS

Baseline Characteristics

Of the 223 patients included (median age, 60; interquartile range [IQR], 50-67] years), 21% were women, 13.5% had associated coronary artery disease, 11% had history of atrial fibrillation, and 18% were in NYHA class III to IV. There were no significant differences in the clinical or surgical characteristics according to postoperative LV function (Table 1). Median time between Echo and CMR was 14 (IQR, 1-38) days. Only 4 (1.8%) patients had LV regional wall motion abnormalities. No differences in LVEF were observed between patients in NYHA class I to II versus those in NYHA class III to IV (Echo LVEF: 64% [61%; 70%] vs 64% [61%-69.5%]; $P = .781$; CMR LVEF: 63% [58%-66%] vs 64% [59%-68%]; $P = .444$). Supplemental Table 1 shows the characteristics of patients according to NYHA class (I-II vs III-IV).

Among the 179 patients (80%) who underwent MV surgery based on a class I indication, 15 (8%) had an Echo LVEF <60% and an LVESD ≥40 mm, 47 (26%) had LVESD ≥40 mm and Echo LVEF ≥60%, 92 (52%) had LVESD < 40 mm and Echo LVEF ≥60%, and 25 (14%) had LVESD <40 mm and Echo LVEF <60%. One hundred ninety-one patients (86%) had mild tricuspid regurgitation and 7 (3%) had mild-to-moderate tricuspid regurgitation. The decision to perform concomitant tricuspid annuloplasty was made at the time of MV surgery based on the presence of tricuspid regurgitation on Echo, annular dilation (as assessed by transthoracic Echo, transesophageal Echo, or intraoperative findings), in accordance with heart team recommendations and the surgeon's clinical judgment.

Forty-one patients ($n = 18\%$) had postoperative LV dysfunction at Echo follow-up (median follow-up time, 8.7 [IQR, 6.7-12.6] months after MV surgery). These patients had higher LVESDs

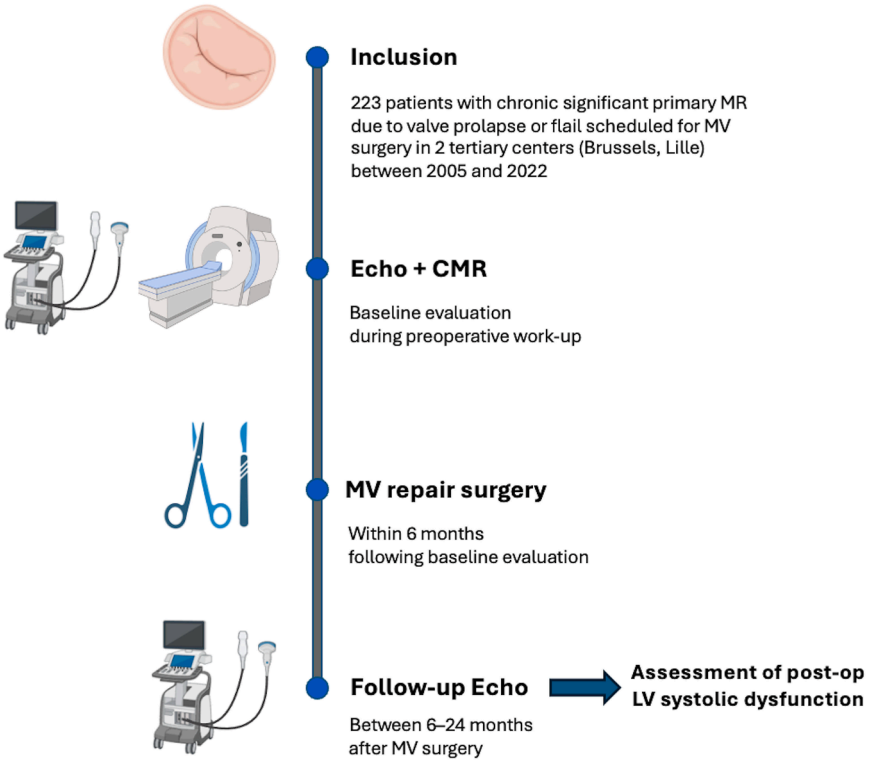

Figure 1 Timeline of study protocol.

Table 1 Clinical and surgical characteristics of the study population according to postoperative LV systolic function

Variable	All (*N* = 223)	Normal postoperative LV function (*n* = 182)	Postoperative LV dysfunction (*n* = 41)	Overall *P* value
Clinical characteristics				
Age, years	60 [50; 67]	60 [50; 67]	59 [47; 67]	.689
Gender, female	46 (21)	38 (21)	8 (19.5)	1.000
Body surface area, m^2	1.93 [1.80; 2.04]	1.94 [1.81; 2.05]	1.88 [1.79; 2.01]	.369
NYHA functional class				.216
I	94 (42)	77 (42)	17 (41.5)	
II	89 (40)	76 (42)	13 (32)	
III/IV	40 (18)	29 (16)	11 (27)	
Hypertension	88 (39.5)	71 (39)	17 (41.5)	.910
Diabetes mellitus	7 (3)	7 (4)	0 (0)	.364
Dyslipidemia	62 (28)	54 (30)	8 (19.5)	.263
Coronary artery disease	30 (13.5)	26 (14)	4 (10)	.607
History of atrial fibrillation	24 (11)	20 (11)	4 (10)	1.000
Surgical characteristics				
EuroSCORE II (%)	0.97 [0.67; 1.46]	0.97 [0.68; 1.45]	0.87 [0.60; 1.72]	.435
Indication for MV surgery:				1.000
Class I	179 (80)	146 (80)	33 (81)	
Class IIa	6 (3)	5 (3)	1 (2)	
Early surgery	38 (17)	31 (17)	7 (17)	
Surgical approach:				.529
Robotic-assisted surgery	63 (28)	51 (28)	12 (29)	
Median sternotomy	142 (64)	118 (65)	24 (58.5)	
Video-assisted minimally invasive surgery	18 (8)	13 (7)	5 (12)	
Cross-clamp time, min	98 [71; 119]	95 [71; 116]	110 [82; 127]	.155
Cardiopulmonary bypass time, min	134 [99; 157]	132 [95; 154]	145 [111; 164]	.256
Mitral annulus size, mm	34 [32; 36]	34 [32; 36]	34 [32; 36]	.464
Associated CABG	24 (11)	19 (10)	5 (12)	.776
Associated tricuspid annuloplasty	70 (31)	60 (33)	10 (24)	.377
Early postoperative mitral pressure gradient, mm Hg	3.6 [3; 4]	3 [3; 4]	4 [3; 4.6]	.336
Postoperative atrial fibrillation	67 (30)	53 (29)	14 (34)	.656
Beta-blockers at discharge	102 (46)	82 (45)	20 (49)	.796
ACE/ARB at discharge	60 (27)	53 (29)	7 (17)	.169
Diuretics at discharge	37 (17)	31 (17)	6 (15)	.888
Median time between MV surgery and follow-up Echo	8.7 [6.7; 12.6]	8.95 [6.8; 13.1]	7.10 [6.3; 12]	**.040**

Bold indicates statistical significance ($P < .05$).
ACE, Angiotensin-converting-enzyme inhibitor; *ARB*, angiotensin II receptor blockers; *CABG*, coronary artery bypass graft.
Data are presented as n (%) or median [IQR].

and volumes (all $P \leq .009$; Figure 2, Table 2), lower preoperative CMR LVEF ($P = .003$), and a trend for lower Echo LVEF ($P = .072$). Mitral regurgitation RegVol values obtained by Echo or CMR poorly correlated ($r = 0.36$, $P < .001$). No relationship was observed between any of the preoperative MR quantitative parameters (MR effective regurgitant orifice area [EROA], Echo RegVol, CMR RegVol, CMR RegFrac) and postoperative LV function (all $P > .196$). Also, in patients who underwent late gadolinium enhancement imaging ($n = 183$), no relationship was found between presence of late gadolinium enhancement and postoperative LV function ($P = .802$).

Reproducibility

Interobserver agreement ranged from fair (Echo LVEF: ICC, 0.80 [0.53-0.92]; CV, 3.4%) to excellent (CMR LVESV: ICC, 0.98 [0.93-0.99]; CV, 2.5%; Table 3).

Exploratory Analysis of the Relationship between Preoperative Imaging Variables and Postoperative LV Dysfunction

We first evaluated the individual discriminative ability of preoperative Echo and CMR variables using ROC curves. The AUCs ranged

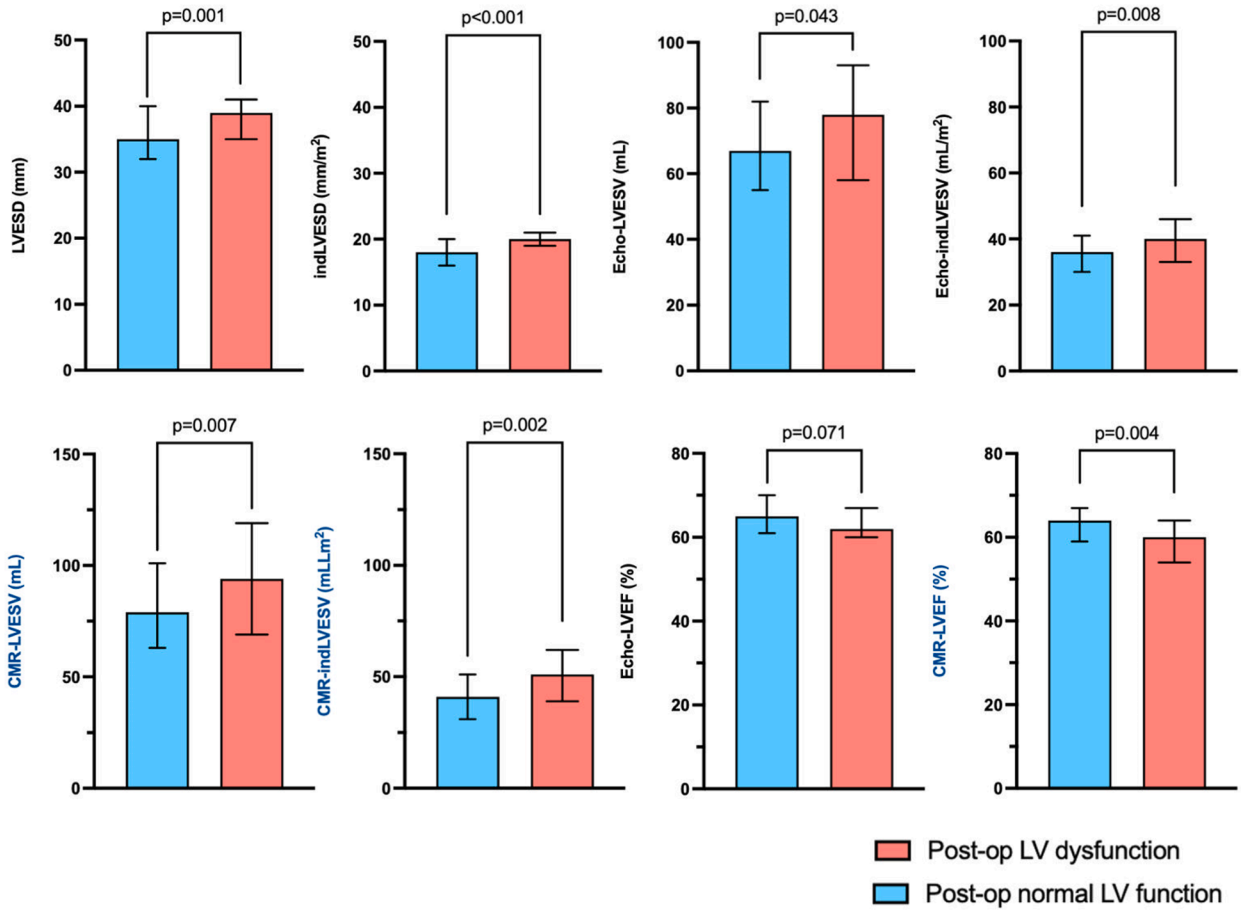

Figure 2 Preoperative LV echocardiographic and CMR characteristics according to normal versus postoperative LV systolic dysfunction. For continuous variables, IQRs are displayed in *bar plots*.

from 0.59 (95% CI, 0.49-0.68) for Echo LVEF to 0.70 (95% CI, 0.61-0.78) for Echo indLVESD, indicating only moderate performance when these characteristics were considered separately (Figure 3).

We did not observe any significant relationship between LV GLS, whether assessed by Echo or CMR, and the risk of postoperative LV dysfunction (AUC, 0.54 [95% CI, 0.43-0.64]; and AUC, 0.57 [95% CI, 0.47-0.67], respectively, Supplemental Figure 3, Table 2). In contrast, CMR LV GCS was associated with postoperative LV dysfunction but with weak discriminative performance (AUC, 0.62 [95% CI, 0.52-0.72]). Median Echo and CMR LA reservoir strain measurements were, respectively, 27% (IQR, 20%-35%) and 22% (IQR, 16%-32%). No relationship was found between Echo and CMR LA strain measurements and the risk of postoperative LV dysfunction (AUC, 0.50 [95% CI, 0.40-0.60] and AUC [0.54, 95% CI, 0.44-0.65], respectively).

New York Heart Association class (III/IV vs I/II), pulmonary hypertension (RV peak pressure gradient, per 1 mm Hg increment), and history of atrial fibrillation were not significantly associated with postoperative LV systolic dysfunction (OR, 1.93; 95% CI, 0.86-4.22; $P = .105$; OR, 0.99; 95% CI, 0.95-1.03; $P = .747$; OR, 0.83; 95% CI, 0.27-2.56; $P = .744$, respectively).

Model-Based Comparison of Echo and CMR for Risk Stratification of Postoperative LV Systolic Dysfunction

Three logistic regression models were constructed: an Echo-only model included Echo LVEF and Echo indLVESD; a CMR-only model included CMR LVEF and CMR indLVESV; and a combined Echo + CMR model incorporated all 4 characteristics. Both Echo and CMR models showed moderate discriminative ability, with AUCs of 0.70 and 0.66, respectively, and no significant difference between them (DeLong's test: $P = .416$; Figure 4). The combined model showed slightly improved performance (AUC, 0.72) compared with the CMR model ($P = .045$) but not compared with the Echo model ($P = .369$). The addition of CMR covariates to the Echo model led to a nonsignificant trend toward improved model fit (likelihood ratio test: $P = .087$), whereas adding Echo parameters to the CMR model significantly improved model fit ($P = .008$). Standardized ORs are presented in Supplemental Table 2, highlighting that Echo-indLVESD remained consistently associated with postoperative LV dysfunction across models.

Relative and absolute contributions of each preoperative imaging covariate to the probability of postoperative LV dysfunction are represented in a nomogram derived from the combined model (Figure 5). The nomogram illustrates that Echo indLVESD and

Table 2 Imaging characteristics of the study population according to postoperative LV systolic function

Variable	All (*N* = 223)	Normal postoperative LV function (*n* = 182)	Postoperative LV dysfunction (*n* = 41)	Overall *P* value	Patients with available data, *n* (%)
Echocardiographic characteristics					
Echo LVEDD, mm	58 [54; 61]	58 [54; 61]	59 [57; 62]	**.045**	223 (100)
Echo LVESD, mm	35 [32; 40]	35 [31; 39]	39 [35; 41]	**.001**	223 (100)
Echo indLVEDD, mm/m^2	31 [28; 33]	30 [28; 33]	31 [29; 34]	**.041**	223 (100)
Echo indLVESD, mm/m^2	19 [16; 21]	18 [16; 20]	20 [19; 21.5]	**<.001**	223 (100)
Echo LVEDV, mL	196 [170; 222]	196 [170; 220]	211 [179; 232]	.174	223 (100)
Echo LVESV, mL	68 [54; 83]	66 [54; 82]	77 [56; 93]	**.031**	223 (100)
Echo indLVEDV, mL/m^2	103 [90; 112]	103 [89.5; 111]	106 [94; 124]	.073	223 (100)
Echo indLVESV, mL/m^2	36 [29; 42]	35.5 [28; 41]	40 [33; 45]	**.007**	223 (100)
Echo LVEF, %	64 [61; 70]	65 [61; 70]	63 [60; 68]	.072	223 (100)
Echo LV GLS, %	−20.9 [−23; −18.6]	−20.9 [−23.1; −18.7]	−20.2 [−22.9; −17.6]	.443	205 (92)
Echo cardiac index, mL/min/m^2	2.3 [1.9; 2.6]	2.3 [1.9–2.6]	2.1 [1.8–2.6]	.474	164 (73)
Echo LAV, mL	104 [81; 131]	100 [80; 130]	108 [85; 147]	.270	217 (97)
Echo indLAV, mL/m^2	54 [42; 69]	53 [42; 69]	56 [46; 78]	.170	217 (97)
RV peak pressure gradient, mm Hg	25 [21; 31]	25.5 [21; 31]	24 [22; 31]	.813	186 (83)
MR EROA, mm^2	50 [39; 63]	50 [39; 64]	52 [39; 60]	.996	217 (97)
Echo RegVol, mL	75 [62; 91]	74.0 [62; 90]	80.0 [57; 95]	.598	217 (97)
MR prolapse localization, *n* (%):				1.000	223 (100)
Anterior	15 (7)	12 (7)	3 (7)		
Posterior	156 (70)	128 (70)	28 (68)		
Bileaflet	52 (23)	42 (23)	10 (25)		
Flail leaflet	98 (44)	79 (43)	19 (46)	.867	223 (100)
Mitral annulus disjunction	65 (29)	54 (30)	11 (27)	.864	223 (100)
CMR characteristics					
CMR LVEDV, mL	223 [189; 260]	218 [187; 256]	235 [203; 273]	.096	223 (100)
CMR LVESV, mL	82 [64; 103]	78 [62.5; 100]	94 [70.0; 119]	**.005**	223 (100)
CMR indLVEDV, mL/m^2	117 [101; 131]	116 [101; 130]	124 [108; 141]	**.030**	223 (100)
CMR indLVESV, mL/m^2	42 [34; 53]	41 [33; 50]	51 [38; 61]	**.001**	223 (100)
CMR indLV mass, g/m^2	75 [67; 83]	75 [67; 82]	79 [70; 84]	.138	223 (100)
CMR LVEF, %	63 [58; 67]	64 [59; 67]	60 [54; 64]	**.003**	223 (100)
CMR indexed aortic forward flow, mL/m^2	37.5 [31; 42]	37 [31; 43]	37.5 [30; 41]	.348	223 (100)
CMR cardiac index, mL/min/m^2	2.5 [2.1; 2.8]	2.6 [2.2; 2.8]	2.4 [2.1; 2.8]	.228	223 (100)
CMR RegVol, mL	63 [48; 89]	61 [47.5; 89]	68 [53; 92]	.204	223 (100)
CMR RegFrac, %	49 [38; 58]	48 [37; 57]	50 [41; 61]	.196	223 (100)
CMR indRVEDV, mL/m^2	77.5 [66; 89]	77 [65; 89]	79 [69; 93]	.501	223 (100)
CMR indRVESV, mL/m^2	37 [30; 47]	37 [29; 47]	39 [31; 50]	.390	223 (100)
CMR RV ejection fraction, %	51 [46; 56]	52 [46; 57]	50 [46; 55]	.302	223 (100)
CMR LAVmax, mL	145 [112; 183]	144 [112; 181]	157 [116; 91]	.413	215 (96)
CMR LAVmin, mL	42 [28; 56]	40 [28; 55]	44 [33; 59]	.360	215 (96)
CMR indLAV, mL/m^2	75 [60; 97]	73 [60; 96]	85.5 [57.5; 99]	.321	215 (96)
CMR LAEF, %	45 [39; 53]	45.5 [39; 53]	45 [35; 53]	.638	215 (96)
LV fibrosis, *n* (%)	39 (21)	33 (22)	6 (18)	.802	183 (82)
CMR LV GLS, %	−15.4 [−16.8; −13.5]	−15.5 [−17.4; −13.7]	−15.1 [−16.5; −13.1]	.190	213 (95)
CMR LV GCS, %	−17.5 [−19.1; −16.1]	−17.5 [−19.3; −16.3]	−16.5 [−18.5; −15.1]	**.020**	213 (95)
CMR LVESD, 4 chamber, mm	37 [34; 42]	37 [33; 40]	42 [37; 44]	**.001**	213 (95)
CMR LVESD, 2 chamber, mm	37.5 [34; 41]	37 [33.5; 41]	39 [36; 45]	**.023**	213 (95)
CMR LVESD, 3 chamber, mm	35 [32; 40]	35 [31; 39]	38 [34; 43]	**.009**	213 (95)

EDD, End-diastolic diameter; *EDV*, end-diastolic volume; *LAEF*, left atrial emptying fraction; *LAV*, left atrial volume.
Data are presented as median [IQR] unless otherwise specified.

Table 3 Reproducibility of LV functional and volumetric parameters

	Interobserver reproducibility		Intraobserver reproducibility	
	ICC (CI 95%)	CV (%)	ICC (CI 95%)	CV (%)
Echo LVESD	0.97 (0.92-0.99)	3.4	0.98 (0.95-0.99)	1.9
Echo LVESV	0.90 (0.77-0.96)	8.3	0.94 (0.71-0.98)	6.1
Echo LVEF	0.80 (0.53-0.92)	3.4	0.88 (0.71-0.95)	2.7
CMR LVESV	0.98 (0.93-0.99)	2.5	0.99 (0.97-0.99)	1.9
CMR LVEF	0.96 (0.90-0.98)	1.4	0.95 (0.87-0.98)	1.4
Echo LV GLS	0.86 (0.69-0.94)	4.5	0.90 (0.77-0.96)	3
CMR LV GLS	0.87 (0.70-0.95)	4.1	0.94 (0.86-0.98)	2.9
CMR LV GCS	0.94 (0.87-0.98)	2.7	0.91 (0.80-0.96)	3

CMR LVEF contributed the most to the model, whereas Echo LVEF and CMR indLVESV had limited impact.

Additive Value of CMR following Echocardiographic Assessment to Stratify Risk of Postoperative LV Dysfunction

Based on the results above, we propose a simplified 2-step risk stratification algorithm integrating Echo and CMR. Echo indLVESD and CMR LVEF were selected based on their respective contributions in the combined model, as highlighted in the nomogram. Given that Echo is the first-line imaging modality, we selected a threshold that prioritizes sensitivity (≥80%) to avoid missing at-risk patients. This yielded a cutoff of 18 mm/m^2 for Echo indLVESD (sensitivity, 80%; specificity, 46%). For CMR LVEF, which was used as a second-line modality to refine risk among patients with Echo indLVESD ≥18 mm/m^2, we selected a threshold that favors specificity (≥80%), resulting in a cutoff of 56% (sensitivity, 34%; specificity, 85%).

This 2-step approach stratified patients into 3 groups with distinct event rates (Figure 6): 8% (7/91) of patients with Echo indLVESD <18 mm/m^2 developed postoperative LV dysfunction; among those with Echo indLVESD ≥18 mm/m^2, 41% (14/34) experienced the event when CMR LVEF was ≤56% and 20% (20/98) when CMR LVEF was >56%.

These results illustrate a stepwise stratification strategy, in which Echo indLVESD identifies a broader population at risk of postoperative LV dysfunction and CMR LVEF refines risk assessment within this group.

DISCUSSION

In this cohort of patients with chronic significant primary MR undergoing MV repair surgery, we evaluated the relationship between preoperative echocardiographic and CMR assessments of LV volumes and function and the risk of postoperative LV systolic dysfunction. When considered separately, both Echo and CMR parameters showed only moderate discriminative ability. Strain imaging, whether assessed by Echo or CMR, did not improve risk stratification in this population. In a multivariable model combining preoperative Echo and CMR LV parameters, Echo indLVESD and CMR LVEF contributed most to the model, supporting their clinical relevance. Based on these findings, a simple 2-step approach based on Echo indLVESD < or ≥18 mm/m^2, followed by CMR LVEF > or ≤56% in patients with Echo indLVESD ≥18 mm/m^2, identified 3 subgroups with distinct risks of postoperative dysfunction (9%, 20%, and 41%, respectively). These results confirm the value of Echo as a first-line modality, underline the importance of assessing Echo indLVESD in routine practice, and support the use of CMR, particularly CMR LVEF, as a complementary tool to refine risk assessment in selected patients with primary MR undergoing MV surgery (Central Illustration).

Head-to-Head Comparison of Echo and CMR Preoperative LV Volumetric and Function Parameters to Stratify Risk of Postoperative LV Systolic Dysfunction

Echo LVESD remains the guideline-endorsed marker of LV remodeling in primary MR, owing to its wide availability, reproducibility, and strong association with long-term mortality.[4,5,14] Consistently, the updated 2025 European Society of Cardiology guidelines on valvular heart disease reaffirm the benefit of early surgery in asymptomatic patients with primary MR and an LVESD ≥40 mm, while also introducing indLVESD ≥20 mm/m^2 as an additional surgical trigger.[15] It is recommended to measure LV internal diameters at or immediately below the level of the MV tips.[13] However, LVESD measured at the basal level of LV may not fully capture the extent of adverse LV remodeling in primary MR, particularly in cases of asymmetric enlargement—such as spherical mid-to-apical LV end-systolic remodeling—where LVESV increases without a corresponding change in LVESD.[16] Preoperative LV volumes better correlate than diameters with changes in LVEDV before and after MV surgery.[17,18] The value of LV volumes in stratifying the risk of postoperative LV dysfunction in primary MR remains poorly studied.[19-21] Compared to Echo LVEF, the utility of CMR LVEF to identify risk of postoperative LV dysfunction is not established.[22] Whether the same LVEF thresholds apply across modalities, given that CMR and Echo LVEF measurements are not systematically interchangeable in clinical practice, remains unclear.[23]

We thus conducted a head-to-head comparison of key preoperative Echo and CMR characteristics to stratify risk of postoperative LV dysfunction. Each showed only moderate discriminative value (AUC ranging from 0.59 for Echo LVEF to 0.70 for Echo indLVESD). The numerically higher AUCs observed for absolute and Echo indLVESD reinforce their value as first-line markers for evaluating LV remodeling in primary MR, as endorsed by current guidelines. Four patients in our cohort had LV regional wall motion abnormalities, which could have limited the theoretical advantage of volumetric over diametric measurements. CMR LVESD measured in the 4- and 3-chamber views showed stronger associations with postoperative LV

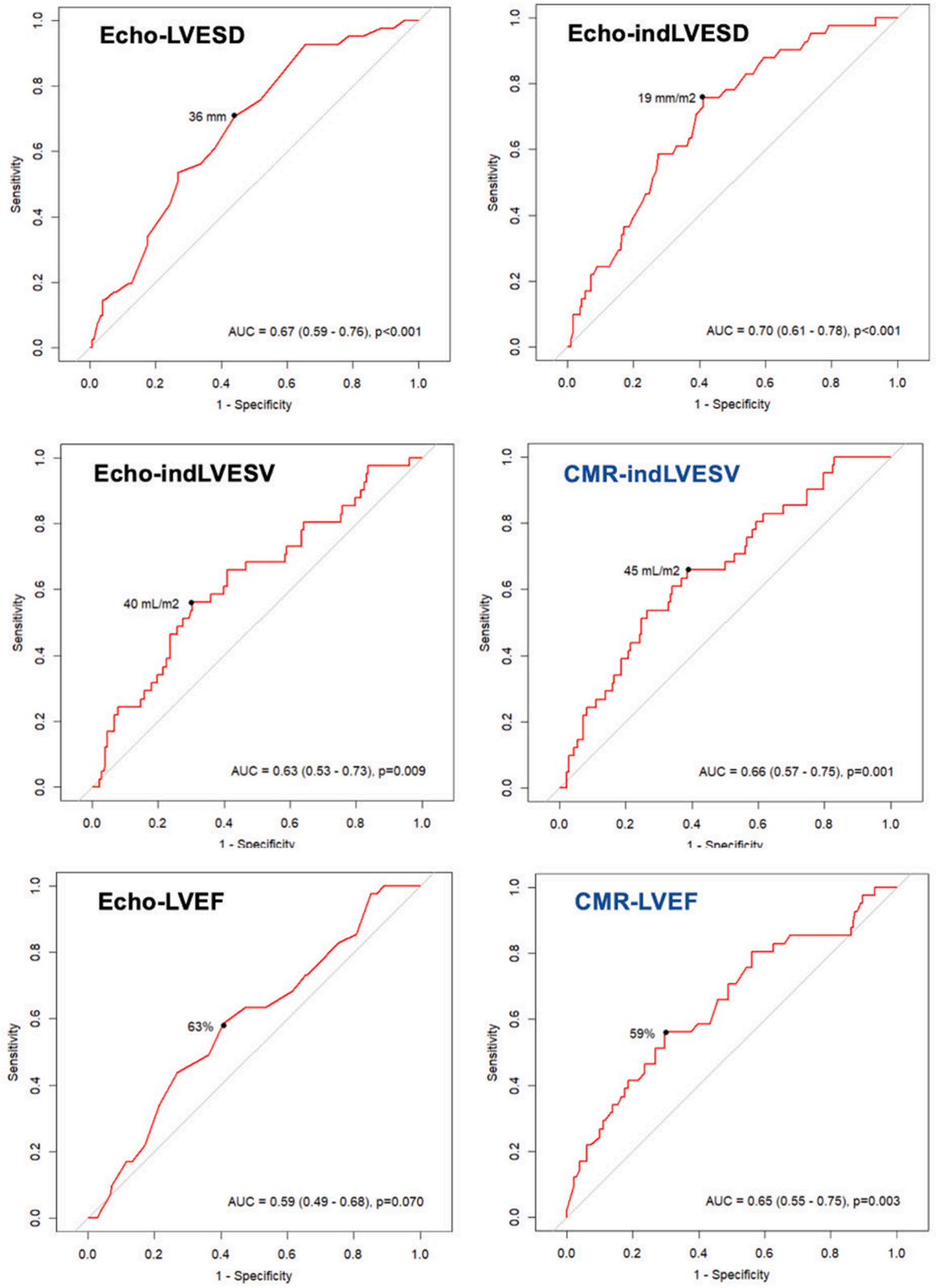

Figure 3 Receiver operating characteristic curves of LV Echo and CMR characteristics associated with risk of postoperative LV dysfunction. These ROC curves display the relationship between preoperative echocardiographic and CMR characteristics of LV remodeling and function and postoperative LV dysfunction.

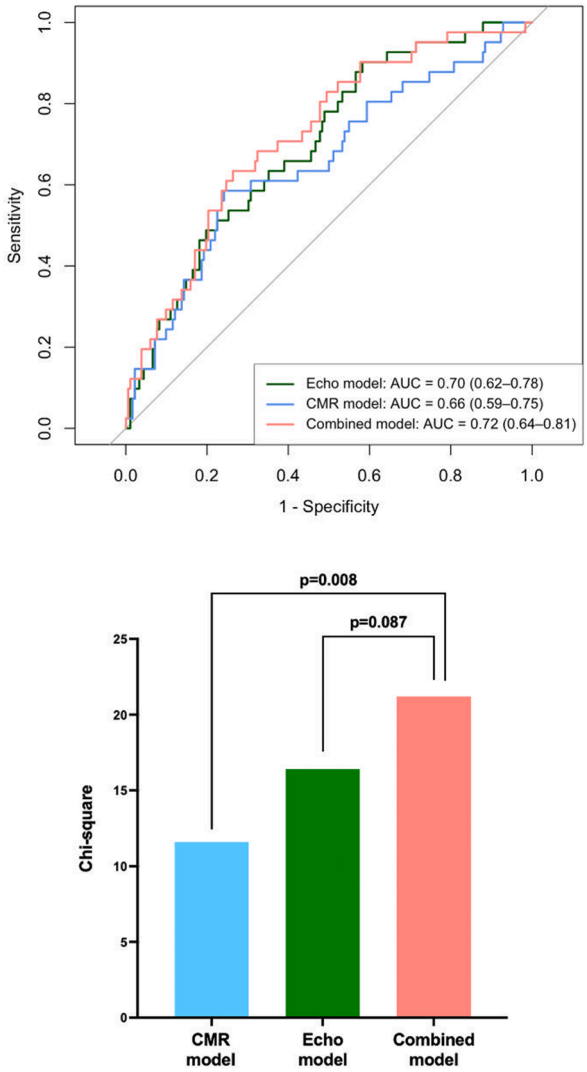

Figure 4 Comparative performance of Echo, CMR, and combined models for risk stratification of postoperative LV systolic dysfunction. ROC curves (*upper panel*) and likelihood ratio test results (*lower panel*) for 3 logistic regression models: Echo-only (Echo LVEF, Echo indLVESD), CMR-only (CMR LVEF, CMR indLVESV), and combined Echo + CMR.

dysfunction than measurements from the 2-chamber view. This may suggest that remodeling along the radial and anteroposterior axes is more closely related to LV systolic impairment than changes occurring in the anteroinferior plane.

Nonetheless, given the limitations of conventional LV volumetric and functional parameters, more advanced imaging markers should be investigated. In our cohort, preoperative LV GLS, whether assessed by Echo or CMR, was not significantly associated with the risk of postoperative LV systolic dysfunction, in contrast with previous reports.[24] Measurements were performed retrospectively for research purposes, and LV GLS is highly load dependent and may be pseudonormal or overestimated in chronic significant primary MR. Additionally, feature-tracking CMR GCS offered no superior discriminative value compared with conventional LV parameters. These findings reinforce the need for further dedicated prospective studies to clarify the role of myocardial strain imaging in this context.

The moderate performance of conventional Echo and CMR parameters to stratify risk of postoperative LV dysfunction supports that additional factors should be considered beyond LV assessment. Although not observed in our study, previous work has identified associations between preoperative pulmonary hypertension, atrial fibrillation, and postoperative LV dysfunction.[25] CMR–derived extracellular volume (ECV) has been associated with MR severity, symptom burden, and earlier referral for MV surgery.[26] Another study reported that increased preoperative indECV—the product of ECV and indLV end-diastolic myocardial volume—was associated with lower postoperative LVEF, whereas ECV alone was not.[27] Left ventricular shape, such as the sphericity index, may also warrant further investigation.[28]

Absence of Relationship between MR Severity and Postoperative LV Systolic Dysfunction

In line with previous studies, mitral RegVol values assessed by Echo or CMR were poorly correlated.[29,30] We aimed to go one step further by evaluating the relationship between preoperative MR quantitative parameters and risk of postoperative LV systolic dysfunction. While previous reports showed univariate associations between MR EROA or Echo RegVol and early postoperative LV dysfunction, these associations often did not persist after adjustment for LV size.[4,21] Similarly, CMR studies reported that although RegVol correlated with postoperative LVEF on univariate analysis, only CMR indLVESV remained independently associated after multivariable adjustment.[17,19] In our study, no significant association was found between preoperative MR quantitative parameters—whether assessed by Echo or CMR—and the risk of postoperative LV systolic dysfunction. Additionally, the presence of preoperative late gadolinium enhancement (available in 183 patients) was not associated with postoperative dysfunction, consistent with previous findings.[17]

Clinical Implications of a Preoperative Combined Evaluation of LV Structure and Function to Stratify Risk of Postoperative LV Systolic Dysfunction

When considered individually, preoperative LV volumetric and functional parameters assessed by Echo and CMR showed only modest discriminative ability for identifying patients at risk of postoperative LV dysfunction. In this context, each parameter may be regarded as a "weak learner"—a variable with limited predictive value when used in isolation. However, combining multiple such parameters can improve overall model performance.

We therefore evaluated whether a combined approach using structural and functional measurements from both modalities could improve risk stratification. As shown in the nomogram, Echo indLVESD and CMR LVEF were the most informative characteristics associated with risk of postoperative LV dysfunction, while Echo LVEF and CMR indLVESV had limited contribution. Echo indLVESD remained significantly associated with the risk of postoperative LV dysfunction after adjusting for other LV characteristics, supporting its prognostic relevance, in line with findings from a recently published large multicenter study.[31] The stronger association of CMR LVEF compared to Echo LVEF may be partly explained by the superior reproducibility of CMR measurements. These findings emphasize the complementary roles of Echo and CMR in assessing both structural and functional LV abnormalities when stratifying the risk of postoperative LV dysfunction in primary MR.

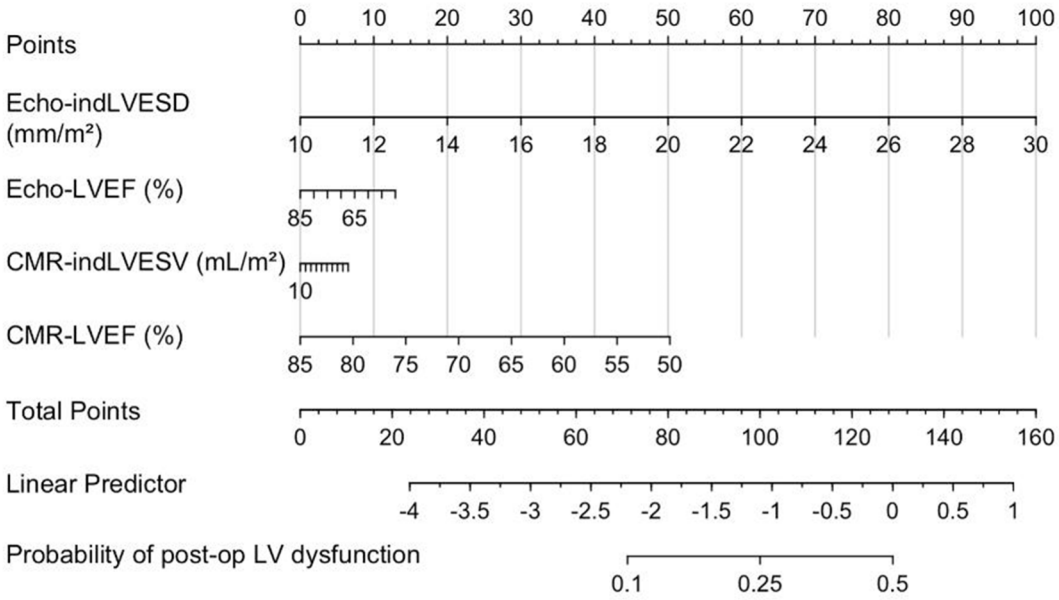

Figure 5 Nomogram to estimate the risk of postoperative LV dysfunction. This nomogram is based on a multivariable logistic regression model incorporating both Echo (Echo indLVESD, Echo LVEF) and CMR (CMR indLVESV, CMR LVEF) measurements. Each imaging parameter corresponds to a point scale at the top, and the sum of these points translates into a probability of postoperative LV dysfunction using the bottom scale. Echo indLVESD and CMR LVEF provide the greatest discriminative value in the model and contribute the most points in the nomogram. In contrast, Echo LVEF and CMR indLVESV contribute minimally and have lower weight in the total score.

A Stepwise Echo CMR Strategy to Stratify Risk of Postoperative LV Dysfunction

Building on these results, we proposed a simplified stepwise algorithm using 2 parameters: Echo indLVESD and CMR LVEF. This strategy was designed to reflect clinical workflow: Echo as the first-line modality to screen patients at risk of postoperative LV dysfunction and CMR as a second-line tool to refine risk assessment when needed.

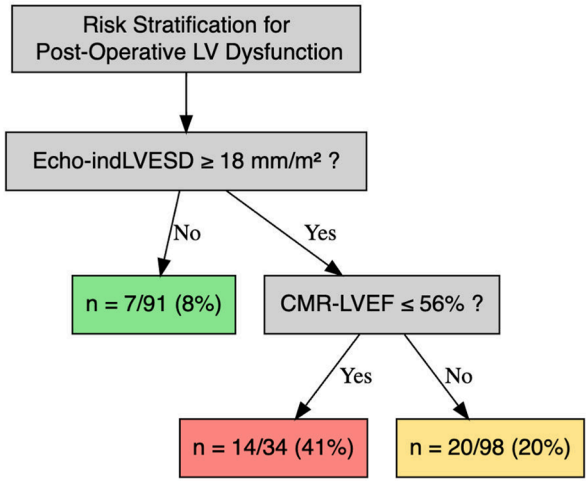

Figure 6 Two-step stratification algorithm for postoperative LV systolic dysfunction based on Echo indLVESD and CMR LVEF. Patients were first stratified using an Echo indLVESD cutoff of 18 mm/m^2. In patients with values ≥18 mm/m^2, risk was further refined using CMR LVEF with a threshold of 56%. Each box shows the number of patients with postoperative LV dysfunction over the total in that subgroup and the corresponding percentage.

Consequently, we used data-driven thresholds that prioritized sensitivity for Echo indLVESD and specificity for CMR LVEF. An Echo indLVESD <18 mm/m^2 identified a low-risk subgroup (9% event rate), suggesting a reassuring profile. Among patients with Echo indLVESD ≥18 mm/m^2, further stratification based on a CMR LVEF threshold of 56% helped isolate a smaller high-risk group (41% event rate), while the remaining had intermediate risk (20%).

This simple, clinically interpretable algorithm may support selective use of CMR in patients with primary MR. However, given the retrospective design and limited number of events, these findings should be considered exploratory. Prospective multicenter, ideally randomized control trials, are needed to confirm this approach, validate thresholds, and assess its potential utility on broader in guiding clinical decision-making. Finally, the potential incremental value of indLV volumes over diameters in chronic primary MR warrants head-to-head evaluation in large prospective studies using hard clinical end points.

Study Limitations

This study has several limitations. It is an observational study involving patients referred for CMR in addition to Echo. As patients were not enrolled consecutively, the potential for selection bias cannot be excluded. A formal comparison with excluded patients was not possible, as detailed clinical and imaging data were not routinely collected for research purposes in patients who did not undergo CMR. The specific reasons for not performing CMR in the excluded patients were not systematically recorded and could not be retrospectively retrieved. Retrospective follow-up data analysis has inherent limitations, preventing the demonstration of a cause-effect relationship. Due to the moderate number of events and absence of a validation cohort, the consistency of our findings requires confirmation in large-scale, independent datasets. We purposefully choose a postoperative LVEF threshold of 50% to define LV systolic dysfunction, as it

represents a widely accepted clinical cutoff with therapeutic relevance in routine practice. Assessing relative changes in LVEF or using a higher threshold may offer an alternative approach. Additionally, postoperative LVEF may be influenced by various hemodynamic and clinical factors, including arrhythmia, pulmonary hypertension, and RV function, which were not systematically assessed in the present study. We focused on a homogeneous population of patients with primary MR due to valve prolapse or flail undergoing MV repair surgery. Therefore, our findings cannot extend to other MR etiologies or those undergoing MV replacement. Three-dimensional Echo assessment of LV volumes and function is increasingly adopted in clinical practice. In primary MR, three-dimensional Echo LVEF shows stronger correlation with CMR LVEF—the reference standard—than two-dimensional Echo LVEF.[32,33] The clinical value of three-dimensional Echo LVEF compared to two-dimensional Echo and CMR LVEF to identify primary MR patients at risk of postoperative LV dysfunction would merit further investigation. Separate 2- and 4-chamber LVEF echocardiographic measurements were not available, as only the biplane Simpson's method was routinely stored in clinical Echo reports. Additionally, none of the patients required contrast injection for LV opacification. Follow-up echocardiographic studies were not exclusively conducted in our centers in a Core Lab manner. This study was not sufficiently powered to explore postoperative clinical events. Further research is needed to assess the added value of CMR following Echo in clinical risk stratification after MV surgery for primary MR. Finally, we focused on postoperative LV function at midterm follow-up after MV surgery. A longer follow-up might have shown further improvements in LV function for some primary MR patients with postoperative LV dysfunction. Additionally, although the median time between MV surgery and follow-up Echo slightly differed between groups, postoperative LV dysfunction in this setting typically occurs early, making late-onset dysfunction unlikely in patients with initially preserved LV function. Nonetheless, we believe our findings offer valuable clinical insights by identifying patient subgroups at higher risk of postoperative LV dysfunction, who may benefit from closer monitoring and/or appropriate medical therapy in the early to midterm postoperative period.

CONCLUSION

In this cohort of patients with chronic significant primary MR due to valve prolapse or flail who underwent MV repair surgery, preoperative LV characteristics assessed by Echo and CMR showed only moderate ability to identify those at risk of postoperative LV dysfunction. Among the imaging variables studied, Echo indLVESD and CMR LVEF contributed the most to risk stratification. Based on these findings, a simplified 2-step approach using Echo indLVESD $<$ or $\geq$18 mm/m^2, followed by CMR LVEF $\leq$ or $>$56% in patients with Echo indLVESD $\geq$18 mm/m^2, identified 3 subgroups with distinct event rates. These exploratory results require confirmation in larger prospective studies.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the author(s) used ChatGPT v4.0 (OpenAI©) to improve readability and language. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CONFLICTS OF INTEREST

None.

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SUPPLEMENTARY DATA

Supplementary data related to this article can be found at https://doi.org/10.1016/j.echo.2025.09.015.

REFERENCES

1. Lazam S, Vanoverschelde JL, Tribouilloy C, et al. Twenty-year outcome after mitral repair versus replacement for severe degenerative mitral regurgitation: analysis of a large, prospective, multicenter, international registry. Circulation 2017;135:410-22.
2. Otto CM, Nishimura RA, Bonow RO, et al. 2020 ACC/AHA guideline for the management of patients with valvular heart disease: executive summary: a report of the American College of Cardiology/American Heart Association Joint Committee on clinical practice guidelines. J Am Coll Cardiol 2021;77:450-500.
3. Galli E, Lancellotti P, Sengupta PP, et al. LV mechanics in mitral and aortic valve diseases: value of functional assessment beyond ejection fraction. JACC Cardiovasc Imaging 2014;7:1151-66.
4. Quintana E, Suri RM, Thalji NM, et al. Left ventricular dysfunction after mitral valve repair–the fallacy of "normal" preoperative myocardial function. J Thorac Cardiovasc Surg 2014;148:2752-60.
5. Tribouilloy C, Rusinaru D, Szymanski C, et al. Predicting left ventricular dysfunction after valve repair for mitral regurgitation due to leaflet prolapse: additive value of left ventricular end-systolic dimension to ejection fraction. Eur J Echocardiogr 2011;12:702-10.
6. Enriquez-Sarano M, Tajik AJ, Schaff HV, et al. Echocardiographic prediction of survival after surgical correction of organic mitral regurgitation. Circulation 1994;90:830-7.
7. Gaasch WH, Meyer TE. Left ventricular response to mitral regurgitation. Circulation 2008;118:2298-303.
8. Delling FN, Noseworthy PA, Adams DH, et al. Research opportunities in the treatment of mitral valve prolapse: JACC expert panel. J Am Coll Cardiol 2022;80:2331-47.
9. Vahanian A, Beyersdorf F, Praz F, et al. 2021 ESC/EACTS Guidelines for the management of valvular heart disease. Eur Heart J 2022;43:561-632.
10. Van De Heyning CM, Magne J, Piérard LA, et al. Assessment of left ventricular volumes and primary mitral regurgitation severity by 2D echocardiography and cardiovascular magnetic resonance. Cardiovasc Ultrasound 2013;11:46.
11. Lachin JM. The role of measurement reliability in clinical trials. Clin Trials 2004;1:553-66.
12. Nashef SA, Roques F, Sharples LD, et al. EuroSCORE II. Eur J Cardiothorac Surg 2012;41:734-44. discussion 44-5.
13. Lang RM, Badano LP, Mor-Avi V, et al. Recommendations for cardiac chamber quantification by echocardiography in adults: an update from

the American Society of Echocardiography and the European Association of Cardiovascular Imaging. J Am Soc Echocardiogr 2015;28:1-39.e14.
14. Tribouilloy C, Grigioni F, Avierinos JF, et al. Survival implication of left ventricular end-systolic diameter in mitral regurgitation due to flail leaflets a long-term follow-up multicenter study. J Am Coll Cardiol 2009;54:1961-8.
15. Praz F, Borger MA, Lanz J, et al. 2025 ESC/EACTS Guidelines for the management of valvular heart disease. Eur Heart J 2025;46:4635-736.
16. Schiros CG, Dell'Italia LJ, Gladden JD, et al. Magnetic resonance imaging with 3-dimensional analysis of left ventricular remodeling in isolated mitral regurgitation: implications beyond dimensions. Circulation 2012;125:2334-42.
17. Craven TP, Chew PG, Dobson LE, et al. Cardiac reverse remodeling in primary mitral regurgitation: mitral valve replacement vs. mitral valve repair. J Cardiovasc Magn Reson 2023;25:43.
18. Uretsky S, Shah DJ, Lasam G, et al. Usefulness of mitral regurgitant volume quantified using magnetic resonance imaging to predict left ventricular remodeling after mitral valve "correction". Am J Cardiol 2020;125:1666-72.
19. Seldrum S, de Meester C, Pierard S, et al. Assessment of left ventricular reverse remodeling by cardiac MRI in patients undergoing repair surgery for severe aortic or mitral regurgitation. J Cardiothorac Vasc Anesth 2019;33:1901-11.
20. Reddy P, Anand V, Rajiah P, et al. Predicting postoperative systolic dysfunction in mitral regurgitation: CT vs. echocardiography. Front Cardiovasc Med 2024;11:1297304.
21. Althunayyan AM, Alborikan S, Badiani S, et al. Determinants of postoperative left ventricular dysfunction in degenerative mitral regurgitation. Eur Heart J Cardiovasc Imaging 2023;24:1252-7.
22. Tribouilloy C, Rusinaru D, Grigioni F, et al. Long-term mortality associated with left ventricular dysfunction in mitral regurgitation due to flail leaflets: a multicenter analysis. Circ Cardiovasc Imaging 2014;7:363-70.
23. Clark J, Ionescu A, Chahal CAA, et al. Interchangeability in left ventricular ejection fraction measured by echocardiography and cardiovascular magnetic resonance: not a perfect match in the real world. Curr Probl Cardiol 2023;48:101721.
24. Kislitsina ON, Thomas JD, Crawford E, et al. Predictors of left ventricular dysfunction after surgery for degenerative mitral regurgitation. Ann Thorac Surg 2020;109:669-77.
25. Varghese R, Itagaki S, Anyanwu AC, et al. Predicting early left ventricular dysfunction after mitral valve reconstruction: the effect of atrial fibrillation and pulmonary hypertension. J Thorac Cardiovasc Surg 2014;148:422-7.
26. Kitkungvan D, Yang EY, El Tallawi KC, et al. Extracellular volume in primary mitral regurgitation. JACC Cardiovasc Imaging 2021;14:1146-60.
27. Liu B, Neil DAH, Bhabra M, et al. Reverse myocardial remodeling following valve repair in patients with chronic severe primary degenerative mitral regurgitation. JACC Cardiovasc Imaging 2022;15:224-36.
28. Zheng J, Li Y, Billor N, et al. Understanding post-surgical decline in left ventricular function in primary mitral regurgitation using regression and machine learning models. Front Cardiovasc Med 2023;10:1112797.
29. Altes A, Levy F, Iacuzio L, et al. Comparison of mitral regurgitant volume assessment between proximal flow convergence and volumetric methods in patients with significant primary mitral regurgitation: an echocardiographic and cardiac magnetic resonance imaging study. J Am Soc Echocardiogr 2022;35:671-81.
30. Uretsky S, Gillam L, Lang R, et al. Discordance between echocardiography and MRI in the assessment of mitral regurgitation severity: a prospective multicenter trial. J Am Coll Cardiol 2015;65:1078-88.
31. Tribouilloy C, Rusinaru D, Grigioni F, et al. Indexing left ventricular end-systolic dimension to body size: association with mortality in patients with degenerative mitral regurgitation. Eur J Heart Fail 2024;26:2563-9.
32. Levy F, Marechaux S, Iacuzio L, et al. Quantitative assessment of primary mitral regurgitation using left ventricular volumes obtained with new automated three-dimensional transthoracic echocardiographic software: a comparison with 3-Tesla cardiac magnetic resonance. Arch Cardiovasc Dis 2018;111:507-17.
33. Marechaux S, Le Goffic C, Ennezat PV, et al. Quantitative assessment of primary mitral regurgitation using left ventricular volumes: a three-dimensional transthoracic echocardiographic pilot study. Eur Heart J Cardiovasc Imaging 2014;15:1133-9.