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Original Article

Predischarge Lung Ultrasound B-Lines as a Robust Predictor of 90-Day Rehospitalization in Heart Failure with Reduced Ejection Fraction (HFrEF): Evidence from Clinical and Classification and Regression Tree (CART)-Based Risk Stratification

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Abstract

Background: Heart failure is a major global health burden, with high morbidity, mortality, and substantial rehospitalization rates. Residual pulmonary congestion at discharge is a key determinant of early readmission but is often underestimated using clinical assessment alone. Lung Ultrasound (LUS) offers an objective, bedside tool for detecting pulmonary congestion through B-line quantification. This study aimed to evaluate whether predischarge B-line measurements predict 90-day rehospitalization due to all cardiovascular causes in patients with Heart Failure with reduced Ejection Fraction (HFrEF).

Methods: This retrospective cohort study included 107 adults hospitalized with HFrEF at Wahidin Sudirohusodo Hospital from March to July 2023. LUS was performed prior to discharge using an eight-zone protocol, and total B-line counts were recorded. Clinical, laboratory, and echocardiographic variables were obtained from the Heart Failure Registry and electronic medical records. Patients were followed for 90 days to identify heart failure–related rehospitalization. Statistical analyses included independent t-test, Mann–Whitney U tests, chi-square test, ROC curves, multivariate logistic regression, and a Classification and Regression Tree (CART) model to identify the strongest predictors of rehospitalization.

Results: Among 107 patients (mean age 58.52 ± 12.16 years; 74.77% male), 48 (44.86%) experienced 90-day rehospitalization due to all cardiovascular causes. Rehospitalized patients had significantly higher predischarge B-line counts (25.98 ± 8.23 vs. 17.63 ± 8.03, $p < 0.0001$). A B-line cutoff of ≥20 predicted rehospitalization with 75.7% accuracy, 77.08% sensitivity, 74.58% specificity, and an AUC of 0.754. Renal dysfunction (eGFR 58.72 ± 29.32 vs. 75.43 ± 27.49 mL/min/1.73 m^2, $p = 0.003$; creatinine 1.86 ± 2.01 vs. 1.21 ± 0.76 mg/dL, $p = 0.021$), lower EF (31.6 ± 8.15% vs. 36.64 ± 9.05%, $p = 0.004$), and higher filling pressures (PCWP, E/e') were also significantly associated with rehospitalization. The CART model identified B-line ≥20 as the strongest primary classifier, with additional risk contributed by renal impairment and reduced EF, yielding an accuracy of 90.65% and an AUC of 0.966.

Conclusions: Predischarge B-line quantification is a strong predictor of 90-day rehospitalization in HFrEF. Integration of B-line assessment with renal function and cardiac parameters substantially improves risk stratification. LUS provides a practical, noninvasive tool for optimizing predischarge evaluation and may guide interventions to reduce early rehospitalization.

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Keywords: B-Line score, lung ultrasound, heart failure, HFrEF, 90-day rehospitalization

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Introduction

Heart failure remains a major global health problem, with an estimated 64.3 million affected individuals worldwide.[1] In Asia, the burden is substantial, accounting for 31.89 million cases, while Indonesia ranks among the countries with the highest prevalence of heart failure in the region.[2] Despite advances in therapy, heart failure is associated with frequent rehospitalization and significant healthcare costs. Data from the EVEREST trial showed that more than half of patients with systolic heart failure experienced rehospitalization, with a substantial proportion occurring within the first 30 days after discharge.[3-4] Early readmission is also associated with increased medical expenditure.[5]

Residual congestion at discharge is a key contributor to early rehospitalization. Clinical assessment alone is often insufficient to detect persistent pulmonary congestion, particularly in patients without overt symptoms. Lung Ultrasound (LUS) has emerged as a practical bedside tool for evaluating pulmonary edema, with diagnostic performance comparable to computed tomography.[6] B-lines, defined as vertical hyperechoic artifacts arising from the pleural line, reflect increased extravascular lung water and correlate strongly with pulmonary congestion in heart failure. Thresholds such as ≥10 B-lines across eight lung zones or ≥3 B-lines in more than two zones have demonstrated high diagnostic sensitivity.[7]

Despite apparent clinical improvement, many patients are discharged with residual pulmonary congestion, which is associated with adverse outcomes, including rehospitalization and mortality.[6] Objective quantification of congestion before discharge may therefore improve risk stratification and guide treatment optimization. Accordingly, this study aimed to evaluate whether predischarge LUS B-line assessment predicts 90-day rehospitalization in patients with Heart Failure with reduced Ejection Fraction (HFrEF).

Methods

Study Design and Population

This study employed a retrospective cohort design and included patients admitted to the Integrated Heart Center at Wahidin Sudirohusodo Hospital with a confirmed diagnosis of congestive heart failure. All participants were identified through the hospital's Heart Failure Registry and were enrolled between March and July 2023.

Inclusion and Exclusion Criteria

Eligible participants were adults aged 18 years or older who were hospitalized with a primary diagnosis of congestive heart failure and demonstrated a left ventricular Ejection Fraction (EF) of 40% or less on the echocardiographic evaluation performed at admission. Patients were excluded if they had undergone interventional cardiac procedures such as cardiac resynchronization therapy or valve replacement, had underlying pericardial diseases, including effusion or constrictive pericarditis, or exhibited atrioventricular dyssynchrony, such as complete heart block or recent pacemaker implantation. These conditions were excluded because they may independently alter intrathoracic fluid distribution, ventricular filling dynamics, or ventricular synchrony, thereby confounding LUS B-line quantification and limiting the reliability of pulmonary congestion assessment. Patients who declined participation in the study procedures were also excluded. Patients who underwent elective percutaneous coronary intervention (PCI) or planned staged PCI during the follow-up period were not excluded from the study; however, these elective or scheduled procedures were not classified as rehospitalization events unless the admission was primarily driven by worsening heart failure symptoms or cardiovascular decompensation.

Data Collection

Clinical information was obtained from the Heart Failure Registry and supplemented with data from electronic medical records as needed. Variables collected included demographic characteristics, such as age, sex, and body mass index; relevant comorbid conditions and baseline heart failure therapies; laboratory results obtained within the first 24 hours of admission; and echocardiographic findings recorded during initial evaluation. Pre-discharge clinical assessment included the performance of lung ultrasonography to quantify pulmonary B-lines.

Lung Ultrasonography Protocol

Pulmonary congestion was assessed using LUS performed with a portable Philips Lumify device equipped with a linear transducer and preset lung imaging mode. Examinations were conducted across eight thoracic zones, with four regions assessed on each hemithorax. Although the 8-zone protocol is commonly interpreted using a semiquantitative approach (≥3 B-lines per zone), this study employed a total B-line count across all scanned zones to provide a continuous measure of pulmonary congestion. This approach was selected to enhance sensitivity to residual congestion at discharge and to allow more precise risk stratification, consistent with emerging evidence supporting quantitative B-line assessment beyond traditional zone-based thresholds. The total number of B-lines visualized was used to stratify congestion severity. Mild congestion was defined as 6–15 B-lines, moderate congestion as 16–30 B-lines, and severe congestion as more than 30 B-lines. (Figure 1)

CART Analysis

This analysis is to precisely identify the combination of clinical variables most strongly influencing the incidence of 90-day re-hospitalization, and the Classification and Regression Tree (CART) method was applied. This approach, which relies on a decision-tree structure, was selected for its ability to construct a hierarchical classification model and to effectively capture complex, non-linear relationships among predictor variables that conventional statistical tests might fail to reveal. The variables incorporated into the CART model were those previously identified in bivariate analysis as having a statistically significant relationship with 90-day re-hospitalization status.

The model prominently featured the B-line score as the primary predictor due to its initial high classification power in assessing pulmonary congestion severity. Other variables analyzed included key indicators of renal function (eGFR and creatinine levels), crucial echocardiography parameters describing left ventricular function and filling pressures (EF, PCWP, and the average E/e' ratio), and relevant comorbidities (Ischemic Heart Disease [IHD] and Chronic Kidney Disease [CKD]). Furthermore, the patient's use of aldosterone receptor antagonists was included, given their significant association with re-hospitalization outcomes in preliminary analyses.

B-Line Score Application

The "B-Line Score" was developed as an interactive predictive dashboard utilizing the R Shiny framework to estimate the 90-day re-hospitalization risk in patients with HFrEF. The application integrates key clinical parameters into a clinically actionable risk score derived from CART statistical modeling. The application is hosted online and secured by a mandatory login system that requires registered user authentication. This security feature ensures data confidentiality, prevents unauthorized access, and facilitates the tracking of user activity alongside the storage of individual prediction history.

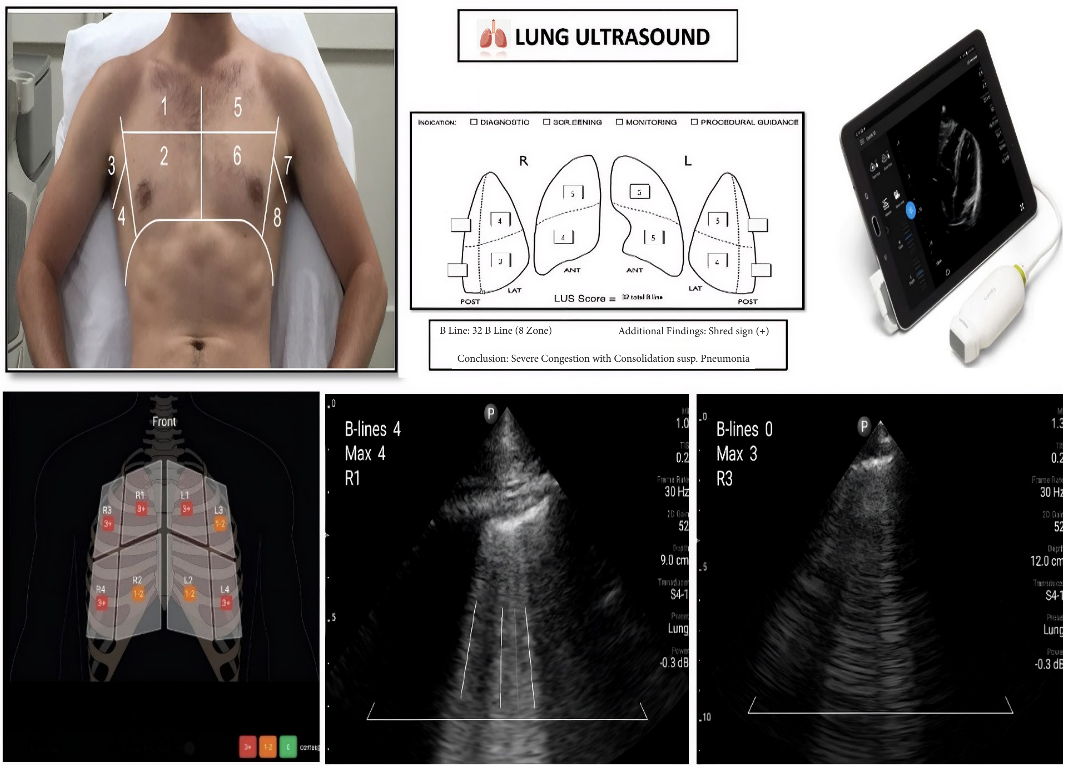

Figure 1. Baseline catient characteristics.

Upon logging in, users enter crucial clinical variables on a dedicated data entry page. These variables include the B-line score obtained from LUS, estimated Glomerular Filtration Rate (eGFR), serum creatinine levels, EF, Pulmonary Capillary Wedge Pressure (PCWP), and the presence of significant comorbidities, namely IHD and CKD. The system processes this data through the pre-trained predictive model and outputs the result as a risk status, either rehospitalization or no rehospitalization, along with the calculated probability percentage. A notable feature is the direct WhatsApp integration, enabling immediate and secure transmission of the prediction results to colleagues or the treating physician via a pre-formatted message link, thereby promoting efficient cross-departmental communication and accelerating evidence-based clinical decision-making. (Figure 2)

Follow-Up and Outcome Measures

All enrolled patients were monitored for 90 days after hospital discharge. Follow-up was conducted by telephone interviews with patients or their caregivers and through review of hospital records. If patients or their caregivers could not be reached after at least three telephone attempts on different days, the patient was classified as lost to follow-up and excluded from the outcome analysis. Rehospitalization events were defined as cardiovascular-related admissions due to worsening congestive heart failure occurring within 90 days after discharge, regardless of whether the admission occurred at Wahidin Sudirohusodo Hospital or at another healthcare facility. Rehospitalizations at other hospitals were identified through structured telephone follow-up, during which patients or their caregivers were specifically asked about

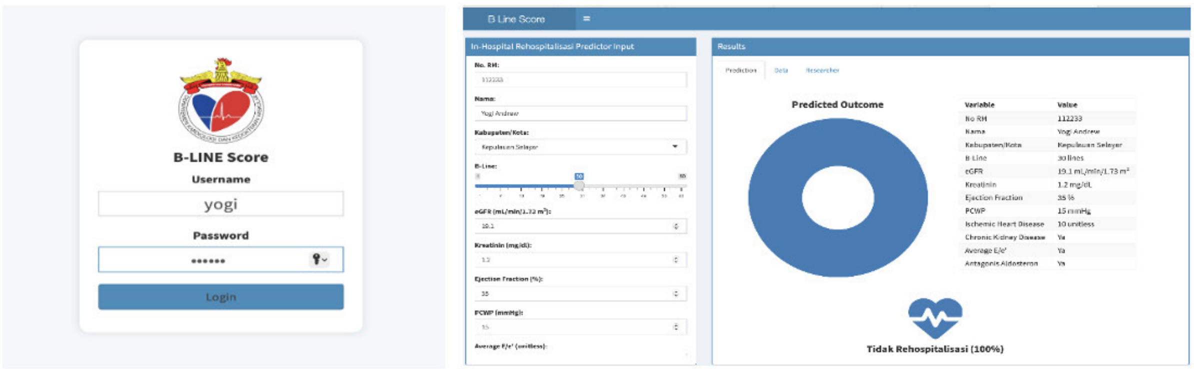

Figure 2. B-Line score application.

interim hospital admissions, admission diagnoses, and dates of hospitalization. When available, supporting medical documentation was requested to corroborate patient-reported events. Hospital admissions solely for elective PCI or planned staged PCI, in the absence of acute heart failure deterioration, were not considered rehospitalization events. The principal outcome of interest was rehospitalization due to cardiovascular causes as a result of worsening congestive heart failure within the 90-day observation period.

Statistical Analysis

Descriptive statistics were used to summarize baseline characteristics. Categorical variables were expressed as frequencies and percentages, whereas continuous variables were presented as mean±standard deviation. Comparative analyses between rehospitalized and non-rehospitalized patients were performed using the independent t-test, Mann–Whitney U test, and chi-square test. Receiver operating characteristic (ROC) curve analysis was used to identify the optimal B-line cutoff for predicting rehospitalization, with the Youden Index used to determine the point that maximizes sensitivity and specificity. Variables exhibiting significant associations in univariate analysis were included in a multivariate logistic regression to adjust for potential confounders. P values ≤ 0.05 were considered significant.

Ethical Considerations

Approval for this study was granted by the Research Ethics Committee of the Faculty of Medicine, Universitas Hasanuddin (Reference No. 1032/UN4.6.4.5.31/PP36/2024). All research procedures adhered to the principles of the Declaration of Helsinki and complied with national and institutional ethical guidelines.

Results

In addition to LUS findings, renal function parameters, natriuretic peptide levels, echocardiographic indices, comorbidities, and medication use were analyzed as complementary markers of congestion severity and heart failure prognosis to contextualize the predictive value of B-lines. A total of 107 patients met the inclusion and exclusion criteria for this study. The descriptive characteristics of the study population are summarized in Table 1. The mean age was 58.52 ± 12.16 years, and the majority were male (74.77%). Rehospitalization due to cardiovascular causes within 90 days occurred in 48 patients (44.86%), while 59 patients (55.14%) did not experience rehospitalization. The mean B-line value was 21.37 ± 9.10, indicating a high burden of interstitial pulmonary congestion. Laboratory assessments showed a mean eGFR of 67.93 ± 29.40 mL/min/1.73 m² and a mean creatinine of 1.50 ± 1.49 mg/dL. NT-proBNP levels averaged 162.87 ± 65.01 pg/mL, with data unavailable in 19 patients (17.75%).

Echocardiographic evaluation demonstrated that all participants had reduced systolic function, with a mean EF of 34.38 ± 8.98%. Diastolic parameters showed elevated filling pressures, reflected by a mean PCWP of 19.86 ± 6.49 mmHg and an average E/e' of 14.48 ± 5.45. Additional comorbidities included IHD in 62 patients (57.94%), hypertensive heart disease in 41 (38.32%), and atrial fibrillation in 17 (15.89%). Hypertension (56.07%) and diabetes mellitus (29.91%) were the most common systemic comorbidities, while CKD was identified in 14 patients (13.08%). Pneumonia was present in 24 patients (22.43%). Regarding medication use, most patients received ACE inhibitors or ARBs (77.57%), beta-blockers (46.73%), diuretics (84.11%), or aldosterone antagonists (56.07%).

Table 1. Baseline patient characteristics.

Variables	Value
Age (years)	58.52±12.16
Gender	
Male	80 (74.77)
Female	27 (25.23)
B-Line	21.37±9.10
90-day rehospitalization	
Yes	59 (55.14)
No	48 (44.86)
Laboratory findings	
eGFR (mL/min/1.73 m²)	67.93±29.4
Creatinine (mg/dL)	1.5±1.49
NT-proBNP (pg/mL)	162.87±65.01
NA	19 (17.75)
Echocardiography	
Ejection Fraction (%)	34.38±8.98
PCWP (mmHg)	19.86±6.49
Average E/e' (unitless)	14.48±5.24
Comorbidity	
Coronary artery disease	30 (28.04)
Ischemic heart disease	62 (57.94)
Hypertensive heart disease	41 (38.32)
Peripheral artery disease	0 (0)
Pulmonary Hypertension	3 (2.8)
Congenital heart disease	1 (0.93)
Atrial Fibrillation	17 (15.89)
Hypertension	60 (56.07)
Diabetes Mellitus	32 (29.91)

Valvular heart disease	27 (25.23)
Rheumatic heart disease	1 (0.93)
Cardiomyopathy	3 (2.8)
Dyslipidemia	23 (21.5)
Cerebrovascular disease	5 (4.67)
Asthma	0 (0)
COPD	0 (0)
Chronic kidney disease	14 (13.08)
Pneumonia	24 (22.43)
Medication	
ACEi/ARB	83 (77.57)
ARNI	5 (4.67)
Calcium channel blocker	3 (2.8)
Beta blocker	50 (46.73)
Diuretics	90 (84.11)
Aldosterone antagonists	60 (56.07)
Tolvaptan	0 (0)
Ivabradin	3 (2.8)
Digoxin	16 (14.95)
SGLT2 inhibitor	1 (0.93)
History of Smoking	
Yes	61 (57.01)
No	46 (42.99)

Values are n (%) or mean ± SD, unless stated otherwise. ACEi: Angiotensin-Converting Enzyme Inhibitor; ARB: Angiotensin Receptor Blocker; ARNI: Angiotensin Receptor–Neprilysin Inhibitor; B-line: B-line Artifact; CKD: Chronic Kidney Disease; COPD: Chronic Obstructive Pulmonary Disease; eGFR: Estimated Glomerular Filtration Rate; E/e': Early Mitral Inflow Velocity to Early Diastolic Mitral Annular Velocity Ratio; NA: Not Available; NT-proBNP: N-terminal Pro-B-type Natriuretic Peptide; PCWP: Pulmonary Capillary Wedge Pressure; SGLT2: Sodium–Glucose Cotransporter-2.

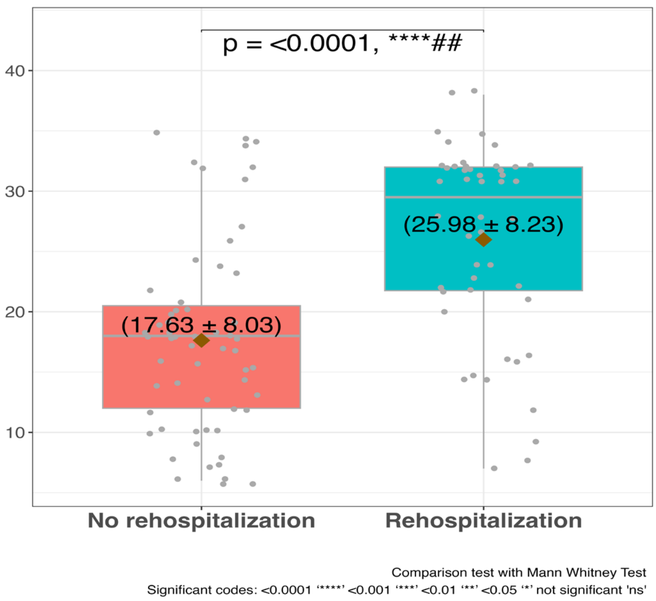

Figure 3. Comparison of B-Line parameters in heart failure patients to 90-day rehospitalization status.

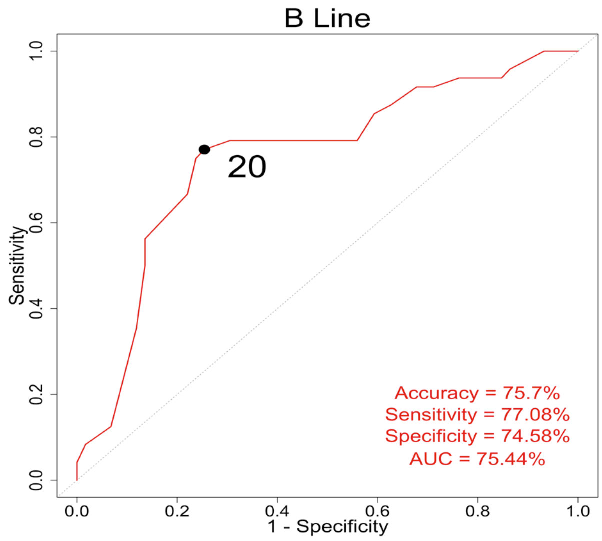

Figure 4. B-line cut-off value ROC curve.

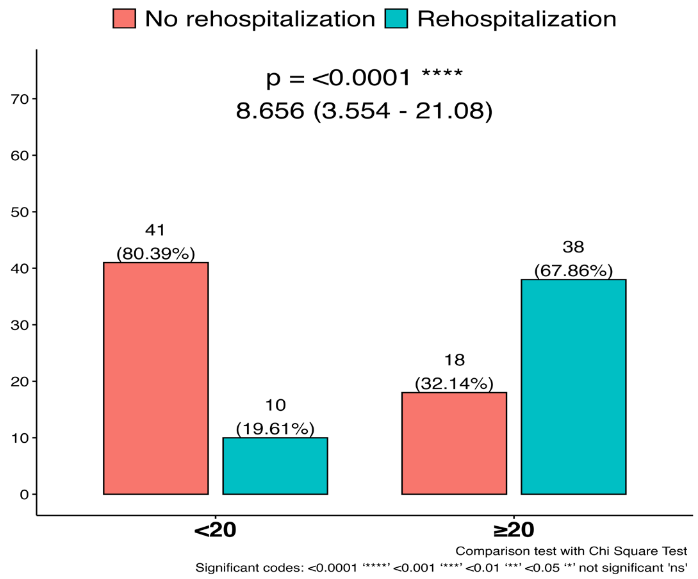

Figure 5. Relationship between B-line cut-off value and 90-day rehospitalization.

As illustrated in Figure 3, the mean B-line value was significantly higher in the rehospitalization group (25.98 ± 8.23) compared with the non-rehospitalization group (17.63 ± 8.03) ($p < 0.0001$). This finding reflects greater pulmonary congestion among patients who experienced rehospitalization. ROC curve analysis (Figure 4) identified a B-line cut-off value of 20, which demonstrated an accuracy of 75.7%, sensitivity of 77.08%, specificity of 74.58%, and an AUC of 75.44% for predicting 90-day rehospitalization. Patients with B-line ≥20 had a significantly higher incidence of rehospitalization ($p <0.0001$), with an odds ratio (OR) of 8.656 (95% CI: 3.554–21.08), as shown in Figure 5.

The association between demographic characteristics and rehospitalization is displayed in Table 2. Neither gender ($p = 0.691$) nor age ($p = 0.085$) was significantly associated with rehospitalization status. These results indicate that demographic factors were not major determinants of early readmission.

Renal and cardiac function were significantly associated with 90-day rehospitalization. Patients without rehospitalization had better renal function, with higher eGFR (75.43 ± 27.49 vs. 58.72 ± 29.32 mL/min/1.73 m², $p = 0.003$) and lower creatinine levels (1.21 ± 0.76 vs. 1.86 ± 2.01 mg/dL, $p = 0.021$). In contrast, NT-proBNP levels did not differ between groups (p = 0.854). Rehospitalized patients also demonstrated worse cardiac function, characterized by lower EF (31.6 ± 8.15% vs. 36.64 ± 9.05%, p = 0.004) and higher filling pressures, as reflected by elevated PCWP (22.09 ± 7.65 vs. 18.04 ± 4.70 mmHg, p = 0.015) and E/e' (16.28 ± 6.17 vs. 13.02 ± 3.79, p = 0.015). Among comorbidities, CKD was more prevalent in the rehospitalization group (22.92% vs. 5.80%, p = 0.007). In comparison, IHD was more frequent in patients without rehospitalization (74.58% vs. 37.50%, p < 0.001), highlighting the combined impact of renal impairment, cardiac dysfunction, and comorbidity profile on rehospitalization risk.

Table 2. Relationship between variables and 90-days rehospitalization.

Variables	No rehospitalization (n=59)	Rehospitalization (n = 48)	P-value
Age (years)	60.41±10.24	56.21±13.93	0.085[a]
Gender			
Male	45 (76.27)	35 (72.92)	0.691[b]
Female	14 (23.73)	13 (27.08)	
Laboratory findings			
eGFR (mL/min/1.73 m²)	75.43±27.49	58.72±29.32	**0.003**[c]
Creatinine (mg/dL)	1.21±0.76	1.86±2.01	**0.021**[c]
NT-proBNP (pg/mL)	155.38±45.74	170.71±80.25	0.854[c]
NA	14 (23.73)	5 (10.42)	
Echocardiography			
Ejection Fraction (%)	36.64±9.05	31.6±8.15	**0.004**[c]
PCWP (mmHg)	18.04±4.70	22.09±7.65	**0.015**[c]
Average E/e' (unitless)	13.02±3.79	16.28±6.17	**0.015**[c]
Comorbidity			
Coronary artery disease			
Yes	18 (30.51)	12 (25.0)	0.528[b]
No	41 (69.49)	36 (75.0)	
Ischemic heart disease			
Yes	44 (74.58)	18 (37.5)	**<0.001**[b]
No	15 (25.42)	30 (62.5)	
Hypertensive heart disease			
Yes	26 (44.07)	18 (37.5)	0.175[b]
No	33 (55.93)	30 (62.5)	
Peripheral artery disease			
Yes	0 (0)	0 (0)	1.000[b]
No	59 (100)	48 (100)	
Pulmonary Hypertension			
Yes	1 (1.69)	2 (4.17)	0.441[b]
No	58 (98.31)	46 (95.83)	
Congenital heart disease			
Yes	0 (0)	1 (2.08)	0.449[d]
No	59 (100)	47 (97.92)	
Atrial Fibrillation			
Yes	7 (11.86)	10 (20.83)	0.207[b]
No	52 (88.14)	38 (79.17)	
Hypertension			
Yes	36 (61.02)	24 (50.0)	0.253[b]
No	23 (38.98)	24 (50.0)	

Diabetes Mellitus			
Yes	17 (28.81)	15 (31.25)	0.784^b
No	42 (71.19)	33 (68.75)	
Valvular heart disease			
Yes	12 (20.34)	15 (31.25)	0.196^b
No	47 (79.66)	33 (68.75)	
Rheumatic heart disease			
Yes	0 (0)	1 (2.08)	0.449^d
No	59 (100)	47 (97.92)	
Cardiomyopathy			
Yes	2 (3.39)	1 (2.08)	0.999^b
No	57 (96.61)	47 (97.92)	
Dyslipidemia			
Yes	13 (22.03)	10 (20.83)	0.880^b
No	46 (77.97)	38 (79.17)	
Cerebrovascular disease			
Yes	4 (6.78)	1 (2.08)	0.377^d
No	55 (93.22)	47 (97.92)	
Asthma			
Yes	0 (0)	0 (0)	1.000^b
No	59 (100)	48 (100)	
COPD			
Yes	0 (0)	0 (0)	1.000^b
No	59 (100)	48 (100)	
Chronic kidney disease			
Yes	3 (5.08)	11 (22.92)	**0.007^b**
No	56 (94.92)	37 (77.08)	
Pneumonia			
Yes	16 (27.12)	8 (16.67)	0.197^b
No	43 (72.88)	40 (83.33)	
Medication			
ACEi/ARB			
Yes	47 (79.66)	36 (75.0)	0.565^b
No	12 (20.34)	12 (25.0)	
ARNI			
Yes	2 (3.39)	3 (6.25)	0.655^d
No	57 (96.61)	45 (93.75)	
Calcium channel blocker			
Yes	1 (1.69)	2 (4.17)	0.586^d
No	58 (98.31)	46 (95.83)	
Beta blocker			
Yes	29 (49.15)	21 (43.75)	0.577^b
No	30 (50.85)	27 (56.25)	
Diuretics			
Yes	46 (77.97)	44 (91.67)	0.054^b
No	13 (22.03)	4 (8.33)	
Aldosterone antagonists			

Yes	25 (42.37)	35 (72.92)	**0.002**[b]
No	34 (57.63)	13 (27.08)	
Tolvaptan			
Yes	0 (0)	0 (0)	1.000[b]
No	59 (100)	48 (100)	
Ivabradin			
Yes	1 (1.69)	2 (4.17)	0.586[d]
No	58 (98.31)	46 (95.83)	
Digoxin			
Yes	6 (10.17)	10 (20.83)	0.124[b]
No	53 (89.83)	38 (79.17)	
SGLT2 inhibitor			
Yes	1 (1.69)	0 (0)	0.999[d]
No	58 (98.31)	48 (100)	
History of Smoking			
Yes	34 (57.63)	27 (56.25)	0.886[b]
No	25 (42.37)	21 (43.75)	

Values are n (%) or mean ± SD, unless stated otherwise. [a]Independent t-test; [b]Chi square test; [c]Mann-Whitney test; [d]Fisher exact test. ACEi: Angiotensin-Converting Enzyme Inhibitor; ARB: Angiotensin Receptor Blocker; ARNI: Angiotensin Receptor–Neprilysin Inhibitor; COPD: Chronic Obstructive Pulmonary Disease; eGFR: Estimated Glomerular Filtration Rate; E/e': Early Mitral Inflow Velocity to Early Diastolic Mitral Annular Velocity Ratio; NA: Not Available; NT-proBNP: N-terminal Pro-B-type Natriuretic Peptide; PCWP: Pulmonary Capillary Wedge Pressure; SGLT2: Sodium–Glucose Cotransporter-2.

Most medications, including ACEIs/ARBs, ARNIs, beta-blockers, diuretics, CCBs, ivabradine, digoxin, and SGLT2 inhibitors, were not significantly associated with rehospitalization (all p >0.05). The only medication showing a significant association was aldosterone antagonists (p = 0.002). Their higher use in the rehospitalization group likely reflects more severe underlying disease rather than a causal association.

Cut-off analyses of renal and echocardiographic parameters (Figure 6) demonstrated moderate discriminatory ability for predicting rehospitalization, including eGFR ≤66 mL/min/1.73 m² (accuracy 69.16%, AUC 66.84%), creatinine ≥1.21 mg/dL (AUC 62.96%), EF <32% (AUC 66.12%), E/e' ≥11.54 (AUC 63.75%), and PCWP ≥16.21 mmHg (AUC 63.75), indicating that impaired renal function and elevated filling pressures are associated with increased rehospitalization risk; however, a B-line cut-off ≥20 showed consistently superior predictive performance. Categorical analysis (Figure 7) confirmed significant associations for eGFR <63 mL/min/1.73 m² (p = 0.0002), EF <32% (p = 0.0012), creatinine ≥1.26 mg/dL (p = 0.0045), E/e' ≥11.54 (p = 0.0022), and PCWP ≥16.21 mmHg (p = 0.0021), with odds ratios indicating substantial increases in 90-day rehospitalization risk.

The CART analysis (Figure 8) identified B-line ≥20 as the strongest initial classifier for rehospitalization. Within the B-line ≥20 subgroup, decreased renal function (eGFR <63 mL/min/1.73 m²), elevated creatinine (≥1.26 mg/dL), and reduced EF (<32%) further increased the risk. Among patients with B-line <20, the presence of ischemic heart disease, elevated PCWP, or reduced EF increased the likelihood of rehospitalization. The CART model demonstrated excellent predictive performance, with an accuracy of 90.65%, sensitivity of 98.31%, specificity of 81.25%, and an AUC of 96.66%.

Discussion

This study evaluated the relationship between pulmonary ultrasound findings, specifically B-line quantification, and the risk of 90-day rehospitalization due to cardiovascular causes in patients with heart failure. The findings demonstrate that the number of B-lines at predischarge is strongly associated with rehospitalization and reflects the degree of residual pulmonary congestion. The principal finding is that a higher B-line burden at discharge, particularly a threshold of ≥20 B-lines, is strongly associated with early rehospitalization and reflects clinically meaningful residual pulmonary

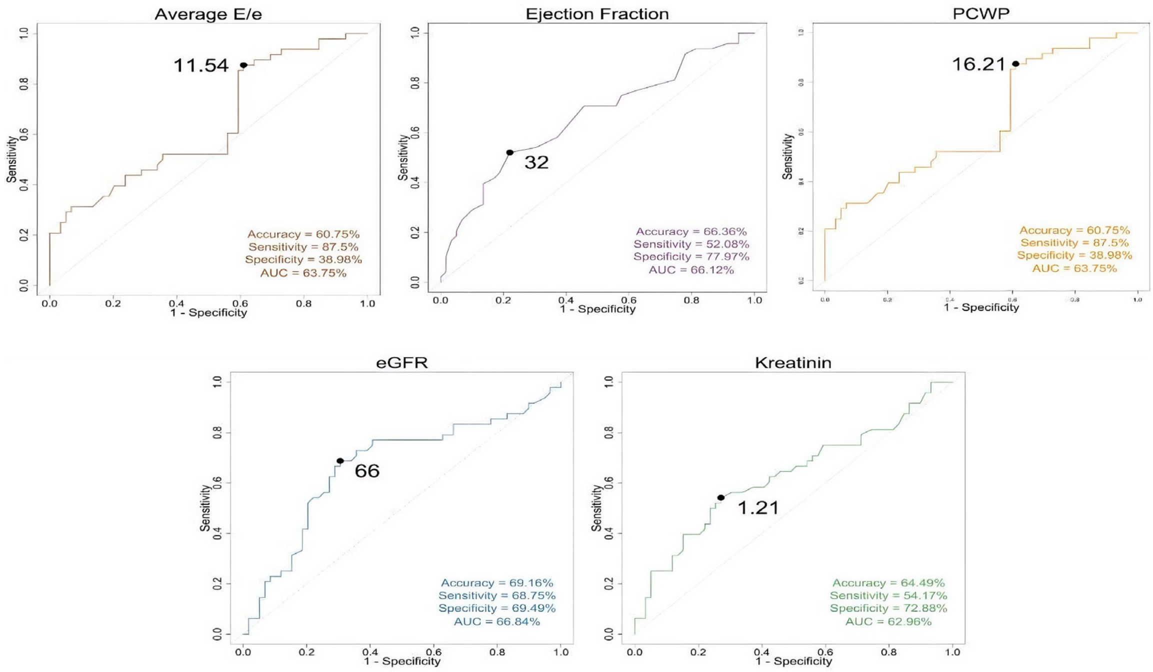

Figure 6. Variables cut-off value ROC curve.

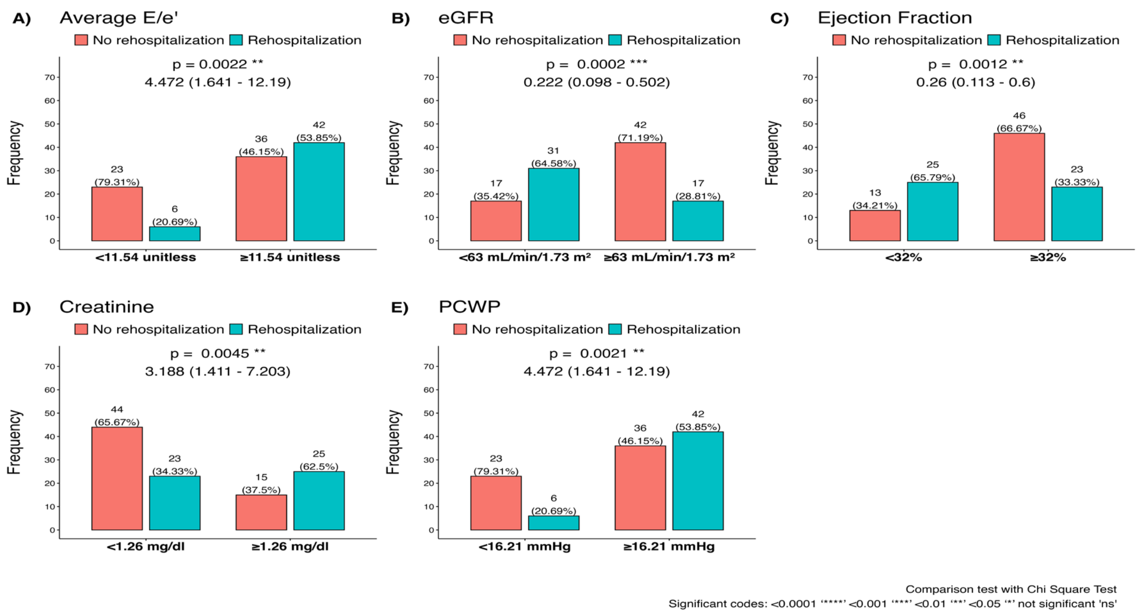

Figure 7. Relationship between the variables, cut-off value, and 90-day rehospitalization.

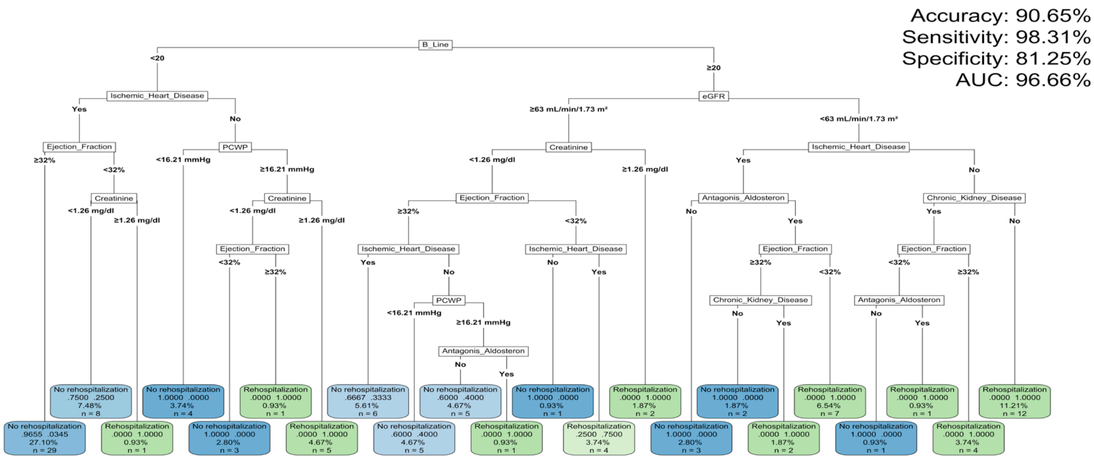

Figure 8. CART model analysis

congestion. These results align with previous studies indicating that clinical congestion at the time of discharge is one of the strongest predictors of adverse outcomes in acute decompensated heart failure. Because clinical signs of congestion do not reliably correlate with filling pressures, the use of additional diagnostic tools is essential to optimize predischarge assessment. Although multiple clinical, laboratory, and echocardiographic variables were associated with rehospitalization, these analyses were performed to contextualize and benchmark the prognostic value of B-lines relative to established markers of congestion and disease severity, rather than to shift the study's primary focus away from LUS. Among all evaluated parameters, B-line quantification demonstrated the most robust and consistent discriminatory performance.[6]

B-lines represent vertical hyperechoic artifacts originating from the pleural line that move synchronously with lung sliding and obscure A-lines, reflecting increased subpleural lung density due to the replacement of air with fluid, collagen, or inflammatory material. Their presence indicates a disturbance in the alveolar-capillary interface and an increase in extravascular lung water.[8] B-lines are considered significant when three or more are visualized between two rib spaces and typically diminish with appropriate management of pulmonary congestion or heart failure.

The present study found a significantly higher number of B-lines in patients rehospitalized within 90 days compared with those not rehospitalized. This supports earlier findings by Rattarasarn et al.,[6] who reported that more than half of hospitalized heart failure patients continued to exhibit residual congestion at predischarge. Their study showed that a B-line count >12 across eight lung zones independently predicted 6-month rehospitalization.[6] Similarly, Gargani et al.,[9] demonstrated that B-line quantification at predischarge is clinically meaningful, with cut-off values >15 and >20 providing optimal accuracy for predicting readmission within 3 and 6 months, respectively.[9] The current study's B-line cut-off of 20 yielded an accuracy of 72.5%, sensitivity of 78.43%, specificity of 68.12%, and an AUC of 72.19%, indicating good discriminatory capability.

Understanding the pulmonary congestion cascade further explains these findings. The process begins with increased left ventricular end-diastolic pressure and elevated PCWP, leading to hemodynamic congestion, which precedes interstitial fluid accumulation and eventually pulmonary edema. The intermediate-stage interstitial pulmonary congestion can be detected by pulmonary ultrasound via B-line visualization before overt symptoms appear.10 In this study, higher PCWP estimates based on E/e' and higher B-line counts were both associated with increased rehospitalization risk, underscoring their role as sensitive markers of congestion.

The EVEREST and ESCAPE trials further support the prognostic significance of congestion markers. The EVEREST trial demonstrated that the presence of significant B-lines was the only independent predictor of heart failure events and 6-month mortality in a multivariate analysis.[3] The ESCAPE trial also emphasized the importance of congestion-related parameters, showing that a substantial proportion of patients developed pulmonary congestion due to elevated left ventricular filling pressures, detectable through B-line assessment.[11]

Renal dysfunction also played a significant role in the risk of rehospitalization in this study. Impaired renal function, reflected by elevated creatinine and reduced eGFR, is a well-established predictor of poor outcomes in heart failure. Rather than acting independently, renal impairment appears to potentiate the prognostic significance of residual pulmonary congestion detected by LUS. A prior study reported increased mortality among patients with eGFR <60 mL/min/1.73 m².[12] Another study also showed that patients with eGFR <45 mL/min/1.73 m² had higher rehospitalization rates.[13] Consistent with these findings, this study identified meaningful cut-off values for creatinine (1.21 mg/dL) and eGFR (66 mL/min/1.73 m²), both of which showed moderate diagnostic accuracy and were significantly associated with rehospitalization. The higher prevalence of CKD in the rehospitalization group reinforces the interplay between renal dysfunction and volume regulation in heart failure.

Importantly, combining multiple significant predictors, including B-line ≥20, reduced EF, impaired renal function, estimated PCWP, and comorbid IHD and CKD, markedly improved the CART model's predictive performance of rehospitalization. This model achieved an accuracy of 90.65%, sensitivity of 98.31%, specificity of 81.25%, and an AUC of 96.66%, demonstrating the advantage of multimodal risk stratification. These results support the growing body of evidence, including the CLUSTER-HF Trial, which showed that LUS-guided management reduces clinical deterioration, rehospitalization, mortality, and NT-proBNP levels, while improving quality of life.[11]

Although the CART analysis demonstrated excellent predictive performance when combining B-lines with renal and echocardiographic parameters, this approach should be interpreted as exploratory. The study was not designed to develop or validate a formal risk stratification model, and such integration is presented to illustrate how LUS may complement conventional assessment in clinical practice. Larger prospective studies are required before such models can be routinely applied. Additionally, B-lines are not specific to heart failure and may be present in other interstitial pulmonary conditions, including fibrosis, pneumonia, and ARDS. However, in patients with established heart failure, especially those with persistent congestion, this limitation becomes less clinically significant.

Conclusion

Predischarge LUS B-line assessment is a strong and clinically relevant predictor of 90-day cardiovascular rehospitalization in patients with HFrEF. A B-line count ≥20 identifies patients with significant residual pulmonary congestion who are at substantially higher risk of early readmission. These findings support the integration of LUS into routine predischarge assessment to improve risk stratification, guide therapy optimization, and potentially reduce rehospitalization rates.

List of Abbreviations

ACEi	Angiotensin-Converting Enzyme Inhibitor
ARB	Angiotensin Receptor Blocker
ARNI	Angiotensin Receptor–Neprilysin Inhibitor
CART	Classification and Regression Tree
CKD	Chronic Kidney Disease
COPD	Chronic Obstructive Pulmonary Disease
EF	Ejection Fraction
eGFR	Estimated Glomerular Filtration Rate
E/e'	Early Mitral Inflow Velocity to Early Diastolic Mitral Annular Velocity Ratio
HFrEF	Heart Failure with reduced Ejection Fraction
IHD	Ischemic Heart Disease
LUS	Lung Ultrasound
NA	Not Available
NT-proBNP	N-terminal Pro-B-type Natriuretic Peptide
PCWP	Pulmonary Capillary Wedge Pressure
ROC	Receiver Operating Characteristic
SGLT2	Sodium–Glucose Cotransporter-2

Ethical Clearance

Approval for this study was granted by the Research Ethics Committee of the Faculty of Medicine, Universitas Hasanuddin (Reference No. 1032/UN4.6.4.5.31/PP36/2024). All research procedures adhered to the principles of the Declaration of Helsinki and complied with national and institutional ethical guidelines.

Publication Approval

Institutional approval for publication has been obtained.

Authors Contributions

AFM: Conceptualization, Methodology, Investigation, Writing- Original Draft preparation; YP: Conceptualization, Methodology, Investigation, Resources, Validation, Writing- Original Draft preparation, Writing - Review & Editing, Supervision; PK: Conceptualization, Methodology, Investigation, Resources, Validation, Writing-Original Draft preparation, Writing - Review & Editing, Supervision; AAM: Validation, Writing - Review & Editing, Supervision. All authors read and approved the final version of the manuscript.

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Conflict of Interest

The authors declare that they have no conflict of interest.

Availability of Data and Materials

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Generative AI and AI-Assisted Technologies in the Writing Process

The authors declare that no generative AI or AI-assisted technologies were used in writing this manuscript. All content was produced entirely by the authors.

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