International Journal of General Medicine

Dovepress
Taylor & Francis Group

Open Access Full Text Article

ORIGINAL RESEARCH

Composite Ultrasound Score Integrating VExUS Grading and Right Ventricular Function for Predicting 90-Day Heart Failure Rehospitalization: A Single-Center Retrospective Cohort Study

Hui Tang[1]*, Lihua Teng[2,]*, Xiurong Xing[1], Qiuli Niu[1], Yawei Guo[1], Xiaohui Zhu[1], Zhi Liu[1]

[1]Department of Emergency, Xuanwu Hospital of Capital Medical University, Beijing, People's Republic of China; [2]Department of Emergency, Beijing Tiantan Hospital, Capital Medical University, Beijing, People's Republic of China

*These authors contributed equally to this work

Correspondence: Hui Tang, Department of Emergency, Xuanwu Hospital of Capital Medical University, No. 45, Changchun Street, Xicheng District, Beijing, 100053, People's Republic of China, Email huitang@xwh.ccmu.edu.cn

Purpose: Systemic venous congestion and right ventricular (RV) dysfunction are important determinants of adverse outcomes in heart failure (HF). This study evaluated the prognostic value of a Composite Ultrasound Score integrating Venous Excess Ultrasound (VExUS) grading and multiparametric RV systolic function for predicting 90-day HF rehospitalization.

Patients and Methods: This single-center retrospective cohort study included 712 patients hospitalized for HF who underwent pre-discharge echocardiographic assessment. The Composite Ultrasound Score ranged from 0 to 3 and combined VExUS-derived venous congestion with RV systolic dysfunction defined by TAPSE, RV S', and RV fractional area change. The primary endpoint was 90-day HF rehospitalization. Predictive performance was assessed using Cox regression, Harrell's C-index, time-dependent receiver operating characteristic analysis, and decision curve analysis.

Results: During follow-up, 154 patients (21.6%) were rehospitalized. The Composite Ultrasound Score showed higher discrimination (C-index: 0.79; 95% CI: 0.75–0.83) than VExUS grading alone (0.74; $P = 0.012$), NT-proBNP (0.71; $P < 0.001$), or individual RV parameters. A score ≥2 identified a high-risk group with a 90-day event rate of 50.0% versus 8.3% in the low-risk group (log-rank $P < 0.001$). A high score remained independently associated with rehospitalization (adjusted HR: 2.85; 95% CI: 1.95–4.16; $P < 0.001$). The association was stronger in patients with chronic kidney disease (P for interaction = 0.038). Decision curve analysis suggested greater net benefit than single-parameter strategies.

Conclusion: The Composite Ultrasound Score was independently associated with 90-day HF rehospitalization and showed moderate incremental prognostic value in this single-center retrospective cohort. It may serve as a promising adjunctive tool for pre-discharge risk stratification, particularly in patients with cardiorenal vulnerability. Prospective multicenter validation is required before routine clinical implementation.

Plain Language Summary:

Why was this Study Done?

Heart failure often leads to fluid buildup and hospital readmissions. Standard predictors like blood tests (e.g. NT-proBNP) can be inaccurate, particularly in patients with kidney problems. We investigated if combining two ultrasound markers—venous congestion (VExUS score) and right heart function—could better predict the risk of readmission.

What did the Researchers Do?

We reviewed medical records of 712 hospitalized heart failure patients who underwent ultrasound before discharge. We developed a "Composite Ultrasound Score" (ranging from 0 to 3) that integrated the severity of fluid congestion with right heart pump function. We tracked 90-day readmission rates and compared the new score's accuracy against standard blood tests and individual ultrasound parameters.

https://doi.org/10.2147/IJGM.S601864
Received: 23 February 2026
Accepted: 12 May 2026
Published: 9 June 2026

What did the Researchers Find?

The Composite Score predicted readmissions significantly better than standard tools. Patients with a high score (≥2) faced a 50% risk of returning to the hospital within 90 days, compared to only 8.3% for those with a low score. Notably, the score remained highly accurate for patients with kidney disease, confirming that assessing both "pressure" (congestion) and "pump" (function) together is superior to single measures.

What do these Results Mean?

This composite score offers a simple, non-invasive tool to identify high-risk patients before discharge. It allows doctors to target intensive monitoring and treatment toward those most likely to relapse, helping prevent unnecessary hospital returns and improving patient outcomes.

Keywords: heart failure, venous excess ultrasound, VExUS, right ventricular function, patient readmission, cardiorenal syndrome

Introduction

Heart failure (HF) represents a growing global health burden, characterized by debilitating symptoms, frequent hospitalizations, and substantial mortality.[1] Despite advances in guideline-directed therapy, hospital readmission after HF hospitalization remains common, particularly during the early post-discharge period.[2] This persistent readmission burden highlights the need for accurate, accessible, and bedside-applicable tools to identify patients at high risk of early decompensation after discharge.

For decades, risk assessment in HF has relied heavily on clinical evaluation and natriuretic peptides, particularly N-terminal pro-B-type natriuretic peptide (NT-proBNP). Although NT-proBNP is clinically useful, its prognostic interpretation can be influenced by several non-cardiac factors, including age, body mass index, atrial fibrillation, and especially renal function.[3,4] Existing HF risk prediction models commonly integrate demographic characteristics, comorbidities, laboratory variables, and conventional echocardiographic parameters; however, many do not directly capture end-organ venous congestion or the interaction between congestion burden and right-sided pump function at the bedside.[3] These limitations have prompted interest in complementary physiological markers that more directly reflect hemodynamic status and residual congestion before discharge.

Increasing attention has focused on congestion-driven HF phenotypes, in which systemic venous congestion and right ventricular (RV) dysfunction contribute to recurrent decompensation and adverse outcomes.[4,5] These mechanisms are not limited to reduced ejection fraction; they are also relevant in HF with preserved ejection fraction and in cardiorenal syndrome, where elevated filling pressures, impaired venous capacitance, and right-sided dysfunction may worsen renal perfusion and promote rehospitalization.[4,6] The Venous Excess Ultrasound (VExUS) score has emerged as a non-invasive point-of-care ultrasound protocol to quantify systemic venous congestion by assessing inferior vena cava diameter and Doppler flow patterns in the hepatic, portal, and intrarenal veins.[7,8] Simultaneously, the prognostic importance of RV systolic function is well established, with echocardiographic parameters such as tricuspid annular plane systolic excursion (TAPSE) providing clinically useful information on morbidity and mortality across HF populations.[9]

Although recent studies have evaluated the prognostic value of VExUS-related congestion assessment and RV dysfunction separately, these interconnected components are rarely incorporated into a simple integrated ultrasound-based model for short-term post-discharge risk stratification in HF.[5,7,9] A given degree of venous congestion may carry different prognostic implications depending on the patient's right-sided pump reserve. Therefore, a specific research gap remains: few studies have developed a bedside-applicable score that integrates end-organ venous Doppler congestion with multiparametric RV systolic function to predict early HF rehospitalization. We hypothesized that combining these "congestion" and "cardiac function" domains could provide more integrated risk estimation than either domain alone. This study aimed to develop and internally evaluate a Composite Ultrasound Score integrating VExUS grading and multiparametric RV systolic function, and to determine its independent and incremental prognostic value for predicting 90-day HF rehospitalization after discharge.

Materials and Methods

Study Design

This single-center, retrospective cohort study was conducted by interrogating the electronic health record (EHR) database of a large, tertiary academic medical center in China. We identified all adult patients (aged ≥18 years) who were hospitalized with a primary discharge diagnosis of heart failure (HF) between January 1, 2022, and December 31, 2024. The study protocol was formally approved by the Institutional Review Board (IRB) of Xuanwu Hospital of Capital Medical University (IRB-REV-2024101). In accordance with national and international guidelines, a waiver for individual patient informed consent was granted by the IRB, owing to the retrospective nature of the analysis, the use of fully de-identified data, and the determination that the research posed no more than minimal risk to subjects. This investigation conformed to the ethical principles outlined in the Declaration of Helsinki, and all patient data were managed with strict adherence to confidentiality and privacy protection protocols.

Study Population

The potential study cohort was identified through a systematic query of the institutional EHR database using International Classification of Diseases, Tenth Revision (ICD-10) codes for heart failure (I50.x). A multi-stage screening and validation process was employed to ensure accurate patient selection. First, an automated algorithm filtered for all hospitalizations meeting the broad initial criteria (age ≥18 years, primary HF discharge diagnosis). Subsequently, two trained physicians, working independently, manually reviewed the complete electronic medical records of these potential candidates to meticulously apply the detailed inclusion and exclusion criteria. Any discrepancies in eligibility assessment were resolved by consensus or, if necessary, by the adjudication of a senior cardiologist with expertise in echocardiography.

To be included in the final analytical cohort, patients had to meet all of the following criteria: (1) a confirmed diagnosis of HF as defined by the 2021 European Society of Cardiology (ESC) guidelines, requiring the presence of relevant symptoms and/or signs and objective evidence of cardiac dysfunction;[10] (2) age of 18 years or older at the time of hospitalization; (3) underwent a comprehensive inpatient transthoracic echocardiographic assessment, including complete right heart evaluation and archived Doppler images required for the Venous Excess Ultrasound (VExUS) score, as originally described.[7] Hepatic, portal, and intrarenal venous Doppler acquisitions were not assumed to be components of conventional TTE; rather, since January 2022, these acquisitions have been incorporated into our institutional "Heart Failure Decongestion" point-of-care ultrasound pathway for primary HF admissions before discharge. Therefore, eligibility for the present retrospective analysis required the availability of complete and interpretable hepatic, portal, and intrarenal venous Doppler waveforms in the archived imaging records; and (4) had sufficiently complete baseline clinical data and follow-up information regarding the primary endpoint. Patients were excluded if any of the following conditions were present: (1) end-stage kidney disease (ESKD) requiring chronic renal replacement therapy (hemodialysis or peritoneal dialysis) at the time of admission, consistent with definitions from the KDIGO guidelines;[11] (2) presence of severe primary valvular heart disease as defined by the 2021 ESC/EACTS guidelines, any uncorrected hemodynamically significant congenital heart disease, or specific cardiomyopathies such as hypertrophic, restrictive, or arrhythmogenic cardiomyopathy known to primarily alter diastolic function or right heart dynamics independent of volume status;[12,13] (3) the index hospitalization was precipitated by an acute coronary syndrome (ACS), according to the Fourth Universal Definition of Myocardial Infarction;[14] (4) suboptimal quality of TTE or Doppler images that precluded accurate and reproducible measurement of one or more key parameters for right heart function or VExUS grading; (5) concurrent medical conditions known to independently confound systemic venous hemodynamics, including decompensated liver cirrhosis with moderate-to-severe ascites, Budd-Chiari syndrome, or known significant external compression of the inferior vena cava or hepatic veins; or (6) presence of a terminal non-cardiac illness (eg, metastatic malignancy) with an expected lifespan of less than 90 days, which would preclude meaningful assessment of the primary endpoint.

Sample Size Calculation

The sample size for this study was determined a priori based on the events per variable (EPV) principle, a widely accepted methodology for developing clinical prediction models to minimize the risk of model overfitting and ensure the stability of the regression coefficients.[15] The primary endpoint for this calculation was the 90-day incidence of HF-related

rehospitalization. Based on a large, contemporary real-world cohort study which reported a 90-day HF-related readmission rate of 21.0%,[2] we conservatively estimated an event rate of 20% for our study population. To construct a robust and generalizable predictive model, we aimed for a high standard of at least 15 to 20 EPV. Our proposed composite ultrasound scoring system is anticipated to incorporate approximately six core predictor variables (eg, VExUS grade, tricuspid annular plane systolic excursion [TAPSE], right ventricular S', and right ventricular fractional area change [FAC]). Therefore, to achieve an EPV of 20, a minimum of 120 outcome events (ie., 20 events × 6 variables) would be required. This dictated an initial sample size of 600 patients (120 events/0.20 expected event rate). To account for potential incomplete data inherent in retrospective study designs and to enhance overall statistical power, the sample size was further increased by 15%. This resulted in a final target enrollment of approximately 700 patients.

Outcomes and Data Collection

Study outcomes were adjudicated by two independent cardiologists blinded to the baseline echocardiographic data by reviewing EHR discharge summaries, outpatient follow-up notes, and records from subsequent hospitalizations. The primary endpoint was the first rehospitalization for HF within 90 days of discharge, defined as an unplanned admission with a primary diagnosis of HF, requiring intravenous diuretic therapy or equivalent advanced HF treatment, consistent with standardized cardiovascular endpoint definitions.[16] Secondary endpoints included all-cause mortality within 180 days and a composite of all-cause mortality or first HF rehospitalization within 90 days. Endpoint-related data were primarily sourced from the institutional EHR, supplemented by structured telephone interviews with patients or their families if necessary to confirm vital status or hospital admission details at external facilities.

All clinical data were extracted retrospectively from the EHR by two trained researchers using a pre-specified electronic case report form. The dataset included baseline demographics (age, sex, body mass index), New York Heart Association (NYHA) functional class,[17] relevant comorbidities (hypertension, diabetes mellitus, coronary artery disease, atrial fibrillation, chronic obstructive pulmonary disease), and laboratory values obtained at index admission, including complete blood count, a comprehensive metabolic panel with creatinine, and N-terminal pro-B-type natriuretic peptide (NT-proBNP). Chronic kidney disease (CKD) was staged based on the estimated glomerular filtration rate (eGFR) according to the 2024 KDIGO guidelines.[11] Pharmacotherapy data, including the prescription and dosage of key HF medications at discharge (ie., angiotensin-converting enzyme inhibitors/angiotensin receptor blockers/angiotensin receptor-neprilysin inhibitors, beta-blockers, mineralocorticoid receptor antagonists, and sodium-glucose cotransporter-2 inhibitors), were also meticulously recorded.All pre-discharge echocardiographic examinations, including the right heart assessment and VExUS-related Doppler acquisitions, were performed within 48 hours before the actual hospital discharge by certified sonographers using commercially available high-end ultrasound systems (LOGIQ E9, General Electric). This time window was selected to reflect the patient's hemodynamic and congestion status after inpatient stabilization and immediately before transition to outpatient care. All measurements were re-analyzed offline by two independent, experienced cardiologists blinded to all clinical and outcome data, with discrepancies resolved by a third senior echocardiographer. Left ventricular ejection fraction (LVEF) and the ratio of early transmitral inflow velocity to early diastolic mitral annular velocity (E/e') were measured to assess left ventricular systolic and diastolic function, respectively. Right heart systolic function was quantified by TAPSE, tissue Doppler-derived tricuspid lateral annular systolic velocity (RV S'), and right ventricular fractional area change (FAC), with measurements performed according to published recommendations.[18] The VExUS score was assessed as originally described,[7] by integrating the diameter of the inferior vena cava with the Doppler flow patterns of the hepatic, portal, and intrarenal veins to generate a grade from 0 (no congestion) to 3 (severe congestion).

A novel composite ultrasound score was constructed to integrate measures of systemic venous congestion and cardiac pump function. This score was calculated by summing points from two discrete components: a VExUS-derived congestion score and a right ventricular dysfunction score. Points for the VExUS component were allocated based on the severity of congestion: 0 points were assigned for VExUS grades 0 and 1, 1 point for VExUS grade 2, and 2 points for VExUS grade 3. The right ventricular dysfunction component was a binary variable, adding 1 point to the total score if at least two of the following three pre-specified criteria were met: (1) TAPSE < 17 mm, (2) RV S' < 9.5 cm/s, or (3) FAC < 35%, based on established guideline-recommended cutoffs.[19] By combining these two components, the final composite ultrasound score

yielded an ordinal scale ranging from 0 to 3, designed to provide a tiered assessment of integrated cardiorenal and hemodynamic risk. The score was intentionally constructed using predefined, guideline-based thresholds and simple point allocation rather than regression coefficient-derived weighting. This approach was chosen to preserve bedside usability, clinical interpretability, and applicability in point-of-care settings, while reducing the risk of sample-specific overfitting in this single-center retrospective cohort.

Data Quality Control and Management of Missing Data

To ensure the accuracy and reliability of the data, a rigorous, multi-tiered validation protocol was implemented. Initial data extraction from the EHR was performed using structured queries with built-in automated range and logical consistency checks. Subsequently, a random patient-level sample comprising 15% of the final cohort underwent independent manual re-abstraction and imaging review by two trained cardiologists with experience in echocardiography and point-of-care ultrasound, both of whom were blinded to patient outcomes. This validation process specifically targeted the primary outcome classification and key echocardiographic predictor variables, including the individual components of the VExUS score and right ventricular functional metrics. Inter-rater reliability was formally assessed using Cohen's Kappa for categorical variables, including VExUS grade, and intraclass correlation coefficients for continuous variables, including TAPSE, RV S', and FAC. Any discrepancies identified were resolved by a senior attending cardiologist.

Recognizing that missing data is an inherent challenge in retrospective research, a systematic approach was employed for its management. The patterns and proportions of missingness were thoroughly examined for all variables. For variables included in the multivariable models and key echocardiographic predictors with missing data, multiple imputation by chained equations (MICE) was performed under the missing-at-random assumption. Missingness was mainly observed for baseline NT-proBNP (6.5%) and quantitative right ventricular parameters (4.2%), whereas the variables required to define the Composite Ultrasound Score were complete and interpretable in all included patients by design. The imputation model included baseline demographic and clinical variables, laboratory indicators, echocardiographic parameters, the event indicator, and the Nelson-Aalen estimate of the cumulative baseline hazard to preserve the relationship between covariates and time-to-event outcomes during imputation. Ten imputed datasets were generated, allowing for the uncertainty associated with imputation to be incorporated into the analysis. All subsequent multivariable Cox regression analyses were performed on each imputed dataset, and the final parameter estimates, hazard ratios, and confidence intervals were pooled according to Rubin's rules.

Statistical Analysis

All statistical analyses were performed using R software, version 4.5.1 (R Foundation for Statistical Computing). Continuous variables were assessed for normality using the Shapiro–Wilk test and are presented as mean ± standard deviation (SD) or median [interquartile range, IQR], compared using the independent samples *t*-test or Mann–Whitney *U*-test, as appropriate. Categorical variables are reported as counts (n) and percentages (%), compared using the chi-square test or Fisher's exact test. The primary analysis for the time-to-event endpoint of 90-day HF rehospitalization was conducted using a Cox proportional hazards regression model. The primary predictor of interest was the pre-specified Composite Ultrasound Score, treated as an ordinal variable. To assess its independent predictive value, a multivariable Cox model was constructed using forced entry of pre-specified covariates. Candidate adjustment variables were selected a priori based on clinical relevance, established associations with HF readmission, and the available number of outcome events, rather than by automated stepwise procedures. The final adjustment set included age, sex, LVEF, baseline NT-proBNP, eGFR, and history of atrial fibrillation. Individual components of the Composite Ultrasound Score, including VExUS grade and right ventricular functional indices, were not simultaneously entered into the same adjusted model to avoid collinearity and overadjustment. With 154 primary outcome events and seven model variables, including the Composite Ultrasound Score and six pre-specified adjustment covariates, the primary adjusted model retained an events-per-variable ratio of approximately 22, which was considered adequate to reduce the risk of overfitting. The proportional hazards assumption was verified for all models by testing the scaled Schoenfeld residuals. All multivariable analyses

were performed independently on each of the 10 imputed datasets, with the final parameter estimates, hazard ratios, and 95% confidence intervals pooled according to Rubin's rules.

The model's discriminative performance was evaluated using Harrell's concordance index (C-index). Comparisons between the C-indices of the Composite Ultrasound Score and other predictors were performed using bootstrap resampling with 1000 replications to determine statistical significance. Internal validation of the primary Cox model was further performed using bootstrap resampling with 1000 repetitions. Model discrimination was reassessed in each bootstrap sample, and the optimism-corrected Harrell's C-index was calculated to estimate the degree of potential overfitting. To specifically assess the diagnostic accuracy at the 90-day horizon, time-dependent Receiver Operating Characteristic (ROC) curve analysis was conducted. The area under the curve (AUC), sensitivity, and specificity were calculated. Risk strata were defined based on an optimal cut-off value of the Composite Ultrasound Score, determined by maximizing Youden's index (sensitivity + specificity - 1) from the time-dependent ROC curve. Calibration was assessed at the 90-day time point by plotting the predicted probabilities derived from the Cox model against the observed event rates. The goodness-of-fit for the Cox model was formally evaluated using the Grønnesby-Borgan test. The clinical utility was quantified using decision curve analysis (DCA) at the 90-day time point. Kaplan-Meier curves were plotted to visualize event-free survival across risk strata defined by the Composite Ultrasound Score, with differences assessed by the Log rank test. Pre-specified subgroup analyses were performed to assess the consistency of the prognostic value across clinically relevant subpopulations defined by the following cut-points: age (< 75 vs. ≥ 75 years), body mass index (< 25 vs. ≥ 25 kg/m^2), LVEF (< 50% vs. ≥ 50%), and chronic kidney disease (eGFR < 60 mL/min/1.73m^2). For these analyses, interaction terms between the composite score and the grouping variable were included in the Cox models to formally test for effect modification. Sensitivity analyses were also conducted within the Cox regression framework to assess the robustness of the findings. All statistical tests were two-sided, with a P-value < 0.05 considered statistically significant.

Results

Baseline Characteristics

The patient selection process is illustrated in Figure 1. A total of 712 patients meeting the inclusion criteria were analyzed. During the 90-day follow-up, 154 patients (21.6%) were rehospitalized for heart failure. Baseline characteristics stratified by readmission status are presented in Table 1. Compared with the non-readmission group, patients who experienced the primary endpoint were significantly older and had a higher prevalence of atrial fibrillation and chronic kidney disease ($p < 0.001$ for all). Clinically, the readmission cohort presented with more severe symptom burden, evidenced by a higher proportion of NYHA functional class III/IV (63.0% vs. 35.1%, $p < 0.001$), alongside significantly elevated NT-proBNP levels and reduced eGFR. Echocardiographic assessment revealed that readmitted patients not only had worse right ventricular systolic function (lower TAPSE, RV S', and FAC) and more severe systemic congestion (higher VExUS grades) but also exhibited higher left ventricular filling pressures, as indicated by a significantly elevated E/e' ratio (17.1 ± 5.6 vs. 14.2 ± 4.9, $p < 0.001$). Consequently, the novel Composite Ultrasound Score was significantly higher in the readmission group ($p < 0.001$). There were no significant between-group differences in the prescription rates of core guideline-directed medical therapies at discharge, including ACEI/ARB/ARNI, beta-blockers, MRA, and SGLT2 inhibitors. However, loop diuretics were more frequently prescribed in patients who experienced readmission. Furthermore, in the 15% random sample cohort (n = 107) utilized for rigorous quality control, inter-observer agreement was confirmed to be excellent. The Cohen's Kappa coefficient for the VExUS grade assignment between the two independent cardiologists was 0.88 (95% CI: 0.82–0.94). Similarly, the intraclass correlation coefficients (ICC) for the quantitative right ventricular parameters were 0.94 for TAPSE, 0.92 for RV S', and 0.91 for FAC.

Predictors of Heart Failure Readmission

To identify factors associated with the 90-day risk of HF rehospitalization, univariable and multivariable Cox proportional hazards regression analyses were performed (Table 2). In the univariable analysis, traditional prognostic markers, including older age, history of atrial fibrillation, lower eGFR, and elevated log-transformed NT-proBNP, were

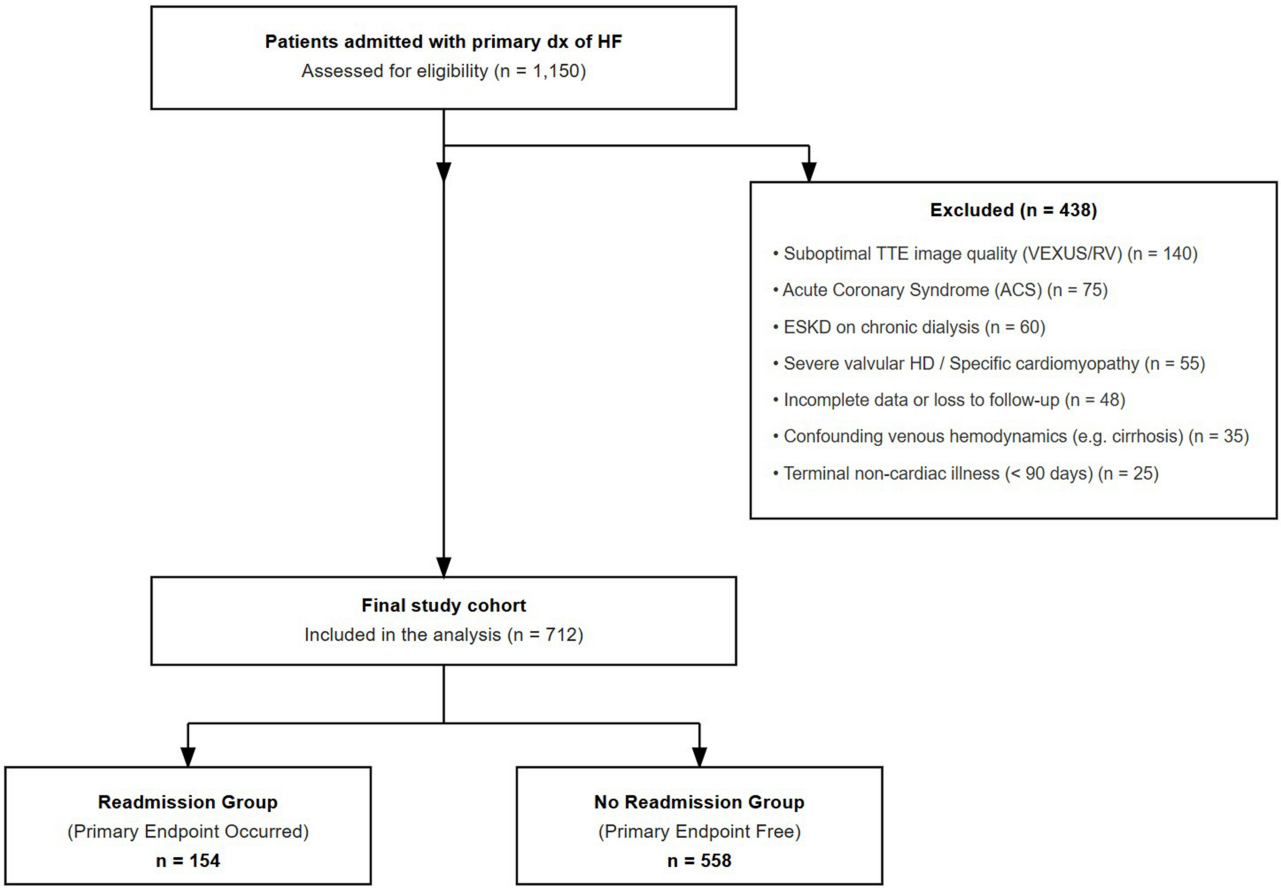

Figure 1 Study flowchart. Flowchart showing patient screening, exclusion, and final cohort construction. A total of 712 patients were included in the final analysis.

significantly associated with an increased hazard of readmission. Echocardiographic parameters reflecting left ventricular filling pressure (E/e' ratio), right ventricular dysfunction (lower TAPSE, RV S', and FAC), and systemic congestion (higher VExUS grade) were also identified as significant predictors. Notably, the novel Composite Ultrasound Score demonstrated a strong, graded association with the primary endpoint, with an unadjusted HR of 1.82 (95% CI: 1.61–2.06) per 1-point increase.To determine the independent predictive value of the Composite Ultrasound Score, a multivariable Cox regression model was constructed, adjusting for clinically relevant confounders established a priori (age, sex, LVEF, baseline NT-proBNP, eGFR, and history of atrial fibrillation). In this adjusted model, the Composite Ultrasound Score remained a statistically significant independent predictor of 90-day HF rehospitalization (adjusted HR: 1.48; 95% CI: 1.24–1.76; $p < 0.001$). Among the covariates, NT-proBNP and eGFR also retained independent prognostic significance, whereas LVEF did not reach statistical significance in the presence of these hemodynamic and renal markers.

Predictive Performance and Optimal Threshold Analysis

The discriminative ability of the Composite Ultrasound Score to predict heart failure rehospitalization was rigorously evaluated. As illustrated in Figure 2A, the Composite Ultrasound Score demonstrated superior overall performance with an apparent Harrell's C-index of 0.79 (95% CI: 0.75–0.83). Bootstrap internal validation with 1000 resamples showed limited optimism in discrimination, with an optimism estimate of 0.015 and an optimism-corrected Harrell's C-index of 0.78. This was higher than that of the VExUS score alone (C-index: 0.74, $P = 0.012$), Log10 NT-proBNP (C-index: 0.71, $P < 0.001$), and traditional right ventricular functional parameters ($P < 0.001$ for all comparisons shown in Table 3).

To further characterize the diagnostic accuracy at the primary endpoint, a time-dependent ROC curve analysis was performed for the 90-day horizon (Figure 2B). The area AUC at 90 days for the Composite Ultrasound Score was 0.81 (95% CI: 0.76–0.85). The optimal cutoff value, determined by maximizing the Youden index (Sensitivity + Specificity - 1), was

https://doi.org/10.2147/IJGM.S601864

Table 1 Baseline Clinical Characteristics and Echocardiographic Parameters Stratified by 90-Day HF Rehospitalization Status

Variable	Total (N = 712)	No Readmission (n = 558)	Readmission (n = 154)	Test Statistic	P-value
Demographics					
Age, years	70.1 ± 10.2	69.1 ± 10.5	73.4 ± 8.2	t = −5.02	< 0.001
Male sex, n (%)	406 (57.0)	321 (57.5)	85 (55.2)	χ^2 = 0.26	0.612
BMI, kg/m^2	26.4 ± 4.1	26.5 ± 4.0	25.9 ± 4.3	t = 1.58	0.114
Clinical Status					
NYHA Class III/IV, n (%)	293 (41.2)	196 (35.1)	97 (63.0)	χ^2 = 39.85	< 0.001
Comorbidities, n (%)					
Hypertension	491 (69.0)	382 (68.5)	109 (70.8)	χ^2 = 0.30	0.584
Diabetes Mellitus	242 (34.0)	181 (32.4)	61 (39.6)	χ^2 = 2.78	0.095
Coronary Artery Disease	306 (43.0)	234 (41.9)	72 (46.8)	χ^2 = 1.15	0.284
Atrial Fibrillation	272 (38.2)	193 (34.6)	79 (51.3)	χ^2 = 14.21	< 0.001
COPD	98 (13.8)	74 (13.3)	24 (15.6)	χ^2 = 0.54	0.463
CKD (Stage ≥3)	254 (35.7)	180 (32.3)	74 (48.1)	χ^2 = 13.04	< 0.001
Laboratory Findings					
Hemoglobin, g/L	128 ± 18	130 ± 17	124 ± 19	t = 3.65	< 0.001
Serum Sodium, mmol/L	138.2 ± 3.5	138.6 ± 3.4	136.8 ± 3.7	t = 5.62	< 0.001
Creatinine, μmol/L	105 [82–134]	98 [78–122]	128 [95–168]	Z = −6.84	< 0.001
eGFR, mL/min/1.73m^2	59.3 ± 19.2	62.4 ± 18.9	48.2 ± 15.6	t = 8.45	< 0.001
NT-proBNP, pg/mL	2250 [1100–4500]	1890 [980–3450]	4250 [2100–7890]	Z = −11.23	< 0.001
Echocardiography					
LVEF, %	39.5 ± 11.2	40.8 ± 10.9	34.9 ± 11.5	t = 5.82	< 0.001
E/e' ratio	14.8 ± 5.2	14.2 ± 4.9	17.1 ± 5.6	t = −6.04	< 0.001
TAPSE, mm	18.1 ± 4.4	18.9 ± 4.2	15.4 ± 3.8	t = 9.15	< 0.001
RV S', cm/s	10.8 ± 2.5	11.2 ± 2.4	9.1 ± 2.0	t = 9.78	< 0.001
RV FAC, %	36.8 ± 8.5	38.4 ± 8.1	31.2 ± 7.5	t = 9.92	< 0.001
IVC Diameter, mm	20.4 ± 5.1	19.2 ± 4.8	24.5 ± 3.9	t = −12.45	< 0.001
VExUS Grade, n (%)				χ^2 = 76.54	< 0.001
Grade 0	285 (40.0)	260 (46.6)	25 (16.2)		
Grade 1	210 (29.5)	180 (32.3)	30 (19.5)		
Grade 2	122 (17.1)	72 (12.9)	50 (32.5)		
Grade 3	95 (13.3)	46 (8.2)	49 (31.8)		
Composite Ultrasound Score				χ^2 = 112.40	< 0.001
Score 0	256 (36.0)	242 (43.4)	14 (9.1)		
Score 1	228 (32.0)	202 (36.2)	26 (16.9)		
Score 2	135 (19.0)	88 (15.8)	47 (30.5)		
Score 3	93 (13.1)	26 (4.7)	67 (43.5)		
Medication at Discharge					
ACEI/ARB/ARNI	562 (78.9)	446 (79.9)	116 (75.3)	χ^2 = 1.56	0.212
Beta-blockers	615 (86.4)	485 (86.9)	130 (84.4)	χ^2 = 0.65	0.419
MRA	480 (67.4)	374 (67.0)	106 (68.8)	χ^2 = 0.18	0.671
SGLT2i	455 (63.9)	362 (64.9)	93 (60.4)	χ^2 = 1.05	0.305
Loop Diuretics	640 (89.9)	490 (87.8)	150 (97.4)	χ^2 = 11.85	< 0.001

Notes: Values are presented as mean ± SD, median [IQR], or n (%). P-values were calculated using the independent samples *t*-test, Mann–Whitney *U*-test, or Chi-square test as appropriate.

Abbreviations: BMI, body mass index; NYHA, New York Heart Association; COPD, chronic obstructive pulmonary disease; CKD, chronic kidney disease; eGFR, estimated glomerular filtration rate; NT-proBNP, N-terminal pro-B-type natriuretic peptide; LVEF, left ventricular ejection fraction; E/e', ratio of early transmitral inflow velocity to early diastolic mitral annular velocity; TAPSE, tricuspid annular plane systolic excursion; RV S', tricuspid lateral annular systolic velocity; FAC, fractional area change; IVC, inferior vena cava; VExUS, venous excess ultrasound; ACEI, angiotensin-converting enzyme inhibitor; ARB, angiotensin receptor blocker; ARNI, angiotensin receptor-neprilysin inhibitor; MRA, mineralocorticoid receptor antagonist; SGLT2i, sodium-glucose cotransporter-2 inhibitor.

Table 2 Univariable and Multivariable Cox Proportional Hazards Analysis for 90-Day Heart Failure Rehospitalization

Variable	Univariable Analysis		Multivariable Analysis	
	HR (95% CI)	P-value	HR (95% CI)	P-value
Composite Ultrasound Score (per 1-point increase)	1.82 (1.61–2.06)	< 0.001	1.48 (1.24–1.76)	< 0.001
Age (per 10 years)	1.35 (1.18–1.54)	< 0.001	1.12 (0.96–1.31)	0.152
Male Sex (vs. Female)	1.08 (0.78–1.49)	0.645	1.05 (0.75–1.46)	0.782
Atrial Fibrillation (Yes vs. No)	1.68 (1.22–2.31)	0.002	1.15 (0.82–1.61)	0.418
eGFR (per 10 mL/min/1.73m^2 increase)	0.78 (0.71–0.86)	< 0.001	0.89 (0.81–0.98)	0.015
Log10 NT-proBNP (per unit increase)	2.45 (1.95–3.08)	< 0.001	1.72 (1.35–2.19)	< 0.001
LVEF (per 5% decrease)	1.15 (1.06–1.25)	< 0.001	1.06 (0.97–1.16)	0.205
E/e' ratio (per unit increase)	1.09 (1.05–1.14)	< 0.001	—	—
TAPSE (per 1 mm decrease)	1.21 (1.14–1.29)	< 0.001	—	—
VExUS Grade (per grade increase)	1.65 (1.45–1.88)	< 0.001	—	—

Notes: included in the multivariable model were pre-specified and entered using a forced-entry approach: Composite Ultrasound Score, age, sex, atrial fibrillation, eGFR, Log10 NT-proBNP, and LVEF. Dashes (—) indicate variables not included in the multivariable model because they were components of, or closely correlated with, the Composite Ultrasound Score, and were therefore excluded to avoid collinearity and overadjustment.

Abbreviations: HR, hazard ratio; CI, confidence interval; eGFR, estimated glomerular filtration rate; NT-proBNP, N-terminal pro-B-type natriuretic peptide; LVEF, left ventricular ejection fraction; TAPSE, tricuspid annular plane systolic excursion; VExUS, venous excess ultrasound. Variables.

a Composite Score of ≥ 2 points. At this threshold, the scoring system yielded a sensitivity of 74.0% and a specificity of 79.6% for predicting 90-day rehospitalization. In contrast, using a VExUS grade ≥ 2 alone provided a lower specificity (72.5%) for a comparable sensitivity, highlighting the added value of integrating right ventricular dysfunction criteria to reduce false-positive classifications.

Model Calibration and Clinical Net Benefit Calibration

The calibration of the multivariable Cox model was evaluated specifically at the 90-day horizon. As shown in Figure 3A, the calibration plot illustrated a high degree of agreement between the model-predicted 90-day cumulative risk of

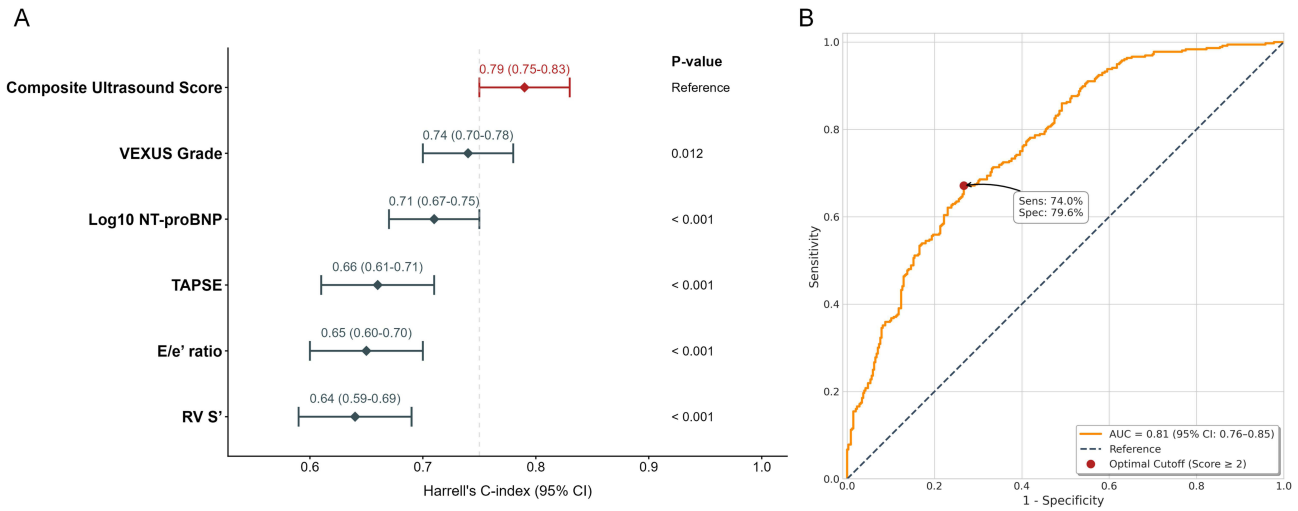

Figure 2 Predictive performance of the Composite Ultrasound Score. (**A**) Forest plot comparing apparent Harrell's C-indices and 95% confidence intervals for the Composite Ultrasound Score and individual echocardiographic or laboratory predictors. Diamond markers indicate point estimates, and horizontal bars indicate 95% confidence intervals; specifically, the red data line (red diamond and horizontal bar) highlights the performance of the novel Composite Ultrasound Score, while the vertical dashed line represents its reference C-index value. Bold text identifies the reference predictor. (**B**) Time-dependent receiver operating characteristic curve for the Composite Ultrasound Score at 90 days. The Orange curve represents the ROC curve, the diagonal dashed line represents the no-discrimination reference line, and the red dot indicates the optimal cutoff of ≥2 determined by the Youden index.

https://doi.org/10.2147/IJGM.S601864

Table 3 Comparative Predictive Performance and Diagnostic Accuracy at 90 Days

Model/Predictor	Overall C-Index (95% CI)	P-value (vs Composite)	90-Day AUC (95% CI)	Optimal Cutoff	Sensitivity (%)	Specificity (%)
Composite Ultrasound Score	0.79 (0.75–0.83)	Reference	0.81 (0.76–0.85)	Score ≥ 2	74.0	79.6
VExUS Grade	0.74 (0.70–0.78)	0.012	0.76 (0.71–0.80)	Grade ≥ 2	64.3	78.9
Log10 NT-proBNP	0.71 (0.67–0.75)	< 0.001	0.73 (0.68–0.77)	> 2850 pg/mL	68.2	70.4
TAPSE	0.66 (0.61–0.71)	< 0.001	0.67 (0.62–0.72)	< 16 mm	61.0	65.8
RV S'	0.64 (0.59–0.69)	< 0.001	0.65 (0.60–0.70)	< 10 cm/s	58.4	63.2
E/e' ratio	0.65 (0.60–0.70)	< 0.001	0.66 (0.61–0.71)	> 15	62.5	60.1

Notes: C-indices were derived from Cox proportional hazards models over the entire follow-up period. The 90-day AUC, sensitivity, and specificity were calculated using time-dependent ROC analysis. P-values represent the comparison of C-indices against the Composite Ultrasound Score using bootstrap resampling with 1000 replications. Internal validation of the primary Cox model was additionally performed using 1000 bootstrap resamples; the estimated optimism for Harrell's C-index was 0.015, yielding an optimism-corrected C-index of 0.78.

Abbreviations: AUC, area under the curve; VExUS, venous excess ultrasound; NT-proBNP, N-terminal pro-B-type natriuretic peptide; TAPSE, tricuspid annular plane systolic excursion; RV S', tricuspid lateral annular velocity; E/e', ratio of early transmitral inflow velocity to early diastolic mitral annular velocity.

rehospitalization and the actual observed risk across risk groups. The curve closely followed the ideal 45-degree reference line, suggesting reliable risk estimation. The Grønnesby-Borgan goodness-of-fit test yielded a P-value of 0.412, indicating no statistically significant deviation between the expected and observed number of events, thereby confirming the model's adequate fit for the survival data.

To assess the practical utility of the scoring system, DCA was performed at the 90-day time point (Figure 3B). The analysis revealed that within a clinically reasonable threshold probability range of 10% to 50%, decision-making based on the Composite Ultrasound Score provided a superior net benefit compared to the default strategies of "treating all" or "treating none." Notably, the net benefit of the Composite Score consistently exceeded that of using the VExUS score or NT-proBNP level alone, indicating that the integrated assessment leads to better clinical outcomes by correctly identifying high-risk patients without increasing unnecessary interventions.

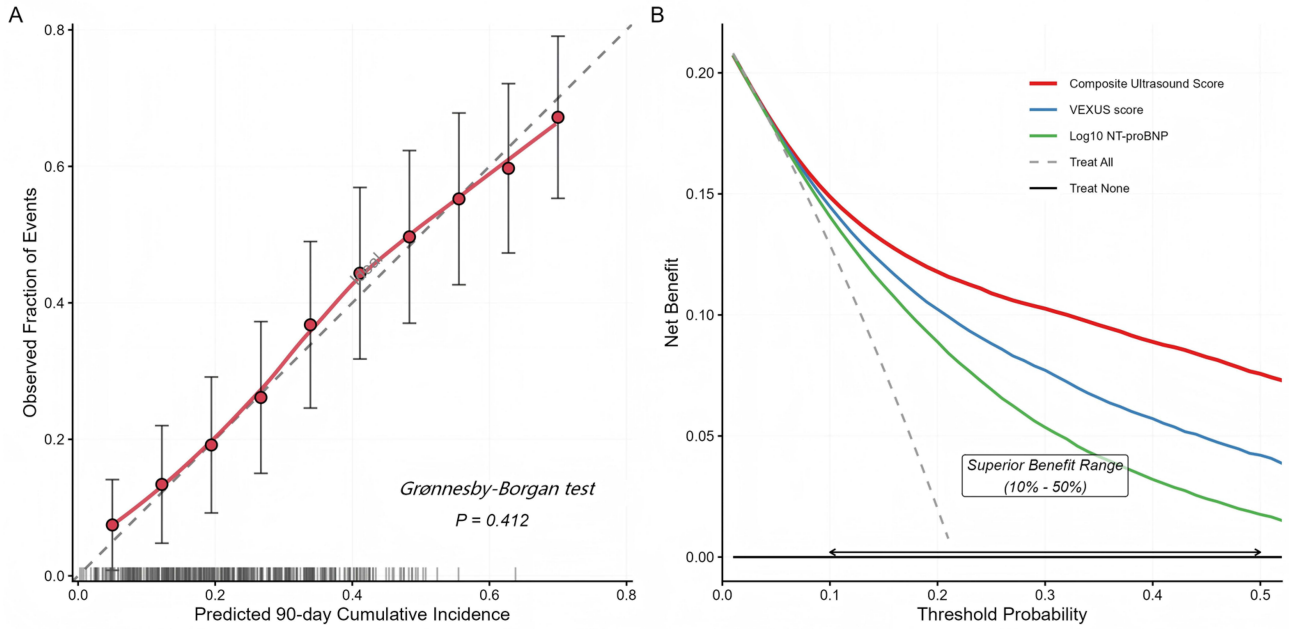

Figure 3 Calibration and decision curve analysis. (**A**) Calibration plot comparing predicted and observed 90-day risk of heart failure rehospitalization. Red circles indicate observed event fractions, vertical bars indicate 95% confidence intervals, the red line represents the fitted calibration curve, and the grey dashed line represents ideal calibration. Short vertical marks along the x-axis indicate the distribution of predicted risk. The Grønnesby-Borgan test indicated acceptable model fit (P = 0.412). (**B**) Decision curve analysis comparing the net benefit of the Composite Ultrasound Score with VExUS grading, Log10 NT-proBNP, and reference strategies. Colored solid lines represent prediction strategies, the grey dashed line represents the treat-all strategy, and the black horizontal line represents the treat-none strategy.

Survival Analysis Stratified by the Composite Ultrasound Score

Consistent with the optimal diagnostic threshold identified in the time-dependent ROC analysis (Score ≥ 2), the study cohort was stratified into a low-risk group (Composite Score 0–1; n = 484) and a high-risk group (Composite Score 2–3; n = 228). Kaplan-Meier survival curves were generated to visualize the cumulative incidence of the primary endpoint (Figure 4).

The analysis revealed a marked and early divergence in clinical trajectories between the two groups. The estimated 90-day cumulative incidence of heart failure rehospitalization was 50.0% (95% CI: 43.5%–56.5%) in the high-risk group, compared with only 8.3% (95% CI: 6.0%–11.1%) in the low-risk group. Cox regression analysis quantified this disparity, demonstrating that patients with a Composite Score ≥ 2 had a greater than six-fold increased risk of rehospitalization compared to those with a lower score (Crude Hazard Ratio: 6.82; 95% CI: 4.95–9.40; P < 0.001). This striking difference underscores the score's potency in identifying a subset of patients at imminent, very high risk, for whom targeted interventions such as intensive transitional care or earlier outpatient follow-up should be prioritized.

Subgroup Analysis and Consistency of Prognostic Value

To assess the generalizability of the Composite Ultrasound Score, we performed prespecified subgroup analyses. As shown in Figure 5, a high score (≥2) remained a statistically significant predictor of 90-day rehospitalization across all key demographic and clinical subgroups, including those stratified by age (<75 vs. ≥75 years), sex, body mass index (<25 vs. ≥25 kg/m^2), and history of atrial fibrillation.

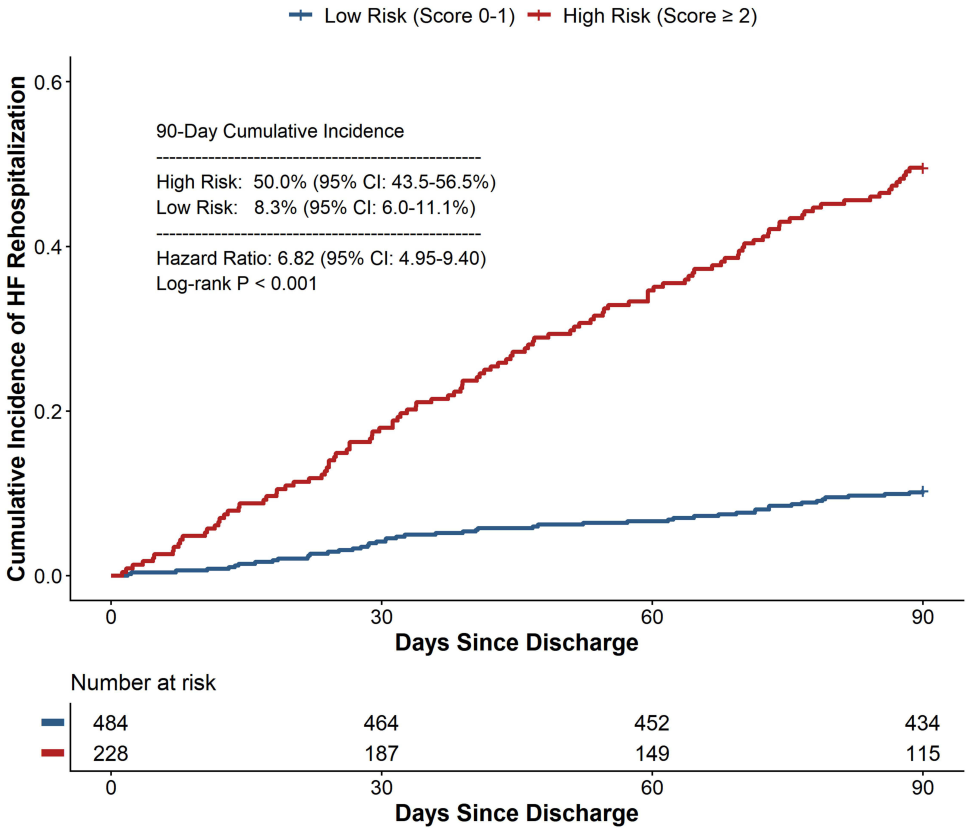

Figure 4 Heart failure rehospitalization stratified by the Composite Ultrasound Score. Kaplan-Meier curves showing 90-day heart failure rehospitalization according to risk group. The blue curve represents the low-risk group, defined as a Composite Ultrasound Score of 0–1, and the red curve represents the high-risk group, defined as a Composite Ultrasound Score ≥2. The inset text summarizes the 90-day cumulative incidence, hazard ratio, and log-rank P value. The number at risk is shown below the x-axis, with colored line indicators corresponding to the same risk groups as the main curves.

https://doi.org/10.2147/IJGM.S601864

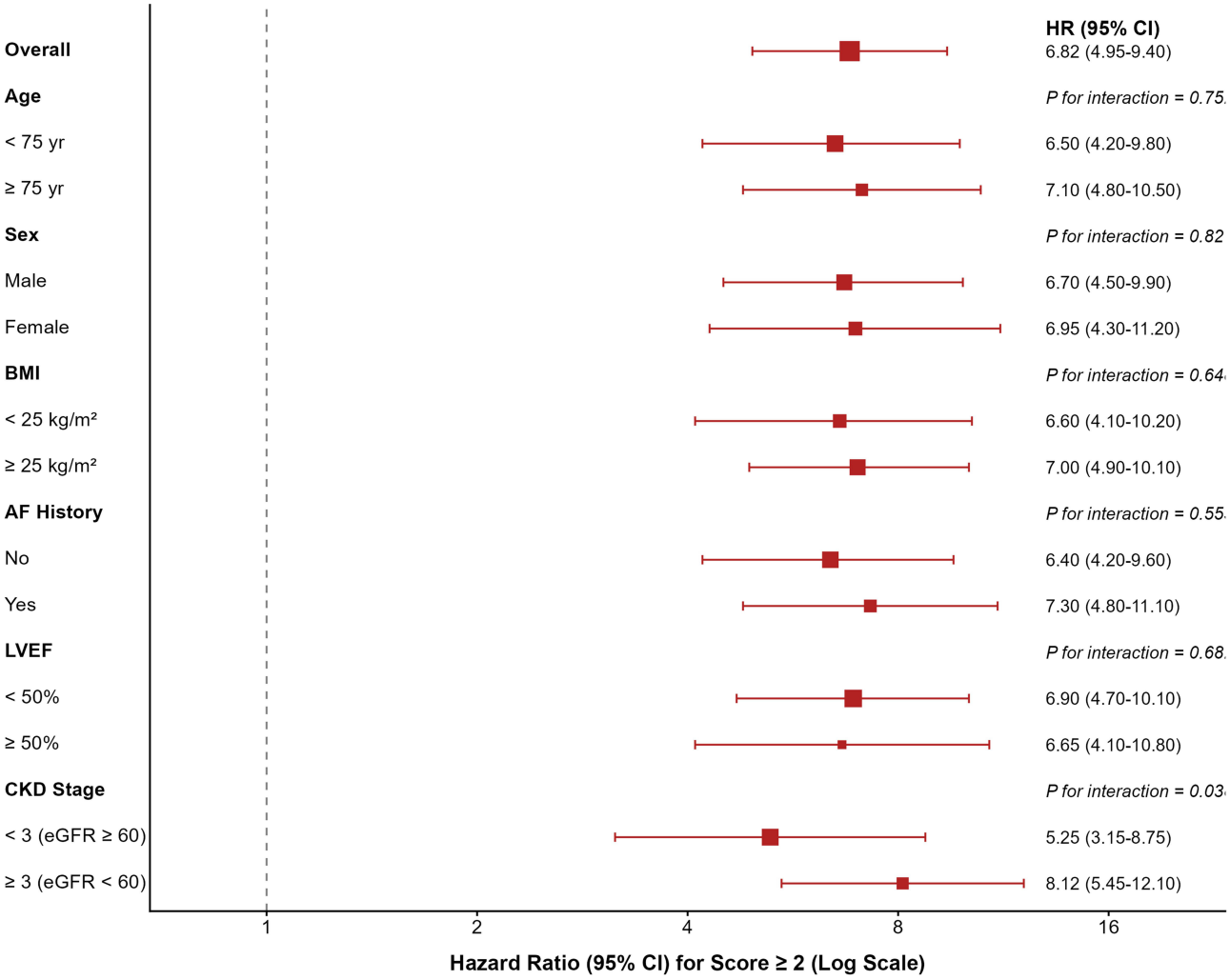

Figure 5 Subgroup analysis of the Composite Ultrasound Score for predicting 90-day heart failure rehospitalization. Forest plot showing hazard ratios and 95% confidence intervals for the association between a Composite Ultrasound Score ≥2 and 90-day heart failure rehospitalization across prespecified subgroups. Red squares indicate hazard ratio point estimates, horizontal red lines indicate 95% confidence intervals, and the vertical grey dashed line indicates the null value of HR = 1. Bold text denotes subgroup headings. Interaction P values were calculated using product terms in Cox regression models.

Crucially, the predictive utility was independent of LVEF. The hazard associated with a high score was comparable between patients with reduced (<50%) and preserved (≥50%) LVEF (P for interaction = 0.682), supporting the score's applicability across the heart failure spectrum.

A statistically significant effect modification was observed for renal function (P for interaction = 0.038). Although predictive in both groups, the magnitude of risk conveyed by a high Composite Score was substantially greater in patients with coexisting chronic kidney disease (CKD stage ≥3; HR: 8.12, 95% CI: 5.45–12.10) than in those without significant renal dysfunction (HR: 5.25, 95% CI: 3.15–8.75). This suggests that the integrated assessment of venous congestion and right ventricular function is a particularly potent risk stratifier in the context of cardiorenal syndrome, possibly due to amplified pathophysiological consequences of volume overload in this vulnerable population.

Sensitivity Analyses

To rigorously verify the robustness of the primary findings, a series of sensitivity analyses were conducted by restricting the study cohort or modifying variable definitions (Table 4).

First, to address the potential interference of atrial arrhythmias on venous Doppler waveforms, patients with atrial fibrillation were excluded. In this sub-cohort, the adjusted HR per 1-point increase was 1.52 (95% CI: 1.21–1.90), closely

Table 4 Multivariable Cox Regression Analysis for 90-Day HF Rehospitalization Across Sensitivity Scenarios

Sensitivity Scenario	No. of Patients	Adjusted HR (95% CI)*	% Change from Primary HR†	P-value
Primary Analysis (Full Cohort)	712	1.48 (1.24–1.76)	Reference	< 0.001
1. Excluding Atrial Fibrillation	440	1.52 (1.21–1.90)	+ 2.7%	< 0.001
2. Excluding Severe CKD (eGFR < 30)	658	1.45 (1.19–1.75)	−2.00%	< 0.001
3. Excluding Early Readmissions (< 7 days)	698	1.42 (1.18–1.71)	−4.10%	< 0.001
4. Binary Score Definition (≥ 2 vs. < 2)	712	2.85 (1.95–4.16)	N/A‡	< 0.001

Notes: *Models were adjusted for age, sex, LVEF, Log10 NT-proBNP, eGFR, and history of atrial fibrillation. Exception for Scenario 1: History of atrial fibrillation was removed from the adjustment model as it was the exclusion criterion. Note for Scenario 2: eGFR remained in the adjustment model as a continuous variable despite the range restriction. †Represents the relative percentage difference in the point estimate of the HR compared to the primary analysis [(Scenario HR - Primary HR)/Primary HR]. ‡Not applicable as the predictor variable was transformed from an ordinal scale (per 1-point) to a binary category.
Abbreviations: HR, hazard ratio; CI, confidence interval; CKD, chronic kidney disease; eGFR, estimated glomerular filtration rate.

mirroring the primary estimate of 1.48. Second, to rule out the confounding effect of primary renal fluid retention, patients with severe renal dysfunction (eGFR < 30 mL/min/1.73m^2) were excluded. The association remained robust (HR: 1.45, 95% CI: 1.19–1.75), demonstrating minimal attenuation compared to the main analysis. Third, to isolate readmissions driven by physiological decompensation rather than procedural issues or social factors, patients readmitted within the first 7 days post-discharge were excluded. The prognostic value of the score persisted (HR: 1.42, 95% CI: 1.18–1.71), suggesting the score reflects true hemodynamic stability.

Finally, the Composite Score was re-analyzed as a binary variable (High Risk [Score ≥ 2] vs. Low Risk [Score 0–1]) within the fully adjusted model. This yielded an adjusted HR of 2.85 (95% CI: 1.95–4.16). While lower than the unadjusted HR of 6.82 observed in the survival analysis, this substantial effect size confirms that the specific threshold identified by ROC analysis retains strong independent predictive power even after rigorous adjustment for confounders.

Discussion

In this investigation, we developed and validated a novel composite ultrasound score that integrates systemic venous congestion and right ventricular systolic function to predict 90-day rehospitalization in patients with heart failure. The primary finding of our study is that this composite score serves as an independent predictor of the primary endpoint, and its predictive performance was higher than that of the VExUS score alone, N-terminal pro-B-type natriuretic peptide, or any single conventional echocardiographic parameter. Our analysis identified a score of 2 or greater as a clinically meaningful threshold, effectively stratifying patients at higher risk for short-term adverse outcomes. However, the improvement in discrimination over established markers was statistically significant but moderate in magnitude; therefore, the Composite Ultrasound Score should be interpreted as an incremental risk stratification tool rather than a replacement for established clinical assessment, natriuretic peptides, or conventional echocardiographic evaluation. These results suggest that a combined hemodynamic and functional assessment at the point of care may provide a more integrated estimation of post-discharge risk than relying on markers of either congestion or cardiac function in isolation. Although data-driven weighting could potentially improve apparent performance within the derivation cohort, it may also reduce bedside usability and increase the risk of sample-specific overfitting. Therefore, we prioritized a parsimonious, threshold-based score that can be readily applied during pre-discharge assessment; however, comparison with coefficient-weighted models in external cohorts remains warranted.

The enhanced predictive capacity of our composite score is grounded in fundamental cardiorenal pathophysiology. The progression of heart failure involves a vicious cycle of declining cardiac function and increasing systemic congestion. The VExUS protocol, first described by Beaubien-Souligny and colleagues, provides a robust, non-invasive method for quantifying the end-organ consequences of this congestion.[7] However, congestion as measured by VExUS is the downstream effect. The right ventricle acts as the central pump governing the transit of this volume from the systemic to the pulmonary circulation. As outlined in the classic Guytonian model of circulatory dynamics, a compromised right ventricle fails to maintain a low right atrial

pressure, which in turn impedes venous return and raises mean systemic filling pressure, driving fluid into the interstitial space.[19,20] Landmark work by Mullens et al has firmly established that elevated central venous pressure, a direct result of this process, is the predominant driver of worsening renal function in heart failure, a phenomenon more critical than forward cardiac output itself.[21] Our composite score captures both of these interconnected elements, assessing the functional state of the pump (right ventricular function) and the severity of its failure to clear volume (VExUS grade). This dual assessment allows for the identification of patients who not only have a high pressure head in the venous system but also lack the right ventricular reserve to overcome it, leading to a critical reduction in organ perfusion pressure and subsequent adverse events.[22] The present findings are also consistent with prior observations that impaired right ventricular–pulmonary arterial coupling is associated with adverse outcomes in heart failure. Although our study did not directly quantify RV–PA coupling using load-adjusted indices, the combination of impaired right ventricular systolic parameters and severe venous congestion may reflect the downstream clinical consequences of insufficient right-sided reserve relative to hemodynamic load.[6]

Our findings build upon and extend the existing literature. While prior studies have demonstrated the prognostic value of the VExUS score in predicting outcomes like acute kidney injury and mortality, our study shows a significant incremental benefit of incorporating direct measures of right ventricular function, with the C-index improving from 0.74 to 0.79.[23] This suggests that in the context of heart failure, assessing the degree of congestion alone is insufficient without also quantifying the capacity of the right heart to handle that volume. Similarly, our composite score outperformed NT-proBNP, the established gold-standard biomarker. This is likely because NT-proBNP levels, while reflecting myocardial wall stress, can be influenced by confounding factors such as advanced age, obesity, and particularly renal dysfunction, where clearance is impaired and levels may be paradoxically altered.[24,25] Our score, derived from direct real-time physiological imaging, may provide a more stable and direct reflection of the operative hemodynamics at a given moment. Furthermore, while traditional right ventricular metrics such as TAPSE are invaluable, they are known to be highly load-dependent and can be misleading in the face of fluctuating preload and afterload conditions.[26,27] By contextualizing these functional measures within an assessment of systemic congestion, our Composite Ultrasound Score offers a more hemodynamically integrated evaluation of the right heart's performance relative to the load it is facing. Compared with emerging multimodal risk stratification approaches that combine clinical variables, natriuretic peptides, renal function, lung ultrasound, inferior vena cava assessment, or conventional echocardiographic markers, the present score focuses specifically on the integration of end-organ venous Doppler congestion and right ventricular systolic reserve.[3,8,24] Its potential advantage lies in providing a physiologically interpretable bedside assessment of both congestion burden and right-sided pump function. However, it should be viewed as complementary to, rather than a replacement for, established multimodal risk models, and future studies should evaluate whether adding this score to validated clinical prediction tools improves reclassification and clinical decision-making.

One of the most compelling findings from our study is the profound interaction observed between the composite score and chronic kidney disease. The predictive power of a high score was substantially amplified in patients with pre-existing CKD, who experienced a more than eight-fold increased risk of rehospitalization. This highlights the critical nature of the heart-kidney axis and aligns with the concept of cardiorenal syndrome, a field extensively defined by Ronco et al[28] In patients with CKD, the kidneys are already intrinsically vulnerable. The addition of severe venous congestion, as identified by a high composite score, likely leads to a state of "renal tamponade," where elevated renal venous and interstitial pressures critically reduce the glomerular filtration pressure gradient, accelerating a spiral of decline.[29] The composite score, therefore, appears to be an exceptionally sensitive tool for risk stratification in this particularly vulnerable cardiorenal population. Moreover, our finding that the score's prognostic value was consistent across the LVEF spectrum, including in patients with heart failure with preserved ejection fraction (HFpEF), is of particular clinical importance. Risk stratification in HFpEF is notoriously challenging, and right ventricular dysfunction is increasingly recognized as a central contributor to its pathophysiology and prognosis, a concept extensively explored by Borlaug and colleagues.[6] Our score may thus address a significant unmet need for a simple, effective risk stratification tool in the HFpEF population.

The clinical implications of these findings are potentially relevant for pre-discharge risk stratification. As a non-invasive, rapid, and repeatable bedside assessment, the Composite Ultrasound Score may be suitable for integration into pre-discharge evaluation after further validation. Our decision curve analysis suggested that using this score, particularly the threshold of 2 or greater, provided a greater net benefit than default strategies or single-parameter assessments across clinically relevant threshold probabilities. These findings support the potential value of a stratified risk assessment

approach. For patients with a low score (0–1), standard discharge planning and routine follow-up may be appropriate. Conversely, for patients with a high score (2–3), the result may prompt more careful clinical reassessment of decongestion status, individualized optimization of heart failure therapy, closer transitional care planning, and earlier post-discharge follow-up, rather than serving as a stand-alone determinant of discharge decisions. This interpretation is consistent with current guidelines from the AHA, ACC, and ESC, which emphasize the importance of adequate decongestion before discharge and transitional care planning after hospitalization.[1] Nevertheless, whether score-guided management can reduce rehospitalization requires prospective interventional evaluation.

Several limitations of this study warrant consideration. First, its single-center, retrospective design may introduce selection bias and limit the generalizability of our findings, despite our statistical methods including multiple imputation, sensitivity analyses, and bootstrap internal validation. Accordingly, the present findings should be considered exploratory and hypothesis-generating. Before routine clinical implementation, the Composite Ultrasound Score requires external validation in independent, prospective, multicenter cohorts with standardized acquisition protocols. Second, although discharge medications were recorded and compared between groups, the retrospective design did not allow detailed quantification of dynamic in-hospital treatment intensity, including cumulative intravenous diuretic exposure, changes in diuretic dose, net fluid balance, urine output trajectories, or use of vasoactive therapies. These unmeasured treatment-related factors may have influenced both pre-discharge congestion status and subsequent rehospitalization risk, and therefore residual confounding cannot be excluded. Third, while we performed a sensitivity analysis excluding patients with atrial fibrillation, the acquisition and interpretation of Doppler signals for the VExUS score can remain challenging in patients with significant arrhythmias or severe tricuspid regurgitation, necessitating a degree of operator expertise. Standardized training and certification will be essential for widespread implementation. Fourth, this study utilized a single pre-discharge assessment of the Composite Ultrasound Score rather than serial imaging measurements. Therefore, we could not evaluate temporal trends in VExUS grade, right ventricular function, or the Composite Ultrasound Score during hospitalization, nor could we determine whether improvement or deterioration in these parameters during decongestive therapy provides incremental prognostic information beyond the pre-discharge value. Although the pre-discharge time point was selected to reflect the patient's hemodynamic and congestion status immediately before transition to outpatient care, future prospective studies should incorporate standardized serial ultrasound assessments from admission to discharge to determine whether dynamic changes in venous congestion and right ventricular function further improve risk stratification. Lastly, our multivariable model adjusted for a pre-specified set of known confounders, but the possibility of residual, unmeasured confounding factors inherent to any observational study cannot be entirely eliminated.

Conclusion

This study developed and internally evaluated a novel Composite Ultrasound Score that integrates systemic venous congestion assessed by the VExUS protocol with right ventricular systolic function. The score was independently associated with 90-day rehospitalization for heart failure and showed statistically significant but moderate incremental discriminative performance compared with its individual components and established clinical markers. This association is consistent with the pathophysiological interaction between venous congestion, right-sided pump dysfunction, and cardiorenal vulnerability, particularly among patients with coexisting renal dysfunction. These findings suggest that the Composite Ultrasound Score may serve as a promising adjunctive tool for pre-discharge risk stratification in patients hospitalized for heart failure. However, given the single-center retrospective design and absence of external validation, the results should be considered exploratory and hypothesis-generating, and prospective multicenter validation is required before routine clinical implementation.

Data Sharing Statement

The data that support the findings of this study are available from the corresponding author, H. T, upon special request.

Ethics Approval and Consent to Participate

The study protocol was reviewed and approved by the Medical Ethics Committee of Xuanwu Hospital, Capital Medical University (Approval Number: IRB-REV-2024101). Given the retrospective nature of this study and the use of de-identified patient data, the requirement for obtaining written informed consent was waived by the Medical Ethics Committee of Xuanwu Hospital, Capital Medical University. All procedures involving human participants were strictly performed in accordance with

the ethical standards of the institutional research committee and the principles of the 1964 Declaration of Helsinki and its later amendments. Patient data confidentiality was strictly maintained throughout the study.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

Funding

This study was supported by the Specialized Department Funding of the Emergency Department of Xuanwu Hospital, Capital Medical University.

Disclosure

The authors confirm that there is no conflict of interest related to the manuscript.

References

1. Heidenreich PA, Bozkurt B, Aguilar D, et al. 2022 AHA/ACC/HFSA Guideline for the Management of Heart Failure: a Report of the American College of Cardiology/American Heart Association Joint Committee on Clinical Practice Guidelines. *Circulation*. 2022;145(18):e895–e1032. doi:10.1161/CIR.0000000000001063
2. Wideqvist M, Cui X, Magnusson C, Schaufelberger M, Fu M. Hospital readmissions of patients with heart failure from real world: timing and associated risk factors. *ESC Heart Fail*. 2021;8(2):1388–1397. doi:10.1002/ehf2.13221
3. McDowell K, Kondo T, Talebi A, et al. Prognostic models for mortality and morbidity in heart failure with preserved ejection fraction. *JAMA Cardiol*. 2024;9(5):457–465. doi:10.1001/jamacardio.2024.0284
4. Mocan D, Lala RI, Puschita M, Pilat L, Darabantiu DA, Pop-Moldovan A. The Congestion "Pandemic" in Acute Heart Failure Patients. *Biomedicines*. 2024;12(5):951. doi:10.3390/biomedicines12050951
5. Landi I, Guerritore L, Iannaccone A, Ricotti A, Rola P, Garrone M. Assessment of venous congestion with venous excess ultrasound score in the prognosis of acute heart failure in the emergency department: a prospective study. *Eur Heart J Open*. 2024;4(5):oeae050. doi:10.1093/ehjopen/oeae050
6. Borlaug BA, Kane GC, Melenovsky V, Olson TP. Abnormal right ventricular-pulmonary artery coupling with exercise in heart failure with preserved ejection fraction. *Eur Heart J*. 2016;37(43):3293–3302. doi:10.1093/eurheartj/ehw241
7. Beaubien-Souligny W, Rola P, Haycock K, et al. Quantifying systemic congestion with point-of-care ultrasound: development of the venous excess ultrasound grading system. *Ultrasound J*. 2020;12(1):16. doi:10.1186/s13089-020-00163-w
8. Naddaf N, Dianati Maleki N, Goldschmidt ME, Kalogeropoulos AP. Point of Care Ultrasound (POCUS) in the management of heart failure: a narrative review. *J Pers Med*. 2024;14(7):766. doi:10.3390/jpm14070766
9. Ghio S, Gavazzi A, Campana C, et al. Independent and additive prognostic value of right ventricular systolic function and pulmonary artery pressure in patients with chronic heart failure. *J Am Coll Cardiol*. 2001;37(1):183–188. doi:10.1016/S0735-1097(00)01102-5
10. McDonagh TA, Metra M, Adamo M, et al. 2021 ESC Guidelines for the diagnosis and treatment of acute and chronic heart failure. *Eur Heart J*. 2021;42(36):3599–3726. doi:10.1093/eurheartj/ehab337
11. Kidney Disease: Improving Global Outcomes (KDIGO) Chronic Kidney Disease Work Group. KDIGO 2024 clinical practice guideline for the evaluation and management of chronic kidney disease. *Kidney Int*. 2024;105(4S):S117–S314. doi:10.1016/j.kint.2023.10.018
12. Vahanian A, Beyersdorf F, Praz F, et al. 2021 ESC/EACTS Guidelines for the management of valvular heart disease. *Eur Heart J*. 2022;43(7):561–632. doi:10.1093/eurheartj/ehab395
13. Arbelo E, Protonotarios A, Gimeno JR, et al. 2023 ESC Guidelines for the management of cardiomyopathies. *Eur Heart J*. 2023;44(37):3503–3626. doi:10.1093/eurheartj/ehad194
14. Thygesen K, Alpert JS, Jaffe AS, et al. Fourth universal definition of myocardial infarction (2018). *Circulation*. 2018;138(20):e618–e651. doi:10.1161/CIR.0000000000000617
15. Riley RD, Ensor J, Snell KIE, et al. Calculating the sample size required for developing a clinical prediction model. *BMJ*. 2020;368:m441. doi:10.1136/bmj.m441
16. Hicks KA, Mahaffey KW, Mehran R, et al. 2017 Cardiovascular and Stroke Endpoint Definitions for Clinical Trials. *Circulation*. 2018;137(9):961–972. doi:10.1161/CIRCULATIONAHA.117.033502
17. The Criteria Committee of the New York Heart Association. *Nomenclature and Criteria for Diagnosis of Diseases of the Heart and Great Vessels*. 9th ed. Little, Brown & Co; 1994:253–256.
18. 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):1–39.e14. doi:10.1016/j.echo.2014.10.003
19. Persichini R, Lai C, Teboul JL, Adda I, Guérin L, Monnet X. Venous return and mean systemic filling pressure: physiology and clinical applications. *Crit Care*. 2022;26(1):150. doi:10.1186/s13054-022-04024-x
20. Magder S. Volume and its relationship to cardiac output and venous return. *Crit Care*. 2016;20(1):271. doi:10.1186/s13054-016-1438-7

21. Mullens W, Abrahams Z, Francis GS, et al. Importance of venous congestion for worsening of renal function in advanced decompensated heart failure. *J Am Coll Cardiol*. 2009;53(7):589–596. doi:10.1016/j.jacc.2008.05.068
22. Bocchino PP, Cingolani M, Frea S, et al. Organ perfusion pressure at admission and clinical outcomes in patients hospitalized for acute heart failure. *Eur Heart J Acute Cardiovasc Care*. 2024;13(2):215–224. doi:10.1093/ehjacc/zuad133
23. Velasco Malagón S, Acosta-Gutiérrez E, Atilio Nuñez Ramos J, Salinas S, Mora Pabón G. Subclinical congestion evaluated by Point of Care Ultrasound (POCUS) at discharge predicts readmission in patients with acute heart failure: prognostic cohort study. *POCUS J*. 2024;9(2):125–132. doi:10.24908/pocus.v9i2.17709
24. Vergaro G, Gentile F, Meems LMG, et al. NT-proBNP for risk prediction in heart failure: identification of optimal cutoffs across body mass index categories. *JACC Heart Fail*. 2021;9(9):653–663. doi:10.1016/j.jchf.2021.05.014
25. Bahniwal RK, Sadr N, Schinderle C, Avila CJ, Sill J, Qayyum R. Obesity paradox and the effect of NT-proBNP on all-cause and cause-specific mortality. *Clin Cardiol*. 2024;47(11):e70044. doi:10.1002/clc.70044
26. Nonaka H, Rätsep I, Obonyo NG, Suen JY, Fraser JF, Chan J. Current trends and latest developments in echocardiographic assessment of right ventricular function: load dependency perspective. *Front Cardiovasc Med*. 2024;11:1365798. doi:10.3389/fcvm.2024.1365798
27. Dandel M. Load dependency of ventricular pump function: impact on the non-invasive evaluation of the severity and the prognostic relevance of myocardial dysfunction. *Rev Cardiovasc Med*. 2024;25(8):272. doi:10.31083/j.rcm2508272
28. Kumar U, Wettersten N, Garimella PS. Cardiorenal syndrome: pathophysiology. *Cardiol Clin*. 2019;37(3):251–265. doi:10.1016/j.ccl.2019.04.001
29. Buryskova Salajova K, Malik J, Valerianova A. Cardiorenal syndromes and their role in water and sodium homeostasis. *Physiol Res*. 2024;73 (2):173–187. doi:10.33549/physiolres.935110