

Association of the VExUS Score with Right Atrial Pressure and Organ Dysfunction in Acute Heart Failure and Cardiogenic Shock

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Abstract

Background

Venous congestion is a major determinant of organ dysfunction in acute heart failure (AHF) and cardiogenic shock (CS). The Venous Excess Ultrasound Score (VExUS) provides a noninvasive assessment of systemic venous congestion, but its physiological correlates in the cardiac intensive care unit (CICU) remain incompletely characterized.

Methods

In this prospective single-center study, 94 patients with AHF or CS underwent simultaneous VExUS assessment and invasive right atrial pressure (RAP) measurement within 24 hours of CICU admission. VExUS (graded 0–3; Low 0–1 vs High 2–3) was evaluated for correlation with RAP and associations with hemodynamic, echocardiographic and organ dysfunction indices. Prespecified RAP–VExUS phenotypes (RAP ≤ 10 vs > 10 mmHg; Low vs High VExUS) were used to assess differences in hepato–renal biochemical markers, with adjustment for positive pressure ventilation and SCAI stage. In-hospital mortality was explored using univariate logistic regression.

Results

High VExUS was present in 29 patients (31%). VExUS correlated with RAP ($p = 0.67$), inversely with the MAP–RAP gradient, and was associated with impaired right ventricular function and higher hepato–renal dysfunction biomarkers, but not with lactate or urine output. RAP–VExUS discordance occurred in 30.9% of patients. Among patients with elevated RAP (> 10 mmHg), those with High VExUS showed greater hepato–renal biochemical dysfunction than those with Low VExUS ($p < 0.01$). The incremental contribution of VExUS beyond RAP was mainly evident for bilirubin. In-hospital mortality was numerically higher in High versus Low VExUS patients, without reaching statistical significance (24% vs 15%, $p = \text{NS}$).

Conclusions

In patients with acute heart failure or cardiogenic shock, VExUS was associated with invasively measured RAP and hepato-renal biochemical dysfunction, suggesting a complementary role in congestion phenotyping alongside invasive hemodynamic assessment.

INTRODUCTION

Acute heart failure and cardiogenic shock are characterized by a complex interplay of impaired cardiac output, elevated filling pressures, and systemic congestion^{1,2}. While perfusion abnormalities have traditionally received substantial attention, growing evidence highlights the critical contribution of

venous congestion - particularly at the level of the liver, kidneys, and splanchnic circulation - to clinical deterioration and end-organ dysfunction^{3–6}.

Standard clinical and hemodynamic surrogates of congestion, such as jugular venous distention, peripheral edema, right atrial pressure (RAP), and inferior vena cava dimensions, offer only a partial representation of the underlying venous burden^{7,8}. They are often insensitive to early organ involvement and may be confounded by individual variations in compliance, respiratory mechanics, and acute preload fluctuations⁹.

The Venous Excess Ultrasound Score (VExUS) was originally developed to characterize venous congestion by integrating Doppler-derived waveforms from the hepatic, portal, and intrarenal veins¹⁰. This approach has been shown to predict the risk of acute kidney injury in patients undergoing cardiac surgery, outperforming conventional measures such as central venous pressure^{11,12}. However, its application in the specialized environment of a Cardiac Intensive Care Unit (CICU), where venous congestion plays a central pathophysiological role, remains insufficiently characterized^{13,14}.

In this context, VExUS should not be interpreted merely as a surrogate of intravascular volume status, but rather as an integrated expression of the complex and dynamic interactions between stressed blood volume, mean systemic filling pressure, and right ventricular function^{15,16}. The latter is itself modulated by right ventriculo–arterial coupling and by left ventricular performance, all of which may undergo acute and profound alterations during episodes of acute heart failure and cardiogenic shock¹.

In this prospective cohort of patients admitted to a CICU with acute heart failure (AHF) or cardiogenic shock (CS), we sought to evaluate the physiological significance of VExUS in relation to invasively measured RAP and to explore its associations with hepato–renal biochemical dysfunction, invasive and echocardiographic parameters, and in-hospital mortality.

METHODS

This study is reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement.

Study design and population

This was a prospective, observational, single-center study conducted in a tertiary Cardiac Intensive Care Unit (CICU) at Fondazione Policlinico Universitario Agostino Gemelli IRCCS, Rome, Italy. Adult patients (≥ 18 years) admitted with AHF or CS, regardless of etiology, were eligible for inclusion if both a complete VExUS assessment and an invasively measured RAP were available within 24 hours of admission. AHF and CS were considered as different degrees of severity within the shared clinical spectrum of acute cardiovascular decompensation. Accordingly, the distinction between the two conditions was operationally based on the SCAI shock classification,¹⁷ with SCAI stages A–B classified as AHF and

stages C–E as CS. Key exclusion criteria were inadequate or incomplete VExUS assessment, unreliable invasive RAP measurement, pre-existing end-stage renal disease, defined as eGFR < 15 mL/min/1.73 m² or chronic dialysis dependence, and clinically significant chronic liver disease, including Child–Pugh class B or C hepatic dysfunction. Patients were enrolled consecutively between January 2024 and January 2025. The final analytical cohort consisted of 94 patients.

Study aims and prespecified analyses

Primary aim. The primary aim was to quantify the relationship between VExUS grade (0–3) and simultaneously invasively measured RAP. This relationship was examined (i) by assessing the association between VExUS grade (ordinal) and RAP (continuous), and (ii) by evaluating concordance and discordance between RAP and VExUS after categorization using literature-informed cutoffs^{18,19,20}: low RAP ≤ 10 mmHg versus high RAP > 10 mmHg, and low VExUS 0–1 versus high VExUS 2–3, respectively. Based on these thresholds, four congestion phenotypes were defined a priori: low RAP/low VExUS, high RAP/low VExUS, low RAP/high VExUS, and high RAP/high VExUS.

Secondary aims. Secondary aims were to evaluate the relationship between VExUS grade and: (i) biomarkers of elevated intracardiac filling pressures (N-terminal pro-B-type natriuretic peptide (NT-proBNP)); (ii) markers of hypoperfusion (serum lactate, urine output); (iii) biomarkers of renal and hepatic dysfunction (serum creatinine, total bilirubin, aspartate aminotransferase (AST), alanine aminotransferase (ALT)); (iv) right ventricular systolic function indices (tricuspid annular plane systolic excursion [TAPSE] and the TAPSE/pulmonary artery systolic pressure [TAPSE/PASP] ratio); (v) and effective perfusion pressure (defined as the MAP–RAP gradient).

Exploratory analysis. In-hospital mortality was assessed as an exploratory outcome.

Measurements and data collection

Invasive hemodynamics. RAP was measured invasively using a central venous catheter or pulmonary artery catheter, according to clinical indication. Pressure transducers were zeroed at the mid-axillary line, and RAP values were recorded at end-expiration, defined as the phase of minimal respiratory variation, in both spontaneously breathing and mechanically ventilated patients. Mean arterial pressure (MAP) was obtained invasively in all patients. Effective perfusion pressure was calculated as the MAP–RAP gradient.

Echocardiography. Transthoracic echocardiography was performed by experienced operators (CICU cardiologists). TAPSE was measured by M-mode in the apical four-chamber view. Pulmonary artery systolic pressure (PASP) was estimated from the peak tricuspid regurgitation jet velocity using the modified Bernoulli equation with the addition of RAP. Right ventricular–pulmonary arterial coupling was expressed as the TAPSE/PASP ratio²¹.

VExUS ultrasound protocol. VExUS was assessed using a standardized, stepwise protocol^{10,22} at the earliest clinically feasible time after admission and within 24 hours of CICU admission, and was performed simultaneously with invasive RAP measurement. The protocol started with inferior vena cava (IVC) diameter measurement in the subcostal long-axis view. In accordance with the original VExUS framework¹⁰, an IVC diameter < 2.0 cm was classified as VExUS grade 0, whereas an IVC diameter ≥ 2.0 cm prompted venous Doppler assessment. In patients with a plethoric IVC, pulsed-wave Doppler was acquired from the hepatic, portal, and intrarenal veins. Hepatic vein waveforms were categorized based on the relative predominance of systolic (S) and diastolic (D) components: S > D (normal), S < D (mildly abnormal), and systolic flow reversal (severely abnormal). Portal venous congestion was quantified using the pulsatility fraction, defined as (Vmax – Vmin)/Vmax, with < 30% considered normal, 30–49% mildly abnormal, and ≥ 50% severely abnormal. Intrarenal venous flow was classified as continuous (normal), discontinuous biphasic (mildly abnormal), or discontinuous monophasic with diastolic-only flow (severely abnormal). Doppler findings were integrated into a composite VExUS grade from 0 to 3. Grade 1 (mild congestion) was defined as IVC ≥ 2.0 cm with only normal or mildly abnormal Doppler patterns. Grade 2 (moderate congestion) required IVC ≥ 2.0 cm with one severely abnormal Doppler pattern. Grade 3 (severe congestion) was defined as IVC ≥ 2.0 cm with two or more severely abnormal venous Doppler patterns^{10,22}. For prespecified analyses, VExUS was additionally categorized as low (0–1) versus high (2–3).

All VExUS examinations were performed by experienced operators in critical care echocardiography and Doppler-based venous congestion assessment (S.F., M.G.D.B., G.S., D.P., A.d'A.). Given their prior expertise with the technique, no formal learning-curve phase was planned. When image acquisition was performed by other members of the clinical team, measurements were reviewed and validated under the supervision of one of these operators. The distribution of VExUS grades according to the examining operator is provided in Supplementary Table 1.

Laboratory variables and clinical outcomes. Laboratory variables included serum creatinine, total bilirubin, AST, ALT, NTproBNP and lactate. For each patient, laboratory values closest to VExUS assessment were used for analysis, provided they were obtained within 24 hours of CICU admission. Urine output was recorded over the first 24 hours. In-hospital mortality was recorded as a binary outcome.

Statistical analysis

Continuous variables are reported as median (interquartile range), and categorical variables as counts and percentages. Group comparisons were performed using the Wilcoxon rank-sum or Kruskal–Wallis test for continuous variables and Fisher's exact test for categorical variables, as appropriate. All tests were two-sided, with $p < 0.05$ considered statistically significant.

Associations between VExUS score and clinical, laboratory, and hemodynamic variables were assessed using Spearman's rank correlation, with p-values adjusted for multiple testing using the Benjamini–Hochberg false discovery rate (FDR).

Multivariable linear regression models including both RAP and VExUS were used to evaluate independent associations with creatinine, bilirubin, and ALT. Biomarkers were log-transformed and standardized (z-scores). Standardized regression coefficients (β per 1 SD) with 95% confidence intervals are reported. The incremental contribution of VExUS beyond RAP was assessed using hierarchical model comparison.

A composite organ dysfunction index was constructed by averaging the z-scores of creatinine, bilirubin, and ALT. This exploratory index was intended to summarize hepato–renal biochemical abnormalities rather than to represent a validated clinical score. Each variable was standardized before averaging to account for different measurement scales. ALT was preferred over AST because of its greater liver specificity and to avoid over-weighting closely related transaminase abnormalities. Differences across RAP–VExUS phenotypes were tested using the Kruskal–Wallis test with Dunn’s post hoc comparisons and FDR adjustment. To account for shock severity, multivariable linear regression models were adjusted for SCAI shock stage, treated as an ordered categorical variable (A–E). Additional adjustment included mean arterial pressure and positive-pressure ventilation status. In addition, a prespecified sensitivity analysis was performed using an alternative RAP cutoff of 12 mmHg to assess the robustness of phenotype-based differences in organ dysfunction.

Exploratory analyses of in-hospital mortality were conducted using univariate logistic regression. RAP was modeled both continuously and using clinically relevant thresholds. Discriminatory performance was evaluated using receiver operating characteristic curves, with comparisons performed using DeLong’s test.

All analyses were performed using R (version 4.3.2).

RESULTS

Study population and baseline characteristics

A total of 94 patients were included, with a median age of 70 years (IQR 59–76) and a predominance of males (71.3%). Based on VExUS assessment, 65 (69%) patients were classified in the Low VExUS group (0–1) and 29 (31%) in the High VExUS group (2–3) (Table 1).

Table 1

Demographic, clinical, echocardiographic characteristics and outcomes of the study population (n = 94), compared according to VExUS score. Continuous variables are expressed as median [interquartile range]. Categorical variables are expressed as n (%). Comparisons between groups were performed using the Mann–Whitney U test for continuous variables and the χ^2 test or Fisher's exact test for categorical variables, as appropriate.

Variable	Overall population (n = 94)	VExUS 0–1 (n = 65)	VExUS 2–3 (n = 29)	p-value
Demographic and clinical data				
Age (years)	70 [59–76]	71 [59–78]	69 [59–72]	0.260
BMI (kg/m ²)	26.0 [24.0–28.0]	26.0 [24.0–27.9]	27.3 [24.0–28.1]	0.567
Male sex, n (%)	67 (71.3%)	48 (73.8%)	19 (65.5%)	0.410
Reason for Hospitalization, n (%)				0.027
Acute Heart Failure	49 (52.1%)	39 (60.0%)	10 (34.5%)	
Cardiogenic Shock	45 (47.9%)	26 (40.0%)	19 (65.5%)	
Ischemic etiology	32 (34%)	28 (43.1%)	4 (13.8%)	0.008
SCAI class, n (%)				0.011
A	20 (21.3%)	18 (27.7%)	2 (6.9%)	
B	31 (33.0%)	24 (36.9%)	7 (24.1%)	
C	40 (42.6%)	21 (32.3%)	19 (65.5%)	
D	2 (2.1%)	1 (1.5%)	1 (3.4%)	
E	1 (1.1%)	1 (1.5%)	0 (0.0%)	
Inotropic therapy, n (%)	68 (72.3%)	42 (64.6%)	26 (89.7%)	0.013
Positive pressure ventilation, n (%)	25 (26.6%)	19 (29.2%)	6 (20.7%)	0.456
Echocardiographic and hemodynamic parameters				
Graphical abstract. In patients with acute heart failure or cardiogenic shock, simultaneous assessment of the Venous Excess Ultrasound Score (VExUS) and invasively measured right atrial pressure (RAP) identifies distinct congestion phenotypes. Although VExUS correlated with RAP, discordance was frequent. Patients with elevated RAP but low VExUS exhibited significantly lower hepato–renal dysfunction than those with concordantly elevated RAP and high VExUS, despite similar central venous pressures. These findings indicate that VExUS captures organ-level venous congestion beyond RAP and may help refine physiological phenotyping and decongestive strategies in the cardiac intensive care unit.				

Variable	Overall population (n = 94)	VExUS 0–1 (n = 65)	VExUS 2–3 (n = 29)	p-value
Demographic and clinical data				
Left ventricular ejection fraction (%)	30 [21–40]	31 [24–40]	25 [20–48]	0.228
TAPSE (mm)	17 [13–19]	18 [15–20]	14 [12–18]	0.013
Systolic pulmonary artery pressure (mmHg)	45 [40–55]	45 [40–55]	50 [40–55]	0.576
Right atrial pressure (mmHg)	11 [8–15]	9 [7–12]	15 [12–17]	< 0.001
Δ MAP – RAP (mmHg)	65 [49–82]	72 [56–86]	50 [42–69]	< 0.001
TAPSE/PAPs (n = 72)	0.40 [0.30–0.50]	0.40 [0.40–0.50]	0.35 [0.30–0.40]	0.230
Mean arterial pressure (mmHg)	76 [60–95]	80 [66–100]	65 [57–80]	0.023
Urine output (mL/ first 24h)	3325 [2200–4500]	3050 [2100–4100]	3550 [2520–4790]	0.120
Laboratory parameters				
NT-proBNP (pg/mL)	12459 [4058–24464]	9216 [2912–19141]	13728 [9684–24496]	0.019
Creatinine (mg/dL)	1.39 [1.02–2.04]	1.19 [0.98–1.86]	1.94 [1.39–2.37]	< 0.001
Lactate (mmol/L)	1.65 [1.10–3.40]	1.40 [1.10–3.20]	2.20 [1.10–3.80]	0.191
ALT (IU/L)	49 [22–104]	44 [21–79]	54 [26–364]	0.088
AST (IU/L)	58 [25–138]	48 [25–120]	67 [33–276]	0.083
Bilirubin (mg/dL)	1.00 [0.60–1.50]	0.90 [0.60–1.30]	1.50 [0.90–2.00]	< 0.001
Outcome				
In-hospital mortality (%)	17 (18.1)	10 (15.4)	7 (24.1)	0.388
Graphical abstract. <i>In patients with acute heart failure or cardiogenic shock, simultaneous assessment of the Venous Excess Ultrasound Score (VExUS) and invasively measured right atrial pressure (RAP) identifies distinct congestion phenotypes. Although VExUS correlated with RAP, discordance was frequent. Patients with elevated RAP but low VExUS exhibited significantly lower hepato–renal dysfunction than those with concordantly elevated RAP and high VExUS, despite similar central venous pressures. These findings indicate that VExUS captures organ-level venous congestion beyond RAP and may help refine physiological phenotyping and decongestive strategies in the cardiac intensive care unit.</i>				

Patients in the High VExUS group more frequently presented with cardiogenic shock at admission (65.5% vs 40.0%; $p = 0.027$) with a higher proportion of SCAI C patients. Accordingly, the use of inotropic therapy was significantly higher in the High VExUS group. Conversely, ischemic etiology of acute heart failure or cardiogenic shock was more common in the Low VExUS group (Table 1). Positive pressure ventilation (PPV) use (including both invasive mechanical ventilation and non-invasive ventilation) was similar in patients with VExUS 0–1 compared with VExUS 2–3. Baseline demographic characteristics were otherwise comparable between groups.

Correlation and concordance between VExUS and RAP

VExUS score showed a strong positive correlation with invasively measured RAP ($\rho = 0.67$, $p < 0.001$) (Fig. 1; Supplementary Fig. 1). Consistently, RAP was significantly higher in patients with High VExUS compared with Low VExUS (15 [12–17] vs 9 [7–12] mmHg; $p < 0.001$) (Table 1).

Concordance and discordance between RAP and VExUS were further evaluated using prespecified thresholds (RAP ≤ 10 vs > 10 mmHg; VExUS 0–1 vs 2–3). Four RAP–VExUS phenotypes were identified: Low VExUS/RAP ≤ 10 (43.6%), Low VExUS/RAP > 10 (25.5%), High VExUS/RAP ≤ 10 (5.3%), and High VExUS/RAP > 10 (25.5%). Overall, 30.9% of patients displayed discordant RAP–VExUS classifications (High RAP/Low VExUS or Low RAP/High VExUS).

DISCUSSION

In this prospective single-center study conducted in a tertiary Cardiac Intensive Care Unit, we systematically evaluated the VExUS score in patients admitted with acute heart failure or cardiogenic shock of heterogeneous etiologies, with the aim of clarifying its physiological determinants and clinical relevance.

The main finding of this study is that VExUS identifies clinically relevant heterogeneity in organ congestion among patients with similar central venous pressures.

VExUS demonstrated a robust correlation with invasively measured RAP, confirming that progressive Doppler abnormalities reflect increasing upstream venous pressures²³. Importantly, VExUS was also significantly associated with biochemical markers of hepatic and renal dysfunction, including bilirubin, transaminases, and creatinine. In multivariable analyses including both RAP and VExUS, the latter provided incremental discriminatory value beyond RAP for hepatic congestion, as reflected by serum bilirubin levels. These findings indicate that VExUS captures the effective transmission of venous hypertension to abdominal organs, rather than serving merely as a surrogate of central venous pressure²⁴.

Notably, approximately one third of patients in our cohort exhibited discordance between RAP and VExUS phenotypes. In particular, patients with Low VExUS despite elevated RAP (> 10 mmHg),

representing 25% of the cohort, had a significantly lower degree of hepato–renal dysfunction than those with High VExUS and RAP > 10 mmHg, despite comparable central venous pressures. This finding was robust to alternative RAP thresholds, as the difference between High and Low VExUS phenotypes remained significant when RAP was dichotomized at 12 mmHg, and was also independent of positive pressure ventilation and clinical severity (SCAI stage).

This dissociation highlights the limitations of isolated RAP measurements in critically ill patients, where acute changes in preload, positive pressure ventilation, and vasoactive therapies can substantially influence central venous pressure. These interventions also modulate venous tone, stressed blood volume and mean systemic filling pressure, thereby weakening the link between RAP and downstream organ congestion^{16,25}.

In contrast, VExUS integrates Doppler-derived information from the splanchnic venous circulation and appears to capture the effective transmission of venous hypertension to abdominal organs. As such, VExUS may provide a more physiologically meaningful assessment of “organ afterload” than RAP alone, offering a refined framework for phenotyping congestion and potentially guiding volume and hemodynamic management in the CICU¹⁵.

Consistent with this conceptual framework, VExUS showed no significant association with markers of systemic hypoperfusion such as serum lactate or urine output, underscoring that venous congestion and low-flow states represent distinct pathophysiological domains. Patients with acute heart failure may be severely congested despite preserved perfusion, whereas patients with cardiogenic shock may develop hyperlactatemia in the absence of marked venous congestion²⁶. The lack of a statistically significant relationship between VExUS and early urine output likely reflects the complex interplay between venous congestion, reduced MAP–RAP gradient, acute kidney injury, and non-standardized diuretic strategies in this critically ill population.

Despite its strong physiological coherence and association with organ dysfunction, VExUS was not independently associated with in-hospital mortality. Although mortality tended to be higher among patients with elevated VExUS, both VExUS and RAP demonstrated limited discriminatory performance for short-term outcomes. These findings should be interpreted in the context of the multifactorial determinants of in-hospital mortality in critically ill cardiac patients, including shock severity, comorbid burden, and heterogeneity of therapeutic interventions^{27,28}. The observed numerical gradient in mortality across VExUS categories suggests a potential signal that may not have been fully captured due to the modest sample size and limited statistical power²⁹. Therefore, the absence of formal prognostic significance should not be interpreted as evidence of irrelevance, but rather supports the concept that venous congestion primarily contributes to morbidity, organ dysfunction, and treatment complexity, while its impact on early mortality may require larger cohorts or longitudinal evaluation to be fully elucidated.

Study limitations

Several limitations should be acknowledged. First, this was a single-center study conducted in a tertiary CICU, which may limit generalizability. Second, the sample size was modest, with a limited number of mortality events and a small RAP ≤ 10 /High VExUS subgroup, reducing the precision of prognostic and phenotype-based estimates. Third, VExUS was assessed at a single time point on admission, precluding evaluation of dynamic changes in congestion and their relationship with organ dysfunction or treatment response. Fourth, the composite organ dysfunction index was exploratory and was not intended to represent a validated clinical score; its components reflect distinct biological processes and may be influenced by factors other than venous congestion. In mechanically ventilated patients, RAP values were not corrected for PEEP; although adjustment for positive-pressure ventilation did not materially modify the observed associations, residual effects of intrathoracic pressure cannot be excluded. Finally, therapeutic decisions were not standardized - including diuretic strategy and vasoactive support - and not all forward-flow parameters, such as cardiac output, were available in all patients, leaving possible residual confounding related to systemic perfusion, shock severity, and treatment heterogeneity.

CONCLUSIONS

In critically ill cardiac patients with AHF or CS, VExUS provided a physiologically coherent, organ-level assessment of systemic venous congestion that complemented invasive hemodynamic evaluation. Although VExUS correlated with RAP, patients with similar central venous pressures showed different degrees of hepato–renal biochemical dysfunction according to VExUS profile. The incremental contribution of VExUS beyond RAP was mainly evident for bilirubin, while no independent association with in-hospital mortality was demonstrated. Future studies should determine whether VExUS-guided decongestive strategies can improve organ recovery and longer-term outcomes.

Declarations

Ethics approval and consent to participate:

The study protocol was approved by the local Ethics Committee (Comitato Etico Territoriale Lazio Area 3; ID 5285) and conducted in accordance with the Declaration of Helsinki. All patients provided written informed consent prior to study inclusion.

Consent for publication:

Not applicable.

Competing interests:

The authors declare that they have no competing interests.

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Author Contribution

S.F., M.G.D.B., and T.S. wrote the main manuscript text and analyzed the data. D.P. and T.S. conceptualized the study. S.F., S.M., M.R., M.B., A.d'A., and C.S. collected the data. S.F. prepared Figures 1–3 and the graphical abstract. All authors (S.F., M.G.D.B., G.S., S.M., M.R., M.B., A.d'A., D.P., G.P., L.G., R.A.M., C.S., and T.S.) reviewed the manuscript.

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Data Availability

All data supporting the findings of this study are available within the paper and its Supplementary Information. Additional data are available from the corresponding author upon reasonable request.

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Figures

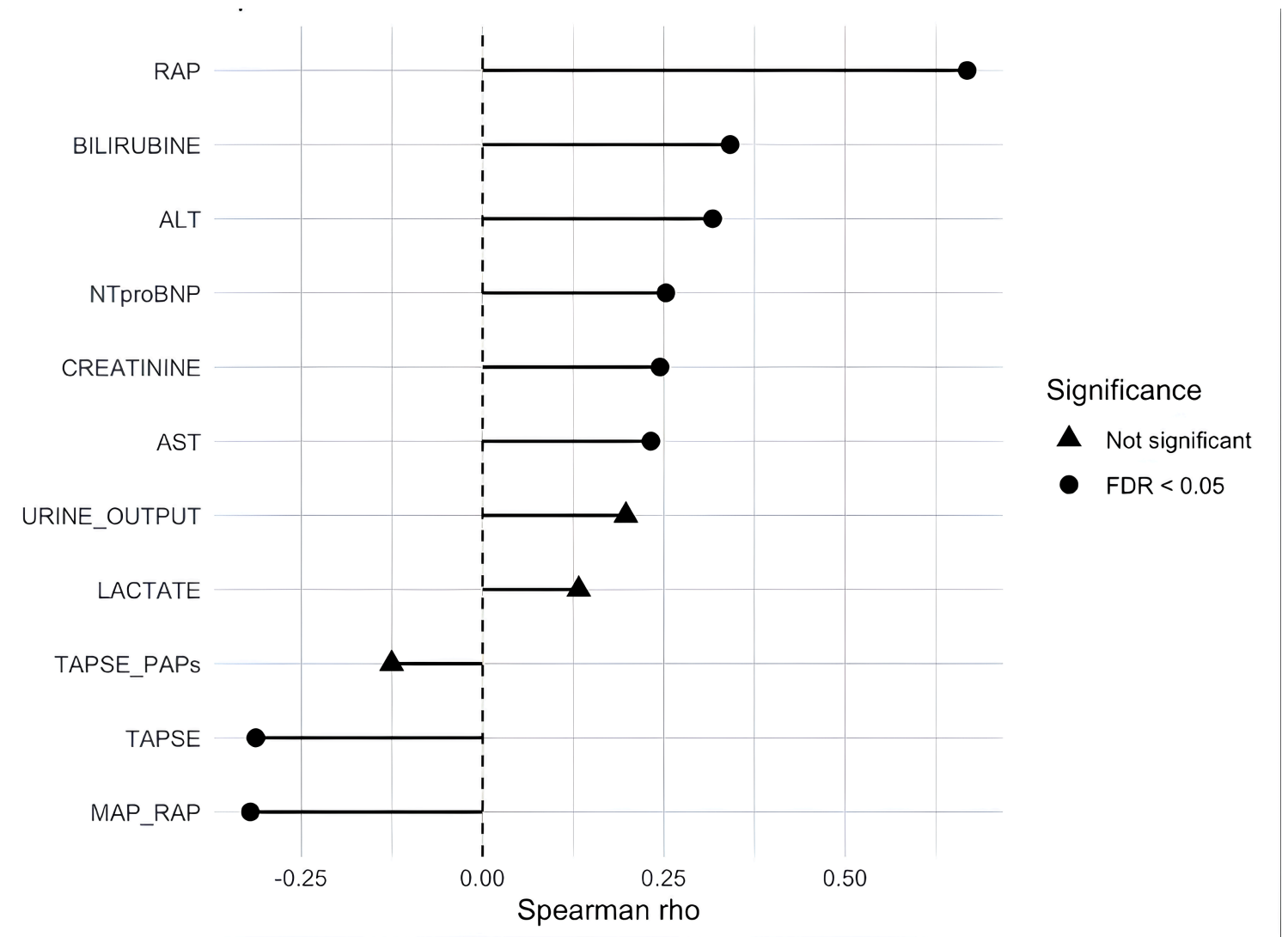


Figure 1

Lollipop plot showing Spearman correlation coefficients between VEXUS score and clinical variables.
Circles indicate correlations that remained statistically significant after false discovery rate (FDR) adjustment (FDR < 0.05), while triangles indicate non-significant associations. Numeric values are reported in Supplementary Table 2.

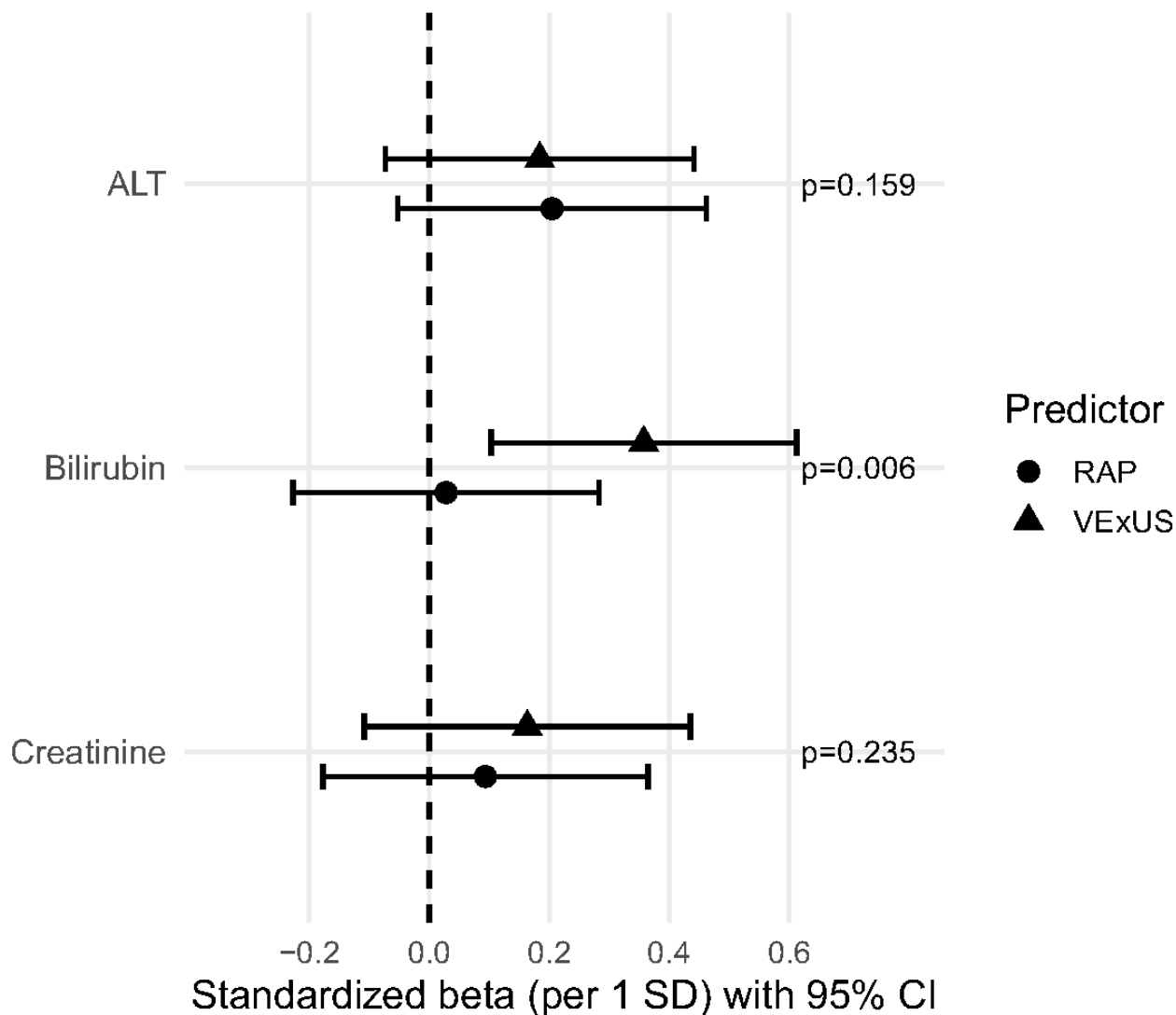


Figure 2

Independent associations of VExUS and RAP with hepato–renal biomarkers. Coefficient plot showing standardized regression coefficients (β per 1 standard deviation, with 95% confidence intervals) for the associations between VExUS and RAP with creatinine, bilirubin, and alanine aminotransferase (ALT). For each biomarker, multivariable linear models simultaneously included RAP and VExUS as predictors. Biomarkers were log-transformed and standardized prior to analysis. P-values displayed on the right indicate the incremental explanatory value of VExUS beyond RAP derived from hierarchical model comparison. Positive β values indicate higher biomarker levels with increasing VExUS. Numeric values are reported in Supplementary Table 3.

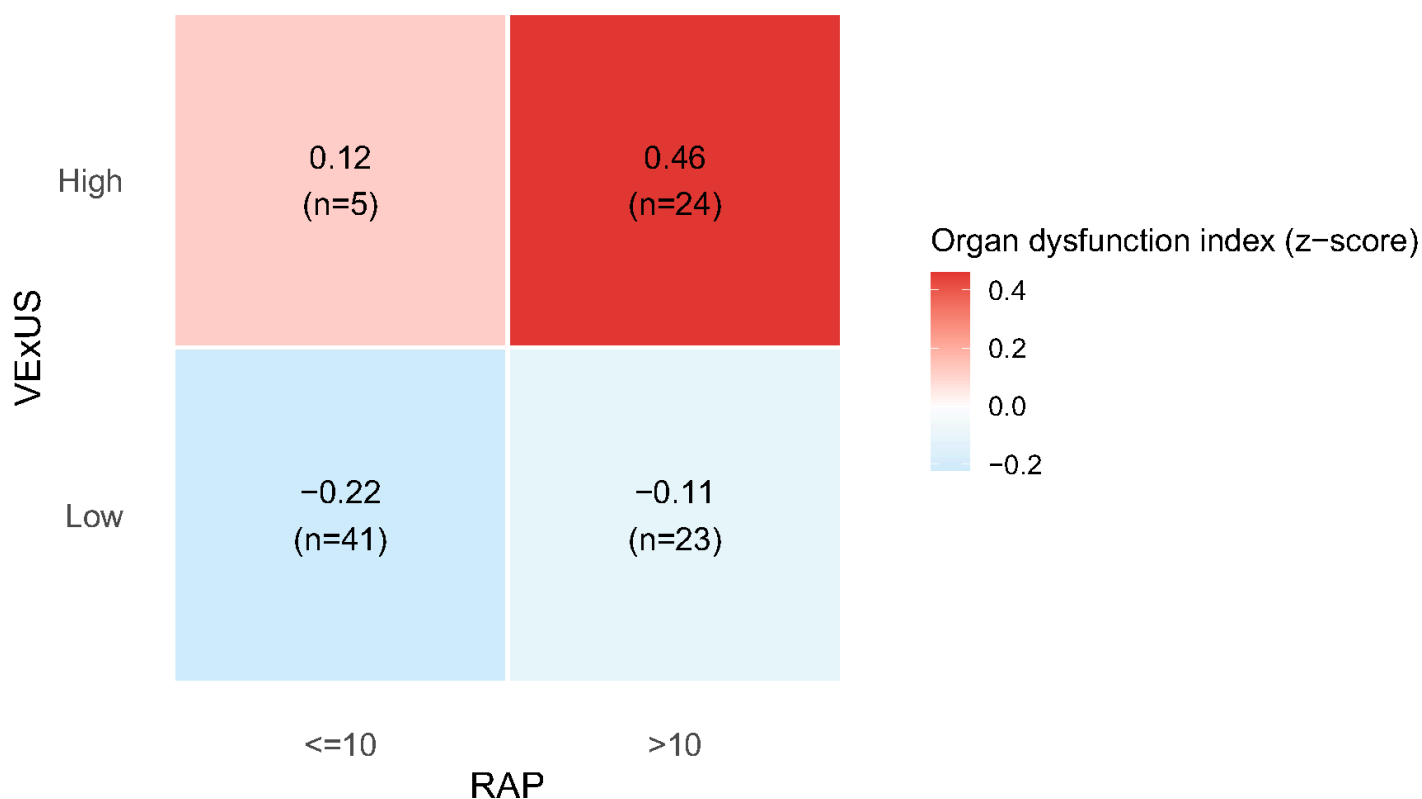


Figure 3

Composite index of organ dysfunction across RAP–VExUS phenotypes.

Heatmap showing the mean standardized organ dysfunction index (composite z-score of serum creatinine, alanine aminotransferase [ALT], and bilirubin) across four phenotypes defined by right atrial pressure (RAP; ≤10 vs >10 mmHg) and VExUS category (Low [0–1] vs High [2–3]). Values represent mean z-scores, with sample size for each cell reported in parentheses. The highest burden of organ dysfunction was observed in patients with concordantly elevated RAP and High VExUS. The RAP × VExUS interaction term for the organ dysfunction index was not statistically significant after adjustment for SCAI stage, MAP, and positive-pressure ventilation status (p for interaction = 0.401). Numeric values are reported in Supplementary Table 4.

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