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Development and Validation of a Multidimensional Ultrasound-based Gastrointestinal Congestion Score (GICS) for Predicting Persistent Acute Gastrointestinal Injury in Critically Ill Patients

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Abstract

Background: Venous congestion is increasingly recognized as a primary driver of organ dysfunction. This study aimed to develop and validate an organ-specific multidimensional ultrasound-based Gastrointestinal Congestion Score (GICS) for the early prediction of persistent acute gastrointestinal injury (AGI) in critically ill patients.

Methods: A secondary analysis of three prospective observational cohorts was conducted in an emergency intensive care unit (ICU) comprising 88 critically ill patients. Point-of-care ultrasound assessed inferior vena cava (IVC) diameter, hepatic venous Doppler patterns (HVDP), and portal venous Doppler patterns (PVDP) within 24 hours of ICU admission. The primary outcome was persistent AGI (duration ≥ 3 days). Predictive models for persistent AGI were constructed using least absolute shrinkage and selection operator (LASSO) regression and evaluated via receiver operating characteristic (ROC) analysis.

Results: An "occult congestion" phenotype—characterized by a normal IVC diameter coupled with splanchnic Doppler abnormalities—was observed in 22.7% of the cohort. Persistent AGI developed in 51 patients (58.0%). The GICS (range 0–7) was formulated by assigning weighted points to the three categorical ultrasound parameters based on multivariable logistic regression. The GICS effectively quantified this organ-specific hemodynamic burden, outperforming the systemic Venous Excess Ultrasound (VExUS) score (area under the curve [AUC], 0.812 [95% CI: 0.729-0.894] vs. 0.654 [95% CI: 0.564-0.744]; P<0.001). The LASSO-derived GICS-Clinical Model achieved an exceptional discriminative capacity (AUC = 0.953, 95% CI: 0.915-0.990). This performance was statistically comparable to a highly complex unintegrated ultrasound model (AUC, 0.954) and substantially outperformed the baseline clinical model (AUC, 0.866).

Conclusions: The GICS provides an objective, organ-specific assessment of gastrointestinal venous congestion. By capturing "occult" splanchnic stasis frequently missed by traditional IVC-dependent protocols, the streamlined GICS-Clinical Model enables the early, non-invasive identification of patients at high risk for persistent AGI, facilitating timely and personalized de-resuscitation strategies.

Trial registration: ChiCTR2500114808 and ITMCTR2025001376.

Keywords: Acute gastrointestinal injury; Venous congestion; Point-of-care ultrasound; Venous excess ultrasound; Critical care

Introduction

Acute gastrointestinal injury (AGI) is a frequent complication in critically ill patients, contributing to prolonged intensive care unit (ICU) stays, increased healthcare costs, and elevated mortality rates[1]. Despite its clinical significance, the early diagnosis of AGI remains challenging. Current guidelines rely heavily on subjective clinical signs, such as abdominal distension or feeding intolerance. However, these symptoms often manifest only after significant mucosal damage has already occurred[2].

Venous congestion plays a pivotal role in the pathophysiology of organ dysfunction[3,4]. Unlike the kidneys or liver, the gastrointestinal tract possesses a highly compliant venous reservoir that may harbor congestion well before systemic venous pressures rise[5,6]. Animal models have confirmed that intestinal injury induced by venous congestion is more severe than that caused by pure arterial ischemia[7]. Point-of-care ultrasound (POCUS) has emerged as a valuable non-invasive modality, increasingly used in the assessment of critically ill patients[8].

While the Venous Excess Ultrasound (VExUS) grading system is widely used to evaluate systemic congestion[9,10], its clinical utility in predicting specific organ trajectories during diuretic therapy has recently been called into question[11]. Furthermore, its mandatory reliance on inferior vena cava (IVC) dilation may overlook localized gastrointestinal stasis. Elevated vascular tone or intra-abdominal hypertension can restrict IVC distensibility while simultaneously exacerbating splanchnic venous backpressure, resulting in an "occult congestion" phenotype characterized by significant visceral stasis despite a non-dilated IVC. Therefore, this study aimed to develop a novel,

organ-specific, multidimensional ultrasound-based Gastrointestinal Congestion Score (GICS) and evaluate its predictive value for persistent AGI.

2. Methods

2.1 Study Design and Population

This research represents a secondary analysis of pooled data from three prospective cohorts conducted in the Emergency Intensive Care Unit (EICU) of Cangzhou Central Hospital between August 2022 and November 2025. The study protocol was designed and reported in accordance with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines12. The study was approved by the Institutional Review Board of Cangzhou Central Hospital (Nos. 2021-053-02[z], 2023-192-01(z), and 2024-171-02), and all methods were carried out in accordance with relevant guidelines and regulations. Written informed consent was obtained from all participants or surrogates.Although the original cohorts shared fundamentally similar study endpoints, slight variations in their specific observational protocols meant that the acquisition of HVDP and PVDP was not universally mandated, resulting in some missing ultrasound data in the present aggregated dataset.

We enrolled critically ill adults (aged ≥ 18 years) exhibiting an initial Acute Physiology and Chronic Health Evaluation II (APACHE II) score exceeding 813. Exclusion criteria were: (1) expected ICU stay < 24 hours; (2) pregnancy; (3) mesenteric vascular abnormalities; (4) mechanical bowel obstruction; (5) absolute contraindications to early enteral feeding; (6) terminal malignancies; or (7) lack of consent.

2.2 Data Collection and Outcome Definitions

Upon admission, baseline demographic and clinical characteristics were systematically recorded. Illness severity was evaluated within the first 24 hours of ICU admission using the APACHE II[13] and Sequential Organ Failure Assessment (SOFA) scoring systems[14], alongside the initial AGI grading (AGI on Day 1)[1]. Concurrent laboratory measurements included white blood cell counts, hemoglobin, procalcitonin, C-reactive protein, serum albumin, electrolytes (potassium and sodium), liver and kidney function panels, and arterial lactate. Additionally, the utilization of advanced life support modalities within the initial 24 hours was documented, including mechanical ventilation (MV), continuous renal replacement therapy (CRRT), and extracorporeal membrane oxygenation (ECMO). The administration intensity of vasoactive agents was quantified using the vasoactive-inotropic score (VIS)[15].

Throughout the ICU stay, daily logs were maintained to track nutritional support strategies (enteral versus parenteral), feeding tolerance, and the administration of prokinetics, laxatives, sedatives, and analgesics (e.g., remifentanil), as well as the dynamic evolution of the daily AGI grade.

The primary endpoint was persistent AGI, defined as the failure to achieve enteral nutrition goals (≤20 kcal/kg/day via enteral feeding) for ≥3 consecutive days due to gastrointestinal symptoms (e.g., high gastric residuals, vomiting, abdominal distension, or diarrhea), consistent with the European Society of Intensive Care Medicine (ESICM) definition of AGI grade II[16].

2.3 Point-of-Care Ultrasound (POCUS) Protocol

A trained intensivist performed bedside ultrasonography within 24 hours of admission using a Mindray M9 system (convex transducer)[8,10]. Patients were examined fasting in a supine/semi-recumbent position.

2.3.1 Inferior Vena Cava (IVC) Assessment

The IVC diameter was measured using a subxiphoid longitudinal approach, approximately 2 cm distal to its confluence with the right atrium[17]. Based on established consensus, an IVC diameter < 2.0 cm was classified as normal, and ≥ 2.0 cm as dilated[10,18] (Figure 1).

2.3.2 Hepatic Venous Doppler Pattern (HVDP)

HVDP waveforms were obtained from the middle hepatic vein via a right intercostal window. The pulsed-wave Doppler sample gate was positioned 2 to 3 cm from the IVC junction to minimize turbulent flow artifacts[19,20] (Figure 1).

- Grade 0 (Normal): S > D.
- Grade 1 (Moderate): S < D.
- Grade 2 (Severe): S-wave reversal.

2.3.3 Portal Venous Doppler Pattern (PVDP)

PVDP was assessed at the main portal vein via a right intercostal or right upper quadrant cross-section during stable, quiet respiration. The degree of portal vein pulsatility was evaluated using the pulsatility index (PI), calculated as *PI*

= *(D - S) / D*[21], where D is the diastolic peak velocity and S is the systolic trough velocity[22,10]. Flow patterns were stratified as (Figure 1):

- Grade 0 (Normal): PI < 30%.
- Grade 1 (Moderate): 30% ≤ PI < 50%.
- Grade 2 (Severe): PI ≥ 50% or interrupted flow.

2.3.4 Simplified Venous Excess Ultrasound (VExUS) Grading Protocol

A modified 3-tier VExUS grading system was implemented utilizing the IVC, HVDP, and PVDP parameters[10,23]. Renal venous Doppler was intentionally omitted to focus exclusively on the hepatosplanchnic hemodynamic circuit.

- Grade 0: Normal IVC.
- Grade 1: Dilated IVC (≥ 2.0 cm) with normal/moderate splanchnic Doppler abnormalities.
- Grade 2: Dilated IVC with at least one severe Doppler abnormality (Grade 2 HVDP or PVDP).

2.4 Statistical Analysis

Statistical analyses were performed using the R programming language (version 4.4.1, R Foundation for Statistical Computing, Vienna, Austria). A two-sided *P*-value < 0.05 was considered statistically significant. For descriptive statistics, continuous variables were tested for normality using the Kolmogorov-Smirnov test[24]. Normally distributed data were presented as mean ± standard deviation (SD) and analyzed using the independent-samples t-test, while skewed data were presented as median (interquartile range [IQR]) and analyzed using the Mann-Whitney U test.

Categorical variables were presented as frequencies and percentages, and compared using the Chi-square or Fisher's exact test, as appropriate.

Associations among systemic (IVC categories) and splanchnic (HVDP, PVDP) congestion markers were assessed using Fisher's exact test, with the strength of association quantified by Cramér's V[25]. A Sankey diagram and a risk heatmap were constructed to visualize hemodynamic progression and the incidence of persistent AGI across ultrasound parameter combinations. The GICS was developed based on a multivariable logistic regression model using persistent AGI (≥ 3 days) as the dependent variable, and a simplified integer scoring system was derived from the regression coefficients (β) to reflect the cumulative burden of venous congestion[26].

For prediction model development, variable selection was performed using LASSO regression with 10-fold cross-validation, applying the 1-standard-error threshold (λ_{1se})[27]. The candidate variable pool included 24 baseline clinical parameters: demographic variables (age, gender, body mass index); illness severity scores (APACHE II, SOFA, AGI grade on Day 1); comorbidities (hypertension, coronary heart disease, diabetes mellitus [DM]); support modalities (VIS, MV, ECMO, CRRT); laboratory measurements (white blood cell count, hemoglobin, procalcitonin, C-reactive protein, albumin, creatinine, potassium, sodium, arterial lactate); and early interventions (enteral nutrition within 24 hours, remifentanil dosage within 24 hours). Based on these, three models were constructed: the Clinical Model (24 parameters only), the Unintegrated Ultrasound-Clinical Model (24 parameters plus IVC, HVDP, PVDP), and the GICS-Clinical Model (24 parameters plus GICS). Nomograms were employed for visual presentation[28].

Model performance was evaluated following Transparent Reporting of a multivariable prediction model for Individual Prognosis Or Diagnosis (TRIPOD) guidelines[26]. Discriminative ability was assessed using the area under the ROC curve (AUC), with model comparisons performed using the DeLong test[29]. Internal validation was conducted using 1,000-iteration bootstrap resampling to obtain optimism-corrected AUCs and 95% CIs[30]. Calibration was evaluated using calibration plots and the Hosmer-Lemeshow test[31]. Clinical utility was assessed using decision curve analysis (DCA) across a range of threshold probabilities[32].

3. Results

3.1 Patient Characteristics and Baseline Profiles

A total of 88 critically ill patients were included in the final analysis (**Figure 2**). The median duration of AGI was 3 days (IQR: 2–6). Patients were stratified into persistent AGI (≥3 days, n = 51, 58.0%) and non-persistent AGI (<3 days, n = 37, 42.0%) groups. Peak AGI severities recorded were: grade 0 (1.1%), I (30.7%), II (54.5%), III (4.5%), and IV (9.1%).

Baseline demographics and most comorbidities were comparable between groups (Table 1). However, the persistent AGI group had a significantly lower prevalence of DM (15.7% vs. 40.5%, $P = 0.013$). As expected, these patients showed greater illness severity at admission, with higher APACHE II scores, SOFA scores, and arterial lactate levels (all $P < 0.01$). They also required more intensive life support (MV and ECMO; both $P < 0.05$) and experienced prolonged MV duration and ICU stay (both $P < 0.001$), though 28-day mortality did not differ significantly between groups.

Regarding gastrointestinal and hemodynamic parameters (Table 2), the persistent AGI group presented with a more severe AGI grade on Day 1 ($P < 0.001$). Admission splanchnic and systemic hemodynamics were also significantly worse in these patients, characterized by higher proportions of abnormal HVDP, abnormal PVDP, dilated IVC, and higher simplified VExUS scores (all $P < 0.05$).

3.2 Correlation Analysis of Three Ultrasound Indicators and the "Occult Congestion" Phenotype

Of the 88 patients, 29 (33.0%) exhibited IVC dilation, 20 (22.7%) had abnormal HVDP, and 25 (28.4%) presented with abnormal PVDP. Correlation analysis revealed a hemodynamic decoupling: IVC dilation was not significantly associated with HVDP ($P = 0.619$) and showed only a marginal association with PVDP ($P = 0.058$). HVDP and PVDP were also not significantly correlated (Cramér's V = 0.232, $P = 0.086$).

Across all observed ultrasound parameter combinations (**Figure 3** and **Figure S1**), the subgroup with completely normal findings across all three metrics had the lowest incidence of persistent AGI (28.2%). Conversely, nine specific permutations (comprising 16 patients) were associated with a 100% persistent AGI rate. Notably, the "occult congestion" phenotype—clinically defined as a normal IVC diameter coupled with splanchnic Doppler abnormalities—was identified in 20 patients (22.7%). Within this specific subgroup, the incidence of persistent AGI was notably high at 92.5%.

To maintain cohort representativeness, three patients with underlying liver cirrhosis were included. All three developed persistent AGI but displayed marked splanchnic hemodynamic heterogeneity: Case 1 showed IVC

dilation combined with abnormal PVDP but normal HVDP; Case 2 presented with isolated IVC dilation only; and Case 3 exhibited an isolated moderate PVDP abnormality without systemic dilation.

3.3 Construction and Evaluation of the Gastrointestinal Congestion Score (GICS)

To quantify splanchnic venous congestion, the GICS was developed using multivariable logistic regression with persistent AGI as the dependent variable. The initial regression coefficients (β) were calculated as follows: IVC dilation (1.26), moderate HVDP (2.24), severe HVDP (16.71), moderate PVDP (1.41), and severe PVDP (17.98) (**Table S1**).

The extreme coefficients for severe abnormalities reflected statistical instability due to limited subgroup sample sizes (severe HVDP, n = 4; severe PVDP, n = 8). Four weighting strategies were evaluated to address this (Table S1). The original categorical model (proportional to raw β) yielded an excessively wide range (0–27; AUC = 0.813). The binary model (collapsing severity grades) narrowed the range (0–4) but compromised discriminative ability (AUC = 0.805). The winsorized model (capping extreme β) maintained performance (AUC = 0.813) but increased complexity.

Therefore, the simplified ordinal model—assigning progressive integer weights reflecting stepwise clinical severity—was adopted, providing comparable discriminative performance (AUC = 0.812) with enhanced bedside applicability. The final GICS (range 0–7) assigns points as follows (**Figure 1**): IVC (normal = 0, dilated = 1); HVDP (normal = 0, moderate = 2, severe = 4); and PVDP (normal = 0, moderate = 1, severe = 2).

3.4 Construction of the Persistent AGI Prediction Models

Variable selection via LASSO regression analysis (**Figure S2**) identified five independent predictors for the GICS-Clinical Model: GICS, AGI on Day 1, SOFA, DM, and MV. The Unintegrated Ultrasound-Clinical Model incorporated individual ultrasound metrics (IVC, HVDP, PVDP) alongside AGI on Day 1, SOFA, DM, and MV. The Clinical Model included only AGI on Day 1, SOFA, DM, and MV.

Multivariable logistic regression analysis (**Table S2**) confirmed that within the primary GICS-Clinical Model, each 1-point increment in the GICS was associated with a nearly 7-fold higher risk of persistent AGI (odds ratio [OR] = 6.82, 95% confidence interval [CI]: 2.85–23.12, $P < 0.001$). Other significant independent risk factors included a higher initial AGI grade on Day 1 (OR = 11.25, 95% CI: 3.30–69.35, $P = 0.001$), the requirement for MV (OR = 12.90, 95% CI: 1.40–213.28, $P = 0.042$), and increasing SOFA scores (OR = 1.28, 95% CI: 1.06–1.64, $P = 0.023$).

To facilitate individualized risk assessment at the bedside, nomograms for the three models were constructed (Figure 4 and Figure S3). These tools translate complex multivariable regression coefficients into a user-friendly point-based interface, enabling quantitative estimation of the individualized probability of persistent AGI.

3.5 Comparison of Model Performance

ROC analysis (Figure 5, Table 3) demonstrated that the GICS-Clinical Model achieved excellent discriminative ability (AUC = 0.953, 95% CI: 0.915–0.990). The optimal cut-off value for the nomogram was 94.1 (total score range: 0–280), yielding 82.4% sensitivity, 97.3% specificity, 97.7% positive predictive value, and 80.0% negative predictive value. The Unintegrated Ultrasound-Clinical Model showed comparable performance (AUC = 0.954,

95% CI: 0.917–0.992). Notably, both integrated frameworks significantly surpassed the baseline Clinical Model (AUC = 0.866, 95% CI: 0.788–0.944, P < 0.05).

GICS (AUC = 0.812, 95% CI: 0.729–0.894) possessed the highest diagnostic accuracy among single parameters. It significantly outperformed PVDP (AUC = 0.675, *P* = 0.0011), Simplified VExUS (AUC = 0.654, *P* = 0.0002), HVDP (AUC = 0.649, *P* < 0.0001), MV (AUC = 0.646, *P* = 0.0069), IVC (AUC = 0.644, *P* = 0.0001), and DM (AUC = 0.624, *P* = 0.0053). However, the GICS did not demonstrate a statistically significant advantage over the initial AGI grade (AUC = 0.736, *P* = 0.2526) or SOFA score (AUC = 0.683, *P* = 0.0603).

Internal validation through 1,000-iteration bootstrap resampling corroborated the robustness of these estimates (**Table 3**). Calibration plots indicated high fidelity between predicted probabilities and clinical observations (**Figure 6A-C**). Furthermore, DCA confirmed that the GICS-Clinical Model offered the greatest clinical net benefit across a broad range of threshold probabilities, exceeding both the clinical-only model and default "treat-all/none" strategies (**Figure 6D**).

4. Discussion

4.1 Principal Findings

This study introduces the GICS, a gastrointestinal-specific multidimensional score integrating IVC, HVDP, and PVDP for personalized hemodynamic congestion assessment in critically ill patients. The GICS alone exhibited superior predictive accuracy (AUC = 0.812) compared to traditional systemic venous markers and the simplified VExUS protocol (AUC = 0.654) in predicting persistent AGI. Furthermore, the integrated GICS-Clinical Model

(AUC = 0.953) achieved excellent predictive performance. These findings underscore the clinical necessity of incorporating splanchnic venous hemodynamics into risk stratification for persistent AGI.

4.2 From Systemic to Local: Pathophysiology of "Occult Congestion"

The pathophysiology of gastrointestinal venous congestion exists along a complex, systemic-to-local hemodynamic continuum. This continuum involves several intersecting mechanisms that drive the "occult congestion" phenotype.

Fundamentally, volume overload acts as the primary catalyst. It distends the venous capacitance system, converting unstressed to stressed volume, which decreases vascular compliance and amplifies venous pulsatility—forming the essential hemodynamic substrate for HVDP and PVDP[33].

Furthermore, vascular tone and regional compliance dictate the heterogeneity of presentation across different vascular beds. IVC dilation relies heavily on passive stretching and is easily constrained by elevated sympathetic or pharmacological tone. Conversely, splanchnic Doppler abnormalities are primarily propelled by decreased visceral compliance and retrograde pressure wave transmission, conditions often exacerbated in high-tone states. This mechanistic divergence elucidates distinct clinical profiles: right ventricular dysfunction typically presents with high vascular tone, restricting IVC dilation while manifesting pronounced Doppler pulsatility[34]; in contrast, the profound vasoplegia of septic shock increases venous capacitance, preserving IVC dilation but paradoxically dampening retrograde Doppler signals[33]. Anatomically, the hepatic vein directly mirrors right atrial pressure, whereas portal flow must overcome the high-resistance hepatic sinusoids, making abnormal portal pulsatility a robust marker of more advanced, downstream congestion[4].

In addition to dynamic physiological factors, underlying hepatic architecture acts as an independent structural confounder. Cirrhosis pathologically elevates intrahepatic resistance and sinusoidal pressure, culminating in portal hypertension and baseline PVDP abnormalities. Paradoxically, the stiffened fibrotic parenchyma dampens retrograde cardiac pulsations, frequently rendering hepatic vein waveforms flattened or monophasic rather than exhibiting the expected S-wave reversal associated with severe congestion[35,36]. The marked splanchnic hemodynamic heterogeneity observed among the cirrhotic patients in our cohort underscores the necessity of integrating structural hepatic assessments when interpreting Doppler findings.

Finally, intra-abdominal hypertension (IAH) exerts a profound dichotomous effect on the venous circuit. IAH compresses the highly compliant splanchnic veins, thereby increasing downstream resistance and exacerbating HVDP and PVDP abnormalities[38]. Simultaneously, the cranial displacement of the diaphragm elevates intrathoracic pressure, actively compressing the IVC and restricting its macroscopic dilation[38]. This anatomical dissociation selectively amplifies organ-specific congestion while masking traditional systemic indicators.

Ultimately, "occult congestion" emerges from the intricate interplay of volume load, vascular tone, hepatic architecture, and intra-abdominal pressure across heterogeneous vascular beds. This dynamic complexity firmly challenges the traditional reliance on IVC dilation as the definitive gold standard for venous congestion[4], reinforcing the clinical imperative for individualized, multidimensional splanchnic hemodynamic monitoring in critically ill patients[21].

4.3 Clinical Implications and Advantages of the GICS Model

The GICS establishes a paradigm shift by prioritizing organ-specific venous patterns over systemic indices like VExUS. By directly evaluating the splanchnic bed, it serves as a sensitive early-warning indicator for localized gastrointestinal congestion[37]. The streamlined GICS-Clinical Model achieves an optimal balance between predictive precision (AUC = 0.953) and bedside utility, matching the performance of a complex multi-parameter model (AUC = 0.954) while avoiding its computational burden. This advantage aligns with recent evidence showing that systemic VExUS may fail to predict organ-specific outcomes[11], reinforcing the need for targeted tools like the GICS[38].

Although the high discriminative capacity of the GICS-Clinical Model is partially attributable to the inclusion of the initial AGI grade, multivariable analysis confirms that the GICS retains significant incremental prognostic value (OR = 6.82) beyond baseline clinical assessment, quantifying the previously unmeasured hemodynamic burden driving persistent gastrointestinal injury[39]. We acknowledge that feeding intolerance is a multifactorial clinical syndrome. However, in strict accordance with the European Society of Intensive Care Medicine (ESICM) guidelines, we utilized it as the primary, measurable clinical surrogate for persistent AGI. Importantly, venous congestion represents a critical, yet previously under-quantified, modifiable hemodynamic driver of this complex syndrome.

4.4 The "Diabetes Paradox" and the Impact of Mechanical Ventilation (MV)

Multivariable analysis revealed DM as a protective factor, aligning with the "diabetes paradox" frequently observed in critical care cohorts[40,41]. While this may involve chronic ischemic preconditioning[42] or medication-related mucosal protection (e.g., metformin)[43], our small subgroup size precludes definitive mechanistic conclusions.

Conversely, MV was a significant risk factor. Positive pressure ventilation increases intrathoracic pressure, impeding venous return and causing retrograde transmission of backpressure into the splanchnic system[44]. The inclusion of MV underscores that splanchnic congestion reflects both intrinsic vascular pathology and extrinsic iatrogenic interventions.

4.5 Strengths, Limitations, and Future Directions

The principal strength of this study lies in its conceptual shift: transitioning from generalized systemic congestion indices to the precise quantification of organ-specific splanchnic venous backpressure, providing a targeted, pathophysiologically grounded hemodynamic framework for the gastrointestinal tract[9,23].

However, several limitations warrant acknowledgment. Methodologically, the single-center observational design and modest sample size (n = 88) inherently restrict generalizability and introduce statistical instability, as evidenced by wide confidence intervals in subgroups with severe Doppler abnormalities. Second, while a substantial proportion of patients were excluded from the final analysis, it is crucial to clarify that this was primarily driven by strict pre-defined clinical exclusion criteria (e.g., expected ICU stay < 24 hours, lack of consent), rather than poor ultrasound acoustic windows. The multidimensional splanchnic ultrasound evaluation remains highly feasible at the bedside for the general ICU population. Third, furthermore, incorporating a broad candidate variable pool within this limited cohort carries an inherent risk of model overfitting, despite our rigorous use of LASSO penalization and internal bootstrap validation. Consequently, the GICS-Clinical nomogram must be interpreted as an exploratory risk-stratification tool requiring external validation. Future investigations should prioritize: (1) robust external validation

of the GICS across diverse, multicenter ICU cohorts (e.g., sepsis, acute heart failure); (2) prospective interventional trials to determine whether GICS-guided de-resuscitation algorithms yield tangible improvements in clinical outcomes; (3) the integration of splanchnic Doppler hemodynamics with morphological assessments (e.g., bowel wall thickness, mucosal perfusion) to establish a comprehensive gastrointestinal point-of-care ultrasound framework[45]; (4) the development of artificial intelligence-assisted analytic tools to mitigate inter-operator variability; and (5) the extension of this "organ-specific hemodynamic monitoring" paradigm to other vulnerable vascular beds in critically ill patients.

5. Conclusions

The GICS provides an objective, organ-specific assessment of gastrointestinal venous congestion. By capturing "occult" splanchnic hypertension frequently missed by traditional IVC-dependent protocols, the GICS-Clinical Model and its associated nomogram enable the early, non-invasive identification of critically ill patients at high risk for persistent AGI. This multidimensional approach facilitates timely, personalized therapeutic interventions, including targeted de-resuscitation and the optimization of mechanical ventilation parameters.

Abbreviations

AGI: Acute gastrointestinal injury

APACHE II: Acute Physiology and Chronic Health Evaluation II

AUC: Area under the curve

CI: Confidence interval

CRRT: Continuous renal replacement therapy

DCA: Decision curve analysis

DM: Diabetes mellitus

ECMO: Extracorporeal membrane oxygenation

GICS: Gastrointestinal Congestion Score

HVDP: Hepatic venous Doppler pattern

IAH: Intra-abdominal hypertension

ICU: Intensive care unit

IQR: Interquartile range

IVC: Inferior vena cava

LASSO: Least absolute shrinkage and selection operator

MV: Mechanical ventilation

OR: odds ratio

PI: Pulsatility index

POCUS: Point-of-care ultrasound

PVDP: Portal venous Doppler pattern

ROC: Receiver operating characteristic

SOFA: Sequential Organ Failure Assessment

STROBE: Strengthening the Reporting of Observational Studies in Epidemiology

VExUS: Venous Excess Ultrasound

VIS: Vasoactive-inotropic score

Declarations

Ethics approval and consent to participate

The authors are solely responsible for the content and integrity of this work. The study protocol was approved by the Ethics Committee of Cangzhou Central Hospital, Hebei Province, China (Approval No. 2021-053-02[z], 2023-192-01(z), and 2024-171-02).

Consent for publication

Written informed consent for the use of clinical data in research was obtained from all patients or their legal surrogates.

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Competing interests

The authors have no conflicts of interest to declare.

Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Code availability

Not applicable.

Authors' contributions

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Data Responsibility Statement: Yong Li had full access to all data in the study and takes responsibility for its integrity and the accuracy of the analysis.

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Figure Legends

Figure 1. Anatomical rationale and representative ultrasound components of the Gastrointestinal Congestion Score (GICS). (A) Hemodynamic schematic illustrating the systemic-to-splanchnic venous circuit and the targeted point-of-care ultrasound assessment sites. (B) The comprehensive GICS scoring framework. This incorporates: IVC evaluation, distinguishing between normal (< 2.0 cm) and dilated (≥ 2.0 cm) states; HVDP, demonstrating the progression from a normal waveform (Grade 0) to moderate (S < D, Grade 1) and severe (S-wave reversal, Grade 2) abnormalities; and PVDP, showing the transition from a normal waveform (Grade 0) to moderate (30% ≤ PI < 50%, Grade 1) and severe (PI ≥ 50% or flow interruption, Grade 2) abnormalities. D, diastolic; GICS, Gastrointestinal Congestion Score; HVDP, hepatic venous Doppler patterns; IVC, inferior vena cava; PI, pulsatility index; PVDP, portal venous Doppler patterns; S, systolic.

Figure 2. Flowchart of patient enrollment. Of 271 screened patients, 84 were from the Doppler cohort (mandatory HVDP/PVDP acquisition). Six were excluded due to inadequate images, yielding 78 patients. The remaining 187 patients (non-Doppler cohorts) did not mandate HVDP/PVDP; 169 were excluded, and 18 had complete data per local protocol. After excluding 8 patients (7 deaths, 1 unable to feed), the final cohort comprised 88 patients (37 with AGI < 3 days, 51 with AGI ≥ 3 days). AGI, acute gastrointestinal injury; HVDP, hepatic venous Doppler patterns; ICU, intensive care unit; PVDP, portal venous Doppler patterns.

Figure 3. Risk heatmap of persistent AGI based on venous ultrasound parameter combinations. The heatmap shows the incidence of persistent AGI for all combinations of IVC, HVDP, and PVDP. The color gradient represents

the incidence rate, revealing that severe splanchnic congestion (the "occult congestion" phenotype) can cause high AGI rates even without IVC dilation. AGI, acute gastrointestinal injury; HVDP, hepatic venous Doppler patterns; IVC, inferior vena cava; PVDP, portal venous Doppler patterns.

Figure 4. Nomogram for predicting persistent AGI using the GICS-Clinical Model. The nomogram uses five predictors (GICS, AGI on D1, SOFA, DM, MV) to estimate the individualized probability of persistent AGI (duration ≥ 3 days). AGI on D1, initial AGI grade on Day 1; DM, diabetes mellitus; GICS, Gastrointestinal Congestion Score; MV, mechanical ventilation; SOFA, Sequential Organ Failure Assessment.

Figure 5. Discriminative performance of the predictive models and individual indicators.

(A) ROC curves for integrated models (GICS-Clinical, Unintegrated Ultrasound-Clinical, Clinical Model) and individual predictors. (B) AUC comparison heatmap (DeLong test). AGI on D1, initial AGI grade on Day 1; AUC, Area under the curve; DM, diabetes mellitus; GICS, Gastrointestinal Congestion Score; HVDP, hepatic venous Doppler patterns; IVC, inferior vena cava; MV, mechanical ventilation; PVDP, portal venous Doppler patterns; SOFA, Sequential Organ Failure Assessment; VExUS, Venous Excess Ultrasound.

Figure 6. Model calibration and clinical utility. (A-C) Calibration curves showing excellent agreement between predicted and observed probabilities for all three models. (D) Decision curve analysis demonstrating superior net clinical benefit of the GICS-Clinical and Unintegrated Ultrasound-Clinical models over the Clinical Model across a wide range of threshold probabilities. HL, Hosmer-Lemeshow; GICS, Gastrointestinal Congestion Score; MAE, Mean Absolute Error.

Figure S1. Sankey diagram of venous patterns and outcomes. Patient flow through IVC, HVDP, and PVDP combinations for non-persistent (A) and persistent (B) AGI. Band width reflects patient numbers. IVC, inferior vena cava; HVDP, hepatic venous Doppler patterns; PVDP, portal venous Doppler patterns; AGI, acute gastrointestinal injury.

Figure S2. LASSO variable selection for three prediction models. (A) GICS-Clinical Model: 5 predictors (GICS, AGI on D1, SOFA, DM, MV). (B) Unintegrated Ultrasound-Clinical Model: 7 predictors (IVC, HVDP, PVDP, AGI on D1, SOFA, DM, MV). (C) Clinical Model: 4 predictors (AGI on D1, SOFA, DM, MV). Left panels: Cross-validation error curves; middle panels: coefficient paths; right panels: variable importance. λ selected by 1-standard-error criterion (λ_{1se}). AGI, acute gastrointestinal injury; AGI on D1, initial AGI grade on Day 1; DM, diabetes mellitus; GICS, Gastrointestinal Congestion Score; HVDP, hepatic venous Doppler patterns; IVC, inferior vena cava; MV, mechanical ventilation; PVDP, portal venous Doppler patterns; SOFA, Sequential Organ Failure Assessment.

Figure S3. Nomograms for Unintegrated Ultrasound-Clinical Model and Clinical Model. (A) Unintegrated Ultrasound-Clinical Model (7 predictors: IVC, HVDP, PVDP, AGI on D1, SOFA, DM, MV). (B) Clinical Model (4 predictors: AGI on D1, SOFA, DM, MV). Total points predict the probability of persistent AGI (≥ 3 days). AGI, acute gastrointestinal injury; AGI on D1, initial AGI grade on Day 1; DM, diabetes mellitus; HVDP, hepatic venous Doppler patterns; IVC, inferior vena cava; MV, mechanical ventilation; PVDP, portal venous Doppler patterns; SOFA, Sequential Organ Failure Assessment.

569 **Table 1. Baseline characteristics of the study patients.**

Variable	All patients (n=88)	AGI < 3 days (n=37)	AGI ≥ 3 days (n=51)	*P* value
Demographics and clinical scores				
Age, years	64.0 (48.8,72.0)	64.0 (55.0,72.0)	60.0 (44.5,69.0)	0.122
Male, n (%)	46 (52.3%)	16 (43.2%)	30 (58.8%)	0.195
BMI, kg/m²	25.5 (21.5,27.8)	25.8 (22.9,28.3)	24.2 (20.8,27.6)	0.259
Hypertension, n (%)	44 (50.0%)	18 (48.6%)	26 (51.0%)	1.000
Coronary Heart Disease, n (%)	19 (21.6%)	8 (21.6%)	11 (21.6%)	1.000
Diabetes Mellitus, n (%)	23 (26.1%)	15 (40.5%)	8 (15.7%)	0.013
APACHE II score	22.0 (17.0,26.2)	18.0 (13.0,26.0)	23.0 (20.0,27.0)	0.009
SOFA score	8.0 (6.0,12.0)	7.0 (4.0,9.0)	11.0 (7.0,13.0)	0.003
Primary Etiologies, n (%)				0.195
Sepsis	27 (30.7)	13 (35.1)	14 (27.5)	
Heart failure	25 (28.4)	7 (18.9)	18 (35.3)	
COPD	9 (10.2)	6 (16.2)	3 (5.9)	
Other etiologies	27 (30.7)	11 (29.7)	16 (31.4)	
Life support within 24 hours				
MV, n (%)	72 (81.8%)	24 (64.9%)	48 (94.1%)	<0.001

CRRT, n (%)	22 (25.0%)	7 (18.9%)	15 (29.4%)	0.323
ECMO, n (%)	7 (8.0%)	0 (0.0%)	7 (13.7%)	0.020
VIS	0.0 (0.0,20.0)	0.0 (0.0,2.0)	5.0 (0.0,36.5)	0.008
Laboratory variables				
White blood cell, ×10^9/L	12.85 (8.76,17.51)	12.96 (8.83,17.76)	12.13 (8.90,17.38)	0.826
Hemoglobin, g/L	113.5 (95.0,130.0)	109.0 (96.0,127.0)	116.0 (94.0,130.0)	0.654
Procalcitonin, ng/mL	2.18 (0.28,12.23)	3.46 (0.48,17.02)	1.99 (0.22,10.66)	0.289
C-reactive protein, mg/L	72.94 (26.41,137.63)	105.75 (39.07,163.00)	52.92 (16.95,101.34)	0.019
Albumin, g/L	31.9 (28.1,35.3)	31.6 (29.4,35.5)	32.0 (27.6,35.2)	0.764
Creatinin, μmol/L	113.5 (72.8,188.0)	116.0 (75.0,187.0)	107.0 (63.5,189.0)	0.310
Potassium, mmol/L	4.08 (3.65,4.55)	4.26 (3.78,4.53)	3.96 (3.58,4.50)	0.179
Sodium, mmol/L	141.0 (135.8,146.0)	140.0 (135.0,144.0)	141.0 (138.0,147.0)	0.090
Lactate, mmol/L	1.9 (1.2,4.0)	1.6 (1.0,2.1)	2.6 (1.6,5.7)	<0.001
Clinical Outcomes				
28-day ICU mortality, n (%)	21 (23.9%)	5 (13.5%)	16 (31.4%)	0.076
28-day survival time, days (n=67)	28.0 (28.0,28.0)	28.0 (28.0,28.0)	28.0 (13.0,28.0)	0.063
MV duration, days (n=67)	7.0 (2.0,12.5)	3.5 (0.0,7.0)	10.0 (7.0,20.0)	<0.001
Length of ICU stay, days (n=67)	11.0 (7.5,25.5)	8.0 (4.0,10.0)	20.0 (11.5,28.0)	<0.001

570 Data are presented as median (Interquartile Range), mean ± Standard Deviation or number (%), as appropriate. The
571 varying denominators (n) reported for each parameter account for missing data. AGI, acute gastrointestinal injury;
572 APACHE II, Acute Physiology and Chronic Health Evaluation II; BMI, body mass index; COPD, chronic
573 obstructive pulmonary disease; CRRT, continuous renal replacement therapy; ECMO, extracorporeal membrane
574 oxygenation; ICU, intensive care unit; MV, mechanical ventilation; SOFA, Sequential Organ Failure Assessment;
575 VIS, vasoactive-inotropic score.
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589 **Table 2. Gastrointestinal and Ultrasound Hemodynamic Indicators at Baseline.**

Variable	All patients (n=88)	AGI < 3 days (n=37)	AGI ≥ 3 days (n=51)	*P* value
Ultrasound Hemodynamic Indicators				
IVC Assessment				
Dilated IVC (≥ 2.0 cm), n (%)	29 (33.0%)	6 (16.2%)	23 (45.1%)	0.006
IVC diameter, cm	1.75 (1.29,2.12)	1.89 (1.55,2.21)	1.62 (1.09,1.86)	0.005
HVDP Grade, n (%)				0.004
Normal	68 (77.3%)	35 (94.6%)	33 (64.7%)	
Moderate	16 (18.2%)	2 (5.4%)	14 (27.5%)	
Severe	4 (4.5%)	0 (0.0%)	4 (7.8%)	
S-wave velocity, cm/s	-24.54 (-29.60, -18.92)	-20.49 (-27.16, -15.70)	-26.32 (-30.44, -22.08)	0.012
D-wave velocity, cm/s	-18.33 (-23.39, -14.38)	-17.76 (-23.47, -12.94)	-18.45 (-22.23, -15.59)	0.780
PVDP Grade, n (%)				0.001
Normal	63 (71.6%)	34 (91.9%)	29 (56.9%)	
Moderate	17 (19.3%)	3 (8.1%)	14 (27.5%)	
Severe	8 (9.1%)	0 (0.0%)	8 (15.7%)	

S-wave velocity, cm/s	14.52 (11.04,18.92)	13.36 (9.77,18.66)	15.84 (13.17,19.50)	0.021
D-wave velocity, cm/s	18.45 (15.03,22.09)	18.42 (14.85,23.13)	18.49 (15.41,20.70)	0.523
Simplified VExUS score, n (%)				0.009
Score 0	59 (67.0%)	31 (83.8%)	28 (54.9%)	
Score 1	23 (26.1%)	6 (16.2%)	17 (33.3%)	
Score 2	6 (6.8%)	0 (0.0%)	6 (11.8%)	
GICS, points	1 (0–2)	0 (0–0)	2 (1–3)	<0.001
Gastrointestinal indicators				
Enteral Nutrition, n (%)	14 (15.9%)	2 (5.4%)	12 (23.5%)	0.036
Remifentanil dosage, μg/kg/min	0.06 (0.04,0.10)	0.06 (0.03,0.09)	0.06 (0.04,0.10)	0.664
AGI grade on Day 1, n (%)				<0.001
Grade 0	3 (3.4%)	3 (8.1%)	0 (0.0%)	
Grade 1	51 (58.0%)	29 (78.4%)	22 (43.1%)	
Grade 2	25 (28.4%)	4 (10.8%)	21 (41.2%)	
Grade 3	3 (3.4%)	0 (0.0%)	3 (5.9%)	
Grade 4	6 (6.8%)	1 (2.7%)	5 (9.8%)	
Highest AGI grade, n (%)				<0.001
Grade 0	1 (1.1%)	1 (2.7%)	0 (0.0%)	
Grade 1	27 (30.7%)	24 (64.9%)	3 (5.9%)	

Grade 2	48 (54.5%)	11 (29.7%)	37 (72.5%)
Grade 3	4 (4.5%)	0 (0.0%)	4 (7.8%)
Grade 4	8 (9.1%)	1 (2.7%)	7 (13.7%)

590 Data are presented as median (Interquartile Range), mean ± Standard Deviation or number (%), as appropriate. AGI,
591 acute gastrointestinal injury; D, diastolic; GICS, gastrointestinal congestion score; HVDP, hepatic venous Doppler
592 pattern; IVC, inferior vena cava; PVDP, portal venous Doppler pattern; S, systolic; VExUS, Venous Excess
593 Ultrasound.

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602 **Table 3. ROC curve analysis and bootstrap internal validation.**

Indicator	AUC (95% CI)	*P* value	Clinical Cutoff	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)	Youden Index
Ultrasound-Clinical Model	0.954 (0.917–0.992)	<0.001	≥61.8	84.3	94.6	95.6	81.4	0.789
GICS-Clinical Model	0.953 (0.915–0.990)	<0.001	≥94.1	82.4	97.3	97.7	80.0	0.797
Clinical Model	0.866 (0.788–0.944)	<0.001	≥73.6	92.2	67.6	79.7	86.2	0.597
GICS	0.812 (0.729–0.894)	<0.001	≥1	78.4	75.7	81.6	71.8	0.541

Indicator	AUC (95% CI)	*P* value	Clinical Cutoff	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)	Youden Index
AGI on D1	0.736 (0.648–0.825)	<0.001	≥2	56.9	86.5	85.3	59.3	0.433
SOFA	0.683 (0.571–0.796)	0.001	≥10	56.9	75.7	76.3	56.0	0.325
PVDP	0.675 (0.593-0.757)	<0.001	Abnormal	43.1	91.9	88.0	54.0	0.350
Simplified VExUS	0.654 (0.564–0.744)	<0.001	≥1	45.1	83.8	79.3	52.5	0.289

Indicator	AUC (95% CI)	*P* value	Clinical Cutoff	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)	Youden Index
HVDP	0.649 (0.574-0.725)	<0.001	Abnormal	35.3	94.6	90.0	51.5	0.299
MV	0.646 (0.562–0.731)	<0.001	Yes	94.1	35.1	66.7	81.2	0.293
IVC	0.644 (0.553–0.736)	0.002	Dilation	45.1	83.8	79.3	52.5	0.289
DM	0.624 (0.530–0.719)	0.01	No	84.3	40.5	66.2	65.2	0.249

603 Notes: Bootstrap internal validation was performed using 1,000 resamples.

AGI on D1, Acute Gastrointestinal Injury grade on Day 1; AUC, area under the receiver operating characteristic curve; CI, confidence interval; DM, diabetes mellitus; GICS, Gastrointestinal Congestion Score; HVDP, hepatic venous Doppler pattern; IVC, inferior vena cava; MV, mechanical ventilation; NPV, negative predictive value; PPV, positive predictive value; PVDP, portal venous Doppler pattern; SOFA, Sequential Organ Failure Assessment; VExUS, Venous Excess Ultrasound.

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