SUPPLEMENTARY METHODS

Sample size calculation

Sample size was calculated using the methodology proposed by Richard D. Riley et al.[1] to develop a multivariable clinical prediction model. This model presupposes 20 predictor variables, with an adjusted R-squared value of 0.1, a shrinkage factor of 10%, and a primary outcome prevalence (rebleeding within 5 days) of 10%. Based on these parameters, the requisite minimum sample size for the model's development was calculated to be 1699 patients with 170 outcome events.

Emergency EVL+PT treatment procedure

All patients underwent endoscopic evaluation within 12 hours to confirm the presence and location of varices. Endoscopic variceal ligation (EVL) was primarily performed by placing rubber bands around the varices to induce thrombosis and fibrosis, thereby preventing rebleeding.[2] Following endoscopic treatment, all patients received vasoactive drugs within 2 days. The pharmacological regimen included vasoactive drugs such as octreotide, somatostatin, or terlipressin. Octreotide was administered as an initial bolus followed by continuous infusion, typically at a dose of 50 μg/hour. Somatostatin was administered similarly, with a bolus dose followed by continuous infusion at a dose of 250 μg/hour. Terlipressin was given at a dose of 2 mg every 4 hours intravenously. These vasoactive agents were chosen for their ability to reduce portal pressure and decrease variceal blood flow, thereby aiding in hemostasis.[3] In the acute management setting, supportive care measures were also implemented, including blood transfusions to maintain hemoglobin levels above 7 g/dL, prophylactic antibiotics to prevent infections, and monitoring of vital signs and laboratory parameters to manage complications such as hepatic encephalopathy and ascites. Patients were closely observed in the intensive care unit (ICU) for any signs of treatment failure, rebleeding, or adverse events, and necessary interventions were promptly carried out to stabilize their condition.

Preemptive TIPS (p-TIPS) procedure for AVB

The p-TIPS procedure was performed under local anesthesia following standard protocols. The procedure began with the insertion of a catheter through the jugular vein to gain access to the hepatic vein under fluoroscopic guidance. Using an interventional radiology technique, a needle was advanced from the hepatic vein into the portal vein to establish a connection between the two. A guide wire was then inserted through the needle into the portal vein, followed by the placement of a balloon-expandable or self-expanding stent (commonly 6-10 mm in diameter), covered with polytetrafluoroethylene (PTFE).[4,5] The stent was deployed to create a channel (shunt) between the hepatic and portal veins, allowing blood to bypass the liver and reduce portal hypertension. The stent was further expanded using a balloon catheter to ensure adequate blood flow through the shunt. Angiographic imaging was used to confirm the patency and position of the stent. The portal pressure gradient (PPG) was measured both before and after stent placement to ensure adequate pressure reduction.

Data collection

Data collection encompassed a comprehensive range of demographic information, medical history, clinical features, and medication usage, all of which were gathered within the first 24 hours of hospital admission. Baseline demographic details included age (years), sex (n, %), and the etiology of cirrhosis (chronic HBV infection, chronic HCV infection, alcohol-related, others, and cryptogenic). Upon admission, patient condition data were recorded, including previous variceal bleeding history (n, %), the location of varices observed during index gastroscopy (esophageal varices only vs. esophageal and gastric varices, n, %), the presence of hepatic encephalopathy (HE) (n, %), ascites severity (mild, moderate, massive, n, %), heart rate at admission (beats/min), systolic blood pressure at admission (mmHg), and diastolic blood pressure at admission (mmHg). Laboratory

evaluations conducted at admission included the following parameters: white blood cell count (WBC, ×10^9 cells/L), red blood cell count (RBC, ×10^9 cells/L), hemoglobin concentration (Hb, g/L), platelet count (PLT, ×10^9/L), neutrophil count (NEC, ×10^9/L), aspartate aminotransferase (AST, U/L), alanine aminotransferase (ALT, U/L), total bilirubin (TBIL, μmol/L), albumin (g/L), international normalized ratio (INR), activated partial thromboplastin time (APTT, s), thrombin time (TT, s), prothrombin time (PT, s), and creatinine (μmol/L). Additionally, risk stratification indices were calculated, including the Model for End-Stage Liver Disease (MELD) score and the Child-Pugh score (points), with Child-Pugh class (A, B, C) also noted.[6,7]

Software and hardware environment

The development and implementation of the AI-driven AVB prediction model were conducted using Python 3.10.4 as the primary programming language. PyTorch 1.13.0 served as the deep learning framework, facilitating the construction and training of the neural network models.[8] The parallel computing framework utilized Cuda 11.6.0, while CUDNN 8.3.2 was employed to accelerate the computation of machine learning algorithms. The computational tasks were executed on a high-performance workstation equipped with two Intel(R) Xeon(R) Gold 6230 CPUs, each providing 20 cores and 40 threads, and two NVIDIA Quadro GV100 GPUs, each with 32 GB of memory, to handle the extensive data processing and model training requirements. The system also included 384 GB of DDR4 RAM, ensuring sufficient memory capacity for handling large datasets and complex computational tasks.

Model Validation

Receiver Operating Characteristic (ROC) curves were generated to assess the model's ability to discriminate between different clinical outcomes, with the Area Under the Curve (AUC) providing a measure of overall performance.[9] The

Confusion Matrix was employed to evaluate the model's classification accuracy, sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV). Decision curve analysis was conducted to quantify the net clinical benefits of the model at various threshold probabilities, facilitating the assessment of its practical application in clinical decision-making. Calibration curves were plotted to compare the predicted probabilities of clinical outcomes with the observed frequencies, ensuring the reliability and accuracy of the predictions across different risk levels. Additionally, SHapley Additive exPlanations (SHAP) analysis was utilized to determine the importance and impact of individual features on the model's predictions. [10]

Comparison with clinical risk stratification systems

To evaluate the impact of early TIPS versus standard therapy on patient outcomes, we employed several established clinical risk stratification systems and compared their predictive performance with our AI-driven AVB prediction model. The traditional clinical risk scores included the Baveno VII criteria, the Model for End-Stage Liver Disease (MELD) score, and the Child-Pugh classification. The Baveno VII criteria stratify patients based on hepatic venous pressure gradient (HVPG) measurements and clinical indicators, guiding the use of aggressive interventions in high-risk patients.[11] The MELD score, which incorporates serum bilirubin, creatinine, and international normalized ratio (INR),[6] categorizes patients into low-risk (MELD ≤11), intermediate-risk (MELD 12–18), and high-risk (MELD ≥19) groups. The Child-Pugh classification evaluates liver disease severity using five clinical measures: bilirubin, albumin, prothrombin time, ascites, and hepatic encephalopathy, stratifying patients into Class A (low risk), Class B (intermediate risk), and Class C (high risk).[7] The early TIPS criteria define low-risk patients as those with Child-Pugh A or Child-Pugh B without active bleeding, and high-risk patients as those with Child-Pugh B with active bleeding or Child-Pugh C (≤13 points) (Table S8-10).

Subgroup Analysis

A comprehensive subgroup analysis was conducted to evaluate the 6-week treatment failure rate and 1-year mortality of AVB patients receiving either EVL+PT or p-TIPS treatment across various patient subgroups. The analysis included patients with esophageal varices alone versus those combined with gastric varices (Figure S4), different Child-Pugh classifications (C versus A+B) (Figure S5), varying MELD scores (>19 versus ≤19) (Figure S6), and different TIPS stent diameters (<8 mm, 8 mm, and 10 mm) (Figure S7, Table S6).

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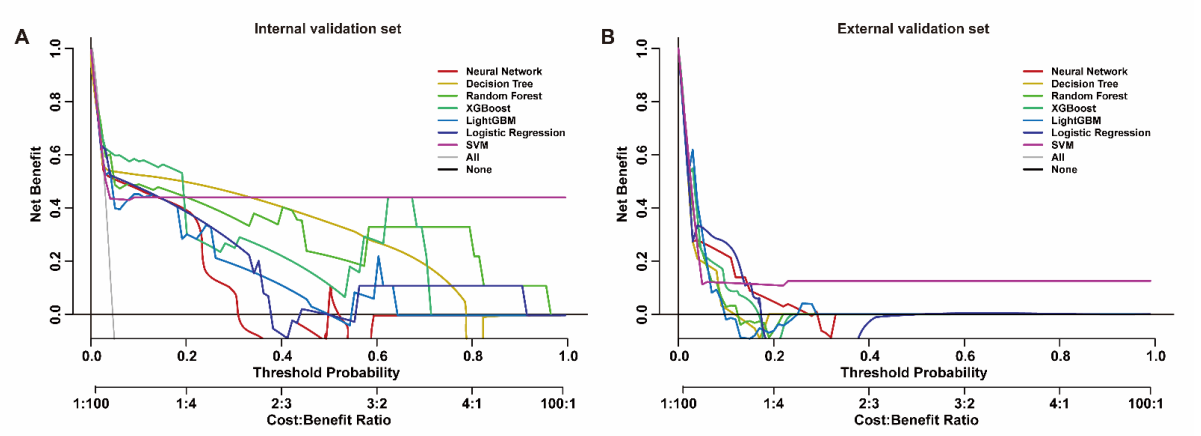
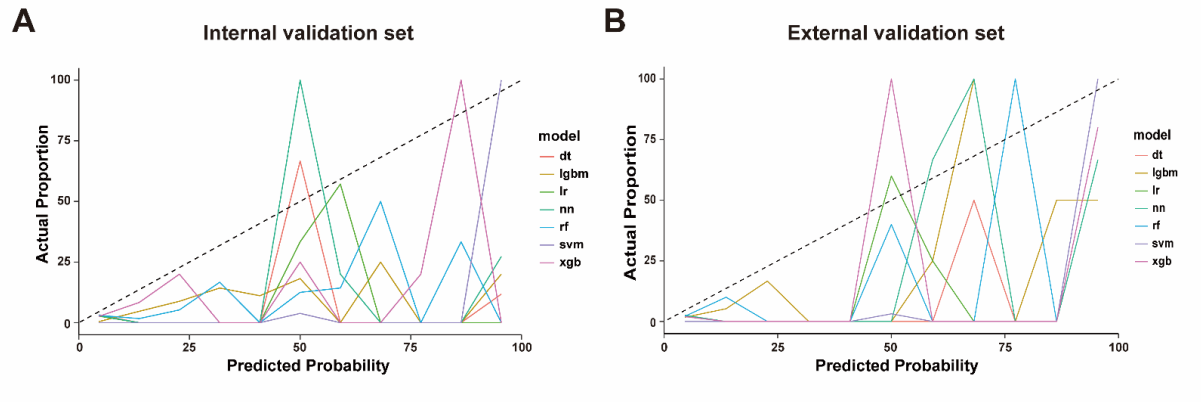
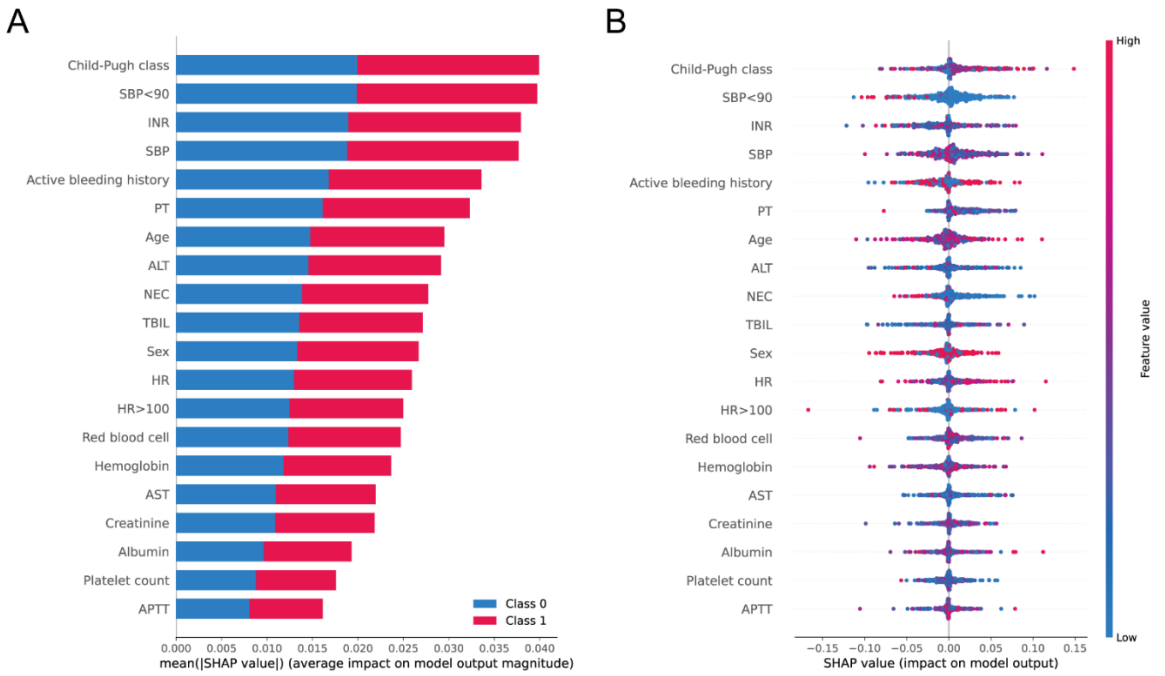


Supplementary Figure 1 Decision curve analysis of different models for clinical outcomes in AVB patients. A: Internal validation set; B: External validation set.



Supplementary Figure 2 Calibration curves of different models for clinical outcomes in AVB patients. A: Internal validation set; B: External validation set.



Supplementary Figure 3 SHAP analysis of feature Importance and impact for clinical outcomes in AVB patients.

Supplementary Table 1 Baseline characteristics and outcomes of AVB patients in the thirty different clinical centers

Characteristics	**North China (*n* = 885)**	**Northeast China (*n* = 74)**	**East China (*n* = 85)**	**West China (*n* = 112)**	**South China (*n* = 57)**	**Central China (*n* = 14)**
Demographic characteristics						
Age (years)	52.5 ± 11.5	56.3 ± 11.3	61.2 ± 12.3	58.7 ± 14.6	52.2 ± 18.1	53.1 ± 14.7
Sex, n (%)						
Male	639 (72.2)	51 (68.3)	63 (74.1)	77 (68.7)	37 (64.9)	10 (71.4)
Female	246 (27.8)	23 (31.7)	22 (25.9)	35 (31.3)	20 (35.1)	4 (28.6)
Etiology of cirrhosis, n (%)						
Chronic HBV infection	550 (62.1)	43 (58.1)	51 (60.0)	74 (66.1)	37 (64.9)	9 (64.3)
Chronic HCV infection	54 (6.1)	5 (6.8)	7 (8.2)	7 (6.3)	6 (10.5）	0 (0.0)
Alcohol	95 (10.7)	11 (14.9)	13 (15.3)	15 (13.4)	7 (12.3)	4 (28.6)
Others	111 (12.5)	9 (12.2)	9 (10.6)	8 (7.1)	3 (5.3)	1 (7.1)
Cryptogenic	75 (8.5)	6 (8.1)	5 (5.9)	8 (7.1)	4 (7.0)	0 (0.0)
Medical history						
Previous variceal bleeding, n (%)	323 (36.5)	32 (43.2)	35 (41.2)	47 (42.0)	25 (43.9)	6 (42.9)
Location of varices, n (%)						
Esophageal varices only	516 (58.3)	41 (55.4)	46 (54.1)	65 (58.0)	31 (54.4)	8 (57.1)

Esophageal and gastric varices	369 (41.7)	33 (44.6)	39 (45.9)	47 (42.0)	26 (45.6)	6 (42.9)
Hepatic encephalopathy, n (%)	85 (9.6)	7 (9.5)	7 (8.2)	11 (9.8)	4 (7.0)	1 (7.1)
Ascites, n (%)						
Mild	316 (35.7)	28 (37.8)	34 (40.0)	45 (40.2)	25 (43.9)	7 (50.0)
Moderate	138 (15.6)	11 (14.9)	15 (17.6)	15 (13.4)	13 (22.8)	3 (21.4)
Massive	62 (7.0)	7 (9.5)	6 (7.1)	8 (7.1)	4 (7.0)	1 (7.1)

Note: Data are mean (SD) or n (%) unless otherwise specified.

Abbreviations: AVB: acute variceal bleeding; HBV: hepatitis B virus; HCV: hepatitis C virus.

Supplementary Table 2 Comparison of performance for predicting 6-week treatment failure between AI-AVB model and other ML methods

	Cohort	Method	AUC	95% CI	ACC	SE	SP	PPV	NPV
6-week treatment failure	Internal validation cohort	SVM	0.819	0.678-0.960	0.940	0.444	0.968	0.444	0.968
		LR	0.752	0.484-1.000	0.940	0.556	0.962	0.455	0.974
		DT	0.808	0.640-0.976	0.964	0.556	0.987	0.714	0.975
		RF	0.828	0.635-1.000	0.958	0.556	0.981	0.625	0.975
		XGB	0.845	0.674-1.000	0.952	0.667	0.968	0.545	0.981
		LGBM	0.813	0.636-0.990	0.940	0.556	0.962	0.455	0.974
		AI-AVB	0.842	0.683-1.000	0.940	0.556	0.962	0.455	0.974

	External validation cohort	SVM	0.733	0.661-0.805	0.911	0.312	0.936	0.172	0.97
		LR	0.721	0.585-0.857	0.934	0.375	0.957	0.273	0.973
		DT	0.734	0.617-0.851	0.929	0.250	0.957	0.200	0.968
		RF	0.708	0.584-0.832	0.913	0.250	0.941	0.154	0.967
		XGB	0.788	0.687-0.889	0.918	0.312	0.944	0.192	0.97
		LGBM	0.799	0.754-0.905	0.913	0.250	0.941	0.154	0.967
		AI-AVB	0.814	0.702-0.926	0.939	0.312	0.965	0.278	0.971

ML: machine learning; SVM: support vector machine; LR: logistic regression; DT: decision tree; RF: random forest; XGB: XGBoost; LGBM: light gradient boosting; AI: artificial intelligence; AVB: acute variceal bleeding; AUC: area under the curve; CI: confidence interval; ACC: accuracy; SE: sensitivity; SP: specificity; PPV: positive predictive value; NPV: negative predictive value.

Supplementary Table 3 Comparison of performance for predicting 1-year mortality of AVB between AI-AVB model and other ML methods

	Cohort	**Method**	**AUC**	**95% CI**	**ACC**	**SE**	**SP**	**PPV**	**NPV**
1-year mortality	Internal validation cohort	SVM	0.890	0.828-0.952	0.928	0.250	0.962	0.250	0.962
		LR	0.733	0.571-0.894	0.940	0.250	0.975	0.333	0.963
		DT	0.792	0.606-0.978	0.964	0.500	0.987	0.667	0.975

	RF	0.939	0.838-1.000	0.970	0.875	0.975	0.636	0.994
	XGB	0.936	0.853-1.000	0.952	0.750	0.962	0.500	0.987
	LGBM	0.896	0.822-0.970	0.928	0.500	0.950	0.333	0.974
	AI-AVB	0.954	0.907-1.000	0.964	0.625	0.981	0.625	0.981
External validation cohort	SVM	0.678	0.544-0.812	0.908	0.273	0.927	0.097	0.978
	LR	0.849	0.732-0.967	0.957	0.455	0.971	0.313	0.984
	DT	0.736	0.579-0.894	0.957	0.273	0.976	0.250	0.979
	RF	0.842	0.730-0.955	0.964	0.364	0.982	0.364	0.982
	XGB	0.830	0.720-0.941	0.959	0.273	0.979	0.273	0.979
	LGBM	0.822	0.691-0.954	0.949	0.273	0.969	0.200	0.979
	AI-AVB	0.889	0.798-0.980	0.959	0.455	0.984	0.455	0.984

Abbreviations: ML: machine learning; SVM: support vector machine; LR: logistic regression; DT: decision tree; RF: random forest; XGB: XGBoost; LGBM: light gradient boosting; AUC: area under the curve; AI: artificial intelligence; AVB: acute variceal bleeding; ACC: accuracy; SE: sensitivity; SP: specificity; PPV: positive predictive value; NPV: negative predictive value.

Supplementary Table 4 Comparison of performance for predicting ICU requirement of AVB between AI-AVB model and other ML methods

Cohort	Method	AUC	95% CI	ACC	SE	SP	PPV	NPV

Requirement of ICU admission	Internal validation cohort	SVM	0.740	0.652-0.828	0.749	0.568	0.800	0.447	0.867
		LR	0.669	0.567-0.772	0.754	0.405	0.854	0.441	0.835
		DT	0.715	0.626-0.804	0.784	0.568	0.846	0.512	0.873
		RF	0.856	0.783-0.930	0.838	0.622	0.900	0.639	0.893
		XGB	0.853	0.776-0.930	0.844	0.649	0.900	0.649	0.900
		LGBM	0.830	0.754-0.905	0.832	0.649	0.885	0.615	0.898
		AI-AVB	0.866	0.806-0.927	0.832	0.595	0.900	0.629	0.886
	External validation cohort	SVM	0.720	0.660-0.779	0.742	0.420	0.826	0.386	0.845
		LR	0.685	0.613-0.756	0.765	0.444	0.849	0.434	0.854

	DT	0.638	0.581-0.695	0.778	0.395	0.878	0.457	0.848
	RF	0.799	0.740-0.857	0.806	0.531	0.878	0.531	0.878
	XGB	0.804	0.749-0.859	0.811	0.519	0.887	0.545	0.876
	LGBM	0.785	0.726-0.844	0.804	0.543	0.871	0.524	0.880
	AI-AVB	0.812	0.757-0.867	0.819	0.568	0.884	0.561	0.887

Abbreviations: ML: machine learning; SVM: support vector machine; LR: logistic regression; DT: decision tree; RF: random forest; XGB: XGBoost; LGBM: light gradient boosting; AUC: area under the curve; AI: artificial intelligence; AVB: acute variceal bleeding; ACC: accuracy; SE: sensitivity; SP: specificity; PPV: positive predictive value; NPV: negative predictive value.

Supplementary Table 5 Causes of death in AVB patients treated with EVL+PT or p-TIPS

Cause of Death	**EVL+PT cohort**		**p-TIPS cohort**	
	High-risk group (n = 82)	Low-risk group (n = 141)	High-risk group (n = 103)	Low-risk group (n = 121)
Liver failure	28 (34.1)	28 (19.9)	35 (34.0)	34 (28.1)

Variceal rebleeding	26 (31.7)	55 (39.0)	5 (4.9)	3 (2.5)
Hepatic encephalopathy	10 (12.2)	22 (15.6)	37 (35.9)	49 (40.5)
Bacterial infection / MSOF	6 (7.3)	8 (5.7)	12 (11.7)	15 (12.4)
Other / NA	12 (14.6)	28 (19.9)	14 (13.6)	23 (19.0)

Note: Data are n (%). Abbreviations: MSOF: multi systemic organ failure; NA: not available.

Supplementary Table 6 Summary of p-TIPS outcomes using different stent diameters

Variables	**< 8mm**	**8 mm**	**10 mm**	
	(n=198)	(n=1579)	(n=89)	*P*-vlaue
Outcome measurements				
6-week treatment failure to control bleeding, n (%)	4 (1.9)	34 (2.1)	2 (2.2)	0.224
ICU requirement, n (%)	39 (19.6)	244 (15.5)	12 (13.5)	0.093
1-year mortality, n (%)	25 (12.6)	187 (11.8)	12 (13.5)	0.061
Treatment-related adverse events				
Hepatic encephalopathy, n (%)	37 (18.7)	529 (33.5)	33 (37.1)	0.005
New or worsening ascites, n (%)	4 (1.9)	16 (1.0)	0 (0.0)	0.088

Supplementary Table 7 Risk of clinical outcomes using competitive risk approaches in the whole, high-risk and low-risk

population

Variables	Groups	Raw analysis	*P*-value	Adjusted treatment weighting	
		HR (95% CI)		HR (95% CI)	*P*-value
Failure to control bleeding/rebleeding					
	All	0.295 (0.185-0.478)	<0.001	0.315 (0.235-0.392)	<0.001
	Low-risk	0.289 (0.178-0.448)	<0.001	0.305 (0.182-0.488)	<0.001
	High-risk	0.332 (0.215-0.473)	<0.001	0.376 (0.254-0.547)	<0.001
1-year mortality					
	All	0.512 (0.295-0.883)	0.017	0.518 (0.298-0.881)	0.021
	Low-risk	0.609 (0.376-1.048)	0.053	0.686 (0.462-1.069)	0.064
	High-risk	0.463 (0.341-0.625)	<0.001	0.426 (0.312-0.593)	0.010
ICU requirement					
	All	0.876 (0.864-0.941)	0.122	0.924 (0.905-1.012)	0.164
	Low-risk	0.926 (0.843-0.939)	0.199	0.942 (0.843-0.987)	0.114
	High-risk	0.809 (0.748-0.891)	0.096	0.910 (0.841-0.994)	0.095
Hepatic encephalopathy					
	All	1.278 (0.993-1.648)	0.066	1.227 (0.993-1.468)	0.098
	Low-risk	1.336 (1.190-1.455)	0.047	1.268 (1.105-1.424)	0.031
	High-risk	1.209 (0.984-1.456)	0.072	1.185 (0.815-1.790)	0.140

New or worsening ascites					
	All	0.265 (0.175-0.402)	<0.001	0.286 (0.128-0.420)	<0.001
	Low-risk	0.365 (0.192-0.703)	0.002	0.315 (0.162-0.612)	0.001
	High-risk	0.207 (0.122-0.359)	<0.001	0.242 (0.148-0.396)	<0.001

Supplementary Table 8 Prediction performance for 6-week treatment failure of different clinical risk scores

	Cohort	**Method**	**AUC**	**95% CI**	**ACC**	**SE**	**SP**	**PPV**	**NPV**
6-week treatment failure	Internal validation cohort	Chile-Pugh class	0.708	0.509-0.908	0.856	0.556	0.873	0.200	0.972
		MELD score	0.615	0.423-0.807	0.545	0.889	0.525	0.096	0.988
		Baveno VII criteria	0.634	0.541-0.689	0.666	0.616	0.687	0.425	0.526
		Early TIPS criteria	0.708	0.619-0.776	0.809	0.790	0.828	0.631	0.686
		ALBI	0.641	0.416-0.866	0.605	0.778	0.595	0.099	0.979
		FIB-4	0.529	0.330-0.728	0.539	0.667	0.532	0.075	0.966

External validation cohort	Child-Pugh class	0.671	0.569-0.773	0.383	0.938	0.359	0.059	0.993
	MELD score	0.624	0.502-0.763	0.617	0.750	0.612	0.076	0.983
	Baveno VII criteria	0.704	0.628-0.788	0.870	0.828	0.725	0.701	0.655
	Early TIPS criteria	0.685	0.627-0.773	0.606	0.511	0.579	0.498	0.600
	ALBI	0.619	0.459-0.779	0.559	0.750	0.550	0.066	0.981
	FIB-4	0.598	0.421-0.775	0.648	0.625	0.649	0.070	0.976

MELD: model for end-stage liver disease; AUC: area under the curve; CI: confidence interval; ACC: accuracy; SE: sensitivity; SP: specificity; PPV: positive predictive value; NPV: negative predictive value.

Supplementary Table 9 Prediction performance for 1-year mortality of different clinical risk scores

	Cohort	**Method**	**AUC**	**95% CI**	**ACC**	**SE**	**SP**	**PPV**	**NPV**
1-year mortality	Internal validation cohort	Child-Pugh class	0.605	0.517-0.694	0.749	0.270	0.885	0.400	0.810

	MELD score	0.658	0.565-0.751	0.629	0.703	0.608	0.338	0.878
	Baveno VII criteria	0.644	0.571-0.729	0.621	0.610	0.599	0.533	0.475
	Early TIPS criteria	0.639	0.586-0.736	0.620	0.547	0.599	0.427	0.535
	ALBI	0.627	0.519-0.737	0.689	0.731	0.541	0.364	0.848
	FIB-4	0.599	0.496-0.701	0.629	0.541	0.654	0.307	0.833
External validation cohort	Child-Pugh class	0.574	0.502-0.647	0.704	0.370	0.791	0.316	0.828
	MELD score	0.618	0.555-0.681	0.467	0.790	0.383	0.250	0.875
	Baveno VII criteria	0.614	0.554-0.672	0.661	0.665	0.673	0.519	0.580
	Early TIPS criteria	0.578	0.484-0.666	0.667	0.623	0.681	0.465	0.506
	ALBI	0.607	0.536-0.678	0.584	0.679	0.559	0.286	0.870
	FIB-4	0.549	0.479-0.619	0.628	0.506	0.659	0.279	0.837

MELD: model for end-stage liver disease; AUC: area under the curve; CI: confidence interval; ACC: accuracy; SE: sensitivity; SP: specificity; PPV: positive predictive value; NPV: negative predictive value.

Supplementary Table 10 Prediction performance for ICU requirement of different clinical risk scores

	Cohort	**Method**	**AUC**	**95% CI**	**ACC**	**SE**	**SP**	**PPV**	**NPV**
Requirement of ICU admission	Internal validation cohort	Child-Pugh class	0.567	0.477-0.660	0.661	0.677	0.507	0.522	0.425

		MELD score	0.680	0.619-0.739	0.596	0.600	0.568	0.462	0.515
		Baveno VII criteria	0.693	0.615-0.748	0.511	0.642	0.613	0.447	0.482
		Early TIPS criteria	0.621	0.546-0.689	0.576	0.540	0.519	0.547	0.454
	External validation cohort	Child-Pugh class	0.545	0.472-0.637	0.689	0.604	0.567	0.492	0.470
		MELD score	0.649	0.575-0.705	0.567	0.645	0.560	0.542	0.473
		Baveno VII criteria	0.702	0.637-0.756	0.787	0.710	0.737	0.715	0.721
		Early TIPS criteria	0.591	0.506-0.687	0.631	0.671	0.530	0.563	0.535

MELD: model for end-stage liver disease; AUC: area under the curve; CI: confidence interval; ACC: accuracy; SE: sensitivity; SP: specificity; PPV: positive predictive value; NPV: negative predictive value.