

Supplementary material

1. Hepatic venous pressure gradient measurement

The hepatic venous pressure gradient (HVPG) measurement was performed by two experienced interventional experts. Calibration of the pressure sensor was first performed, and a catheter sheath was thereafter inserted and placed in the right internal jugular vein. Under X-ray guidance, the catheter passed through the superior vena cava and the right atrium sequentially to reach the right hepatic vein. The free hepatic venous pressure (FHVP) was measured with the deflated balloon, whereas the wedged hepatic venous pressure (WHVP) was measured with the inflated balloon completely blocking the blood flow of the right hepatic vein. The HVPG was calculated as the WHVP minus the FHVP. The HVPG was measured and calculated three times for each patient, and the mean of the three values was recorded as the HVPG value for further study.

2. Acquisition of CT images

In this study, upper abdominal contrast-enhanced computed tomography (CT) was performed in accordance with the standard protocol under the following default settings (tube voltage: 120 kVp or 100 kVp; tube current: 150-600 mA; slice thickness: 1.25 mm; pitch: 1.375). All patients received intravenous injection of a non-ionic contrast agent (Iopromide injection, iodine concentration of 370 mg/mL), with a dosage of 1.5-2.0 ml/kg and an injection rate of 3-5 ml/s. After the injection of the contrast agent, an additional 20 ml of normal saline was injected to ensure complete delivery of the contrast agent. The complete contrast-enhanced CT images included non-contrast phase, arterial phase, portal venous phase, and delayed phase. The arterial phase scanning was conducted 20-30 seconds after the initiation of contrast agent injection, followed by the portal venous phase 20-30 seconds after the beginning of the arterial phase. The interval between the portal venous and delayed phases was adjusted according to the image quality, ranging from 10-30 seconds.

3. ROIs delineation process and consistency evaluation

The delineation of region of interests (ROIs) was primarily performed by two medical researchers in our study (annotator Guo and annotator Han) with 6 and 3 years of clinical experience in gastroenterology and hepatology, respectively. Then all segmented ROIs were subsequently reviewed by a senior hepatologist with 20 years of clinical expertise in liver diseases and portal hypertension (annotator Tong). To objectively evaluate the reproducibility of ROIs delineation, we randomly selected a subset of 10 patients from our dataset. Both annotator Guo and annotator Han independently re-segmented the ROIs for this subset after a washout period of 5 days to prevent memory bias. Annotator Tong also independently segmented the same subset, completely blinded to the initial contours drawn by Annotators Guo and Han. We then used the Dice Similarity Coefficient (DSC) to evaluate the agreement among all three observers. As a result, the intra-observer DSCs for annotator Guo and annotator Han were 0.92 and 0.90, respectively. The inter-observer variability among the three observers achieved a mean pairwise DSC of 0.86, which demonstrated the reliability and reproducibility of our manual ROIs delineation process.

4. Multimodal fusion strategy

In the present study, we employed a late fusion (or post-network fusion) approach based on vector concatenation. Specifically, each of the four computed tomography (CT) image sections was independently processed by the transformer backbone to extract image features, which were subsequently concatenated to generate a unified imaging feature vector. The Child-Pugh classification, encoded as a clinical feature, was then appended to the above imaging feature vector through direct concatenation for late multimodal fusion (Supplementary Figure 1). The fused feature vector was finally fed into the classification layer for hepatic venous pressure gradient (HVPG) prediction.

5. Mathematical description of Boundary-Aware Weighted (BAW) loss

The BAW loss improves learning on imbalanced data by adaptive sample weighting that prioritizes underrepresented hepatic venous pressure gradient (HVPG) ranges through dynamically adjusting loss contributions, and boundary constraints that regulate gradient updates based on data density-expanding margins for sparse regions to enhance feature learning while contracting them for dense regions to prevent overfitting. This dual approach effectively balances model focus across the entire HVPG distribution. The BAW loss function is defined as follows:

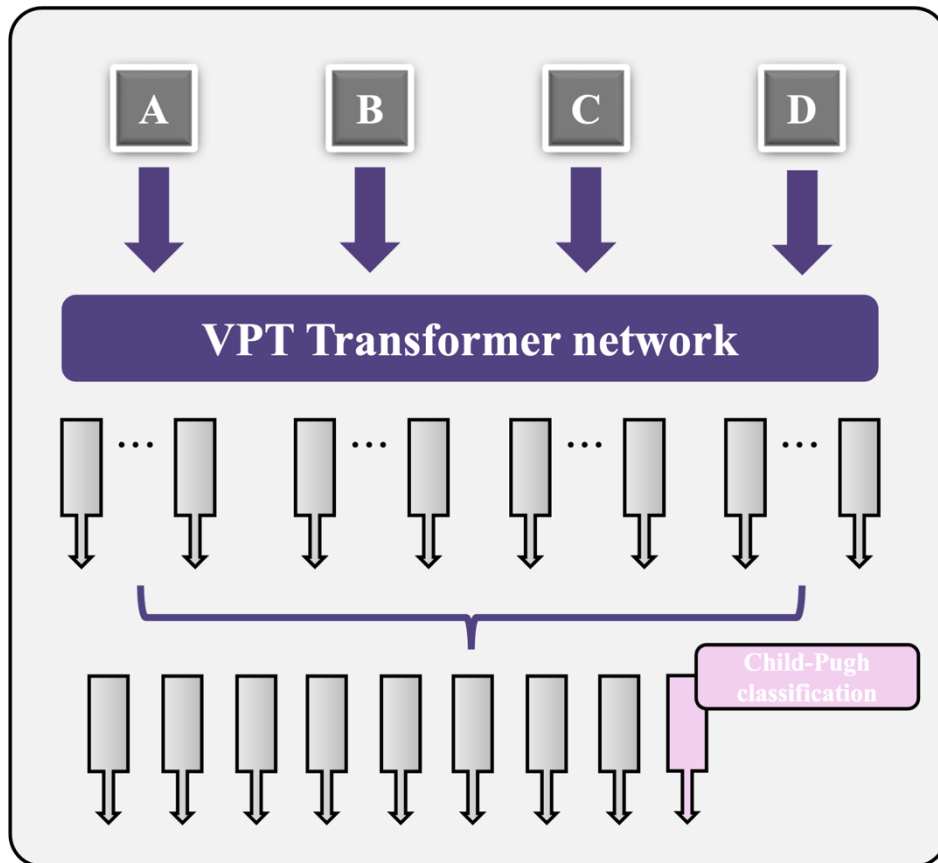
$$L_{\text{BAW}} = \frac{1}{N} \left(\sum_{i=1}^N \{\max(0, w_i \cdot \rho_i - M)\} + \lambda \sum_{j=1}^{B_{in}} (w_j \cdot N_j) \right),$$

where $\rho_i = \delta^2 \cdot \left(\sqrt{1 + \left(\frac{y_i - \hat{y}_i}{\delta} \right)^2} - 1 \right)$ computes the Pseudo-Huber loss for sample i with true label y_i and predicted value $\hat{y}_i$, δ being the hyperparameter. The bucket configuration uses B_{in} in sub-buckets, where w_j and N_j denote the weight and sample count of bucket j respectively.

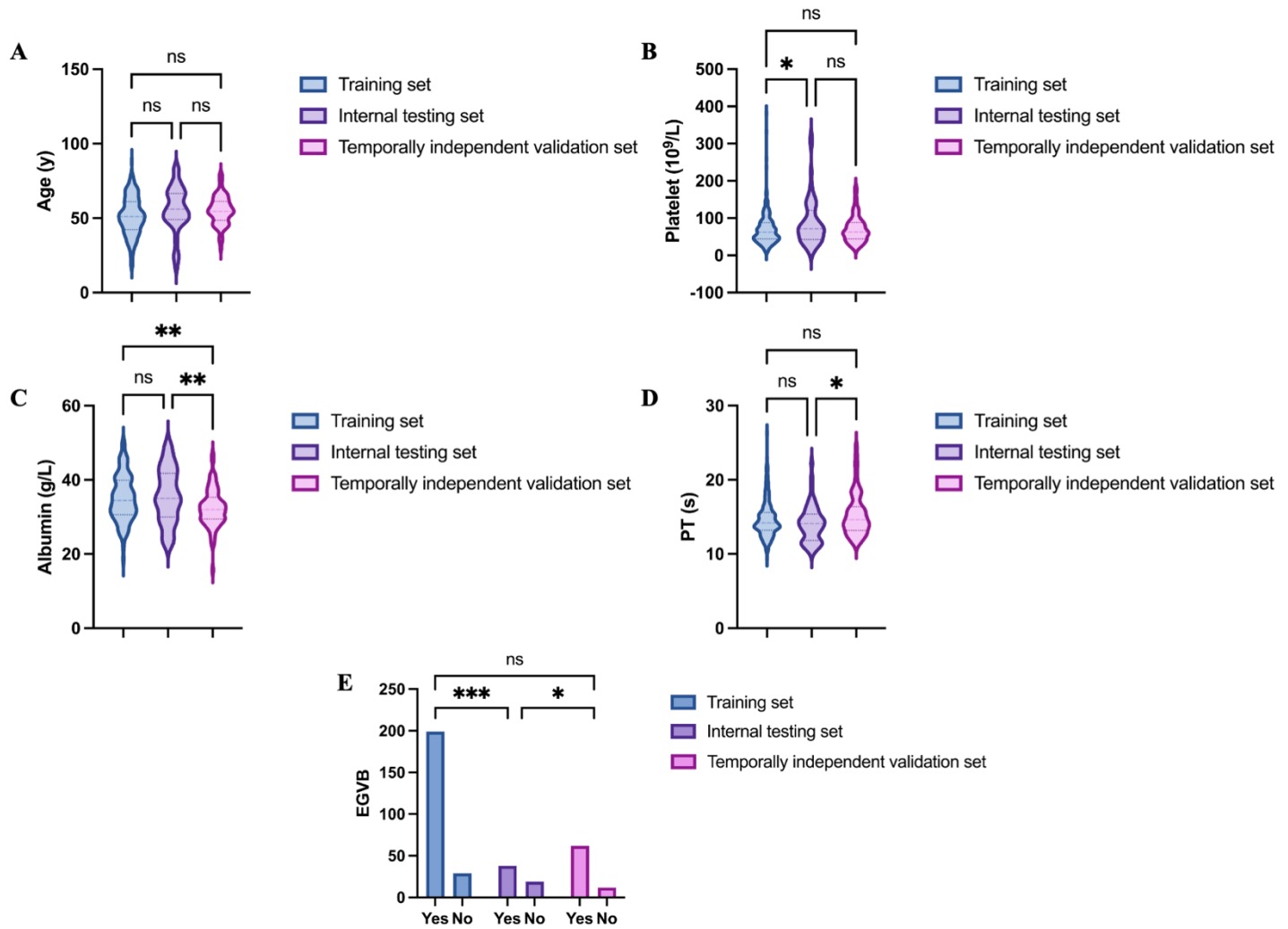
6. Procedure of liver stiffness measurement

Liver stiffness measurement (LSM) was performed by professional ultrasound technicians using the Resona 7 color Doppler ultrasound system (Mindray, Shenzhen, China) with real-time Sound Touch Elastography (STE) technology. A convex array transducer (SC5-1U, 1.0–5.0 MHz) with optimized adult liver presets was utilized for all examinations. Patients fasted for at least 4 hours prior to the examination. During the procedure, patients maintained a supine position with the right arm maximally abducted above the head to widen the intercostal spaces and optimize the acoustic window. The transducer was placed in the right intercostal space along the mid-axillary line (typically

between the 9th and 11th intercostal spaces) and oriented perpendicular to the liver capsule. A baseline B-mode scan was first conducted to locate the right liver lobe, avoiding large intrahepatic vessels, the gallbladder, and focal lesions. Then the measurement region of interest (ROI) box (approximately 2 cm × 2 cm) was placed in the liver parenchyma, and measurements were captured during a brief breath-hold at the end of normal expiration once a stable, uniform elastography color map was displayed. To ensure the data reproducibility, at least 10 valid measurements were acquired for each patient and the median value of all valid measurements was recorded as the final liver stiffness value and expressed in kilopascals (kPa). An examination was considered reliable only if the interquartile range-to-median ratio (IQR/Med) was $\leq 30\%$.



Supplementary Figure 1 Multimodal feature fusion strategy. A, B, C and D refer to the four CT image sections. VPT: visual prompt tuning.



Supplementary Figure 2 Post-hoc pairwise analysis. Subsequent post-hoc pairwise analysis revealed that only platelet counts and history of EGVB presented significant differences in the training and internal testing sets. PT: prothrombin time; EGVB: esophagogastric variceal bleeding.

Supplementary Table 1 Calculation formulas of conventional non-invasive models

Models	Calculation formulas
AAR	AST / ALT
APRI	$(AST / ULN) / \text{platelet} \times 100$
CSPH risk score	$-0.193 - 0.359 \times \text{albumin} + 16.456 \times \text{INR} - 0.016 \times \text{ALT}$
FIB-4	$\text{age} \times AST / (\text{platelet} \times \text{ALT}^{1/2})$
Fibrosis Index	$8.28 - 0.01 \times \text{platelet} - \text{albumin}$
GPR	$\gamma\text{-GGT} / \text{platelet}$
King's score	$\text{age} \times AST \times \text{INR} / \text{platelet}$
Lok score	$-5.56 - 0.0089 \times \text{platelet} + 1.26 \times \text{AST} / \text{ALT} + 5.27 \times \text{INR}$
ANTICIPATE model	$-6.3320165 + 3.1001014 \times \ln(\text{LSM}) - 0.020481545 \times \text{platelet}$ (platelet counts > 150 introduced as 150)

AAR: AST-to-ALT ratio; APRI: AST-to-platelet count ratio index; CSPH: clinically significant portal hypertension; FIB-4: fibrosis index based on four factors; GPR: GGT-to-platelet count ratio; AST: aspartate aminotransferase; ALT: alanine aminotransferase; ULN: upper limit of normal; INR: international normalized ratio; γ -GGT: gamma-glutamyltransferase; LSM: liver stiffness measurement.

Supplementary Table 2 Diagnostic performance of conventional non-invasive models for different hepatic venous pressure gradient thresholds

HVPG	Model	Sensitivity (95%CI)	Specificity (95%CI)	PPV (95%CI)	NPV (95%CI)	AUC (95%CI)
> 5 mmHg	LSM	0.800 (0.659, 0.895)	0.917 (0.598, 0.996)	0.976 (0.856, 0.999)	0.524 (0.303, 0.736)	0.897 (0.806, 0.987)
	AAR	0.920 (0.799, 0.974)	0.250 (0.067, 0.572)	0.836 (0.707, 0.918)	0.428 (0.118, 0.798)	0.600 (0.436, 0.764)
	APRI	0.860 (0.726, 0.937)	0.500 (0.223, 0.777)	0.878 (0.745, 0.949)	0.462 (0.204, 0.739)	0.642 (0.439, 0.844)
	CSPH risk score	0.478 (0.374, 0.584)	0.917 (0.598, 0.996)	0.978 (0.868, 0.999)	0.186 (0.101, 0.313)	0.727 (0.585, 0.870)
	FIB-4	0.880 (0.792, 0.936)	0.500 (0.223, 0.777)	0.931 (0.850, 0.972)	0.353 (0.153, 0.614)	0.589 (0.360, 0.819)
	Fibrosis Index	0.848 (0.754, 0.911)	0.583 (0.286, 0.835)	0.940 (0.859, 0.978)	0.333 (0.155, 0.569)	0.663 (0.446, 0.880)
	GPR	0.870 (0.779, 0.928)	0.333 (0.113, 0.646)	0.909 (0.824, 0.957)	0.250 (0.083, 0.526)	0.584 (0.401, 0.767)
	King's score	0.880 (0.792, 0.936)	0.500 (0.223, 0.777)	0.931 (0.850, 0.972)	0.353 (0.153, 0.614)	0.632 (0.424, 0.840)

≥ 10 mmHg	Lok score	0.652 (0.545, 0.747)	0.750 (0.428, 0.933)	0.952 (0.858, 0.988)	0.220 (0.111, 0.380)	0.717 (0.569, 0.864)
	ANTICIPATE model	0.740 (0.594, 0.849)	0.750 (0.428, 0.933)	0.925 (0.785, 0.980)	0.409 (0.215, 0.633)	0.797 (0.665, 0.928)
	LSM	0.705 (0.546, 0.828)	0.778 (0.519, 0.926)	0.886 (0.723, 0.963)	0.519 (0.324, 0.708)	0.794 (0.663, 0.925)
	AAR	0.590 (0.477, 0.695)	0.714 (0.477, 0.878)	0.891 (0.771, 0.955)	0.306 (0.187, 0.456)	0.649 (0.516, 0.782)
	APRI	0.880 (0.785, 0.938)	0.429 (0.226, 0.656)	0.859 (0.762, 0.922)	0.474 (0.252, 0.705)	0.669 (0.532, 0.806)
	CSPH risk score	0.530 (0.418, 0.639)	0.857 (0.626, 0.962)	0.936 (0.814, 0.983)	0.316 (0.203, 0.454)	0.722 (0.601, 0.844)
	FIB-4	0.916 (0.829, 0.963)	0.429 (0.226, 0.656)	0.864 (0.770, 0.925)	0.563 (0.306, 0.792)	0.662 (0.511, 0.814)
	Fibrosis Index	0.892 (0.799, 0.946)	0.571 (0.344, 0.774)	0.892 (0.799, 0.946)	0.571 (0.344, 0.774)	0.728 (0.574, 0.881)
	GPR	0.783 (0.676, 0.863)	0.476 (0.264, 0.697)	0.855 (0.752, 0.922)	0.357 (0.193, 0.559)	0.610 (0.472, 0.748)
	King's score	0.904 (0.814, 0.954)	0.429 (0.226, 0.656)	0.862 (0.768, 0.924)	0.529 (0.285, 0.761)	0.652 (0.506, 0.799)
	Lok score	0.675 (0.562, 0.771)	0.714 (0.477, 0.878)	0.903 (0.795, 0.960)	0.357 (0.220, 0.520)	0.722 (0.585, 0.859)

≥ 12 mmHg	ANTICIPATE model	0.500 (0.348, 0.652)	0.778 (0.519, 0.926)	0.846 (0.643, 0.950)	0.389 (0.236, 0.565)	0.806 (0.693, 0.918)
	LSM	0.976 (0.856, 0.999)	0.476 (0.264, 0.697)	0.784 (0.643, 0.882)	0.909 (0.571, 0.995)	0.754 (0.615, 0.893)
	AAR	0.575 (0.460, 0.683)	0.625 (0.408, 0.804)	0.836 (0.707, 0.918)	0.306 (0.187, 0.456)	0.576 (0.438, 0.714)
	APRI	0.813 (0.706, 0.888)	0.542 (0.332, 0.738)	0.855 (0.752, 0.922)	0.464 (0.280, 0.658)	0.703 (0.579, 0.828)
	CSPH risk score	0.788 (0.679, 0.868)	0.583 (0.369, 0.772)	0.863 (0.758, 0.929)	0.452 (0.278, 0.637)	0.720 (0.602, 0.838)
	FIB-4	0.663 (0.547, 0.762)	0.708 (0.488, 0.866)	0.883 (0.768, 0.948)	0.386 (0.247, 0.545)	0.675 (0.539, 0.811)
	Fibrosis Index	0.925 (0.838, 0.969)	0.625 (0.408, 0.804)	0.892 (0.799, 0.946)	0.714 (0.477, 0.878)	0.765 (0.627, 0.903)
	GPR	0.788 (0.679, 0.868)	0.458 (0.262, 0.668)	0.829 (0.721, 0.902)	0.393 (0.221, 0.593)	0.599 (0.465, 0.733)
	King's score	0.788 (0.679, 0.868)	0.542 (0.332, 0.738)	0.851 (0.745, 0.920)	0.433 (0.260, 0.623)	0.681 (0.549, 0.812)
	Lok score	0.688 (0.573, 0.784)	0.708 (0.488, 0.866)	0.887 (0.775, 0.950)	0.405 (0.260, 0.567)	0.700 (0.567, 0.832)
	ANTICIPATE model	0.805 (0.646, 0.906)	0.667 (0.431, 0.845)	0.825 (0.666, 0.921)	0.636 (0.408, 0.820)	0.801 (0.692, 0.911)

≥ 16 mmHg	LSM	0.973 (0.842, 0.999)	0.400 (0.218, 0.611)	0.706 (0.560, 0.821)	0.909 (0.571, 0.995)	0.727 (0.595, 0.859)
	AAR	0.838 (0.730, 0.910)	0.367 (0.205, 0.561)	0.765 (0.656, 0.849)	0.478 (0.274, 0.689)	0.584 (0.458, 0.711)
	APRI	0.824 (0.715, 0.900)	0.500 (0.317, 0.683)	0.803 (0.692, 0.882)	0.536 (0.342, 0.720)	0.687 (0.569, 0.804)
	CSPH risk score	0.500 (0.383, 0.617)	0.900 (0.723, 0.974)	0.925 (0.785, 0.980)	0.422 (0.302, 0.552)	0.730 (0.624, 0.836)
	FIB-4	0.716 (0.598, 0.812)	0.767 (0.573, 0.894)	0.883 (0.768, 0.948)	0.523 (0.369, 0.673)	0.737 (0.621, 0.854)
	Fibrosis Index	0.851 (0.745, 0.920)	0.700 (0.504, 0.846)	0.875 (0.771, 0.938)	0.656 (0.468, 0.808)	0.759 (0.628, 0.890)
	GPR	0.784 (0.670, 0.868)	0.400 (0.232, 0.592)	0.763 (0.649, 0.850)	0.429 (0.250, 0.626)	0.562 (0.439, 0.685)
	King's score	0.743 (0.626, 0.835)	0.633 (0.439, 0.795)	0.833 (0.717, 0.910)	0.500 (0.337, 0.663)	0.724 (0.612, 0.837)
	Lok score	0.622 (0.501, 0.730)	0.800 (0.609, 0.916)	0.885 (0.759, 0.952)	0.462 (0.325, 0.604)	0.725 (0.611, 0.838)
≥ 20 mmHg	ANTICIPATE model	0.865 (0.704, 0.949)	0.680 (0.464, 0.843)	0.800 (0.639, 0.904)	0.773 (0.542, 0.913)	0.832 (0.734, 0.931)
	LSM	0.579 (0.340, 0.789)	0.698 (0.537, 0.823)	0.458 (0.262, 0.668)	0.789 (0.622, 0.899)	0.632 (0.483, 0.782)

AAR	0.806 (0.634, 0.912)	0.309 (0.205, 0.434)	0.382 (0.275, 0.501)	0.750 (0.548, 0.886)	0.516 (0.400, 0.633)
APRI	0.750 (0.575, 0.873)	0.500 (0.377, 0.623)	0.443 (0.318, 0.575)	0.791 (0.635, 0.894)	0.640 (0.533, 0.747)
CSPH risk score	0.556 (0.383, 0.717)	0.721 (0.597, 0.819)	0.513 (0.350, 0.673)	0.754 (0.629, 0.849)	0.615 (0.503, 0.727)
FIB-4	0.778 (0.604, 0.893)	0.632 (0.506, 0.744)	0.528 (0.388, 0.665)	0.843 (0.709, 0.925)	0.672 (0.568, 0.777)
Fibrosis Index	0.972 (0.838, 0.999)	0.368 (0.256, 0.494)	0.449 (0.337, 0.565)	0.962 (0.784, 0.998)	0.616 (0.511, 0.722)
GPR	0.111 (0.036, 0.270)	0.956 (0.868, 0.989)	0.571 (0.202, 0.882)	0.670 (0.566, 0.760)	0.517 (0.400, 0.634)
King's score	0.861 (0.697, 0.948)	0.500 (0.377, 0.623)	0.477 (0.353, 0.604)	0.872 (0.718, 0.952)	0.655 (0.550, 0.760)
Lok score	0.556 (0.383, 0.717)	0.676 (0.551, 0.782)	0.476 (0.323, 0.634)	0.742 (0.613, 0.841)	0.599 (0.488, 0.710)
ANTICIPATE model	0.526 (0.295, 0.748)	0.837 (0.687, 0.927)	0.588 (0.335, 0.806)	0.800 (0.649, 0.899)	0.710 (0.570, 0.850)

HVPG: hepatic venous pressure gradient; PPV: positive predictive value; NPV: negative predictive value; AUC: area under the receiver operating characteristic curve; CI: confidence interval; LSM: liver stiffness measurement; AAR: AST-to-ALT ratio; APRI: AST-to-platelet count ratio index; CSPH: clinically significant portal hypertension; FIB-4: fibrosis index based on four factors; GPR: GGT-to-platelet count ratio.