

INTRODUCTION OF CT EQUIPMENT

Contrast-enhanced computed tomography (CECT) was performed using a GE Lightspeed 4-row CT scanner, GE Gemstone 128-slice spiral CT scanner, or GE Lightspeed VCT 64-row CT scanner. All patients first underwent a plain abdominal CT scan to determine the lesion extent. The abdominal CT acquisition parameters were as follows: tube voltage, 120 kVp; tube current, 250–350 mA; slice thickness, 5 mm; slice interval, 5 mm; field of view, 35–50 cm; matrix, 512×512 ; rotation time, 0.7 s; and pitch, 1.375:1.

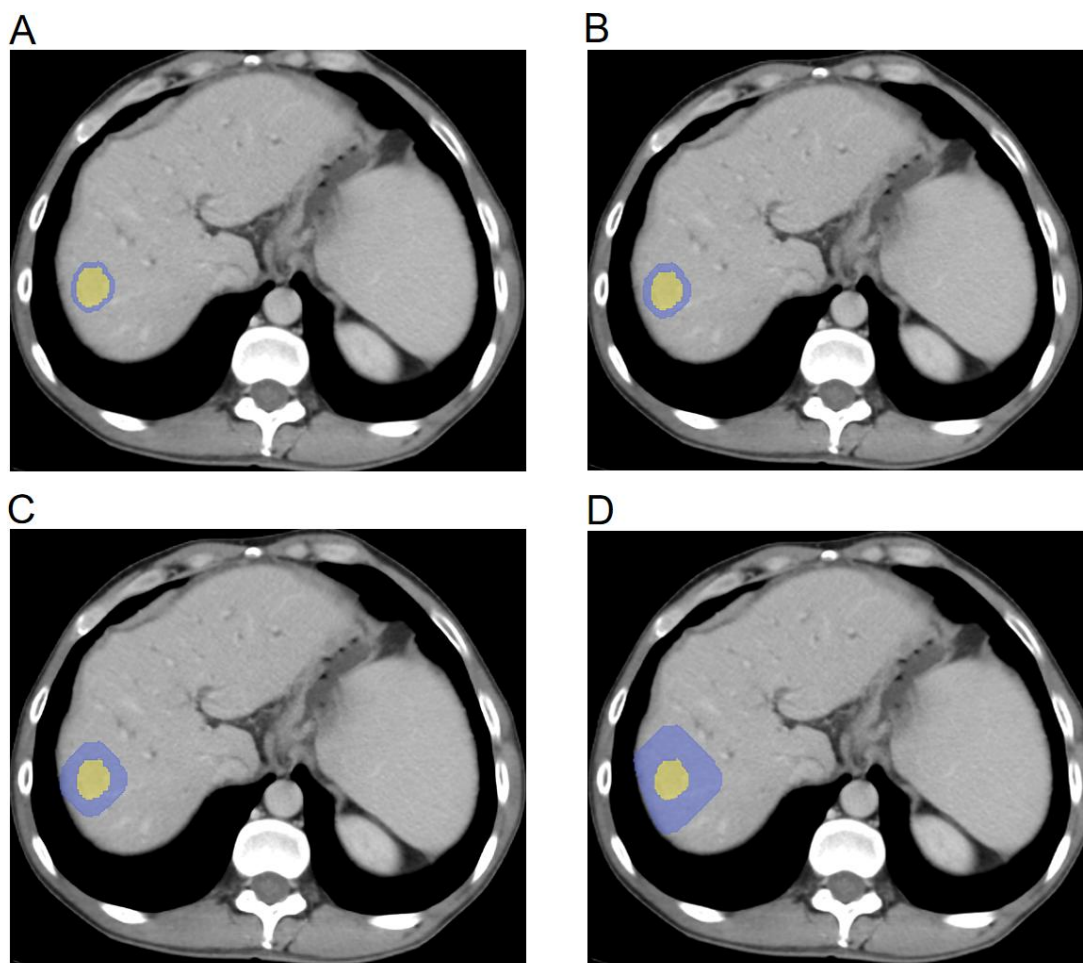
After the plain scan, a nonionic iodinated contrast agent was intravenously injected at a rate of 3.0 mL/s and a dose of 1.5 mL/kg. The arterial phase scan was acquired using bolus tracking, with scanning initiated after the attenuation of the descending aorta reached 95 HU. Portal venous phase and delayed phase scans were performed approximately 35 s and 3 min after the arterial phase scan, respectively.

To reduce heterogeneity related to CT scanners and acquisition protocols, all CECT images underwent a standardized preprocessing pipeline before feature extraction, including image resampling, intensity normalization, and outlier truncation. This preprocessing procedure was applied consistently to all images from the training, internal validation, and external validation cohorts.

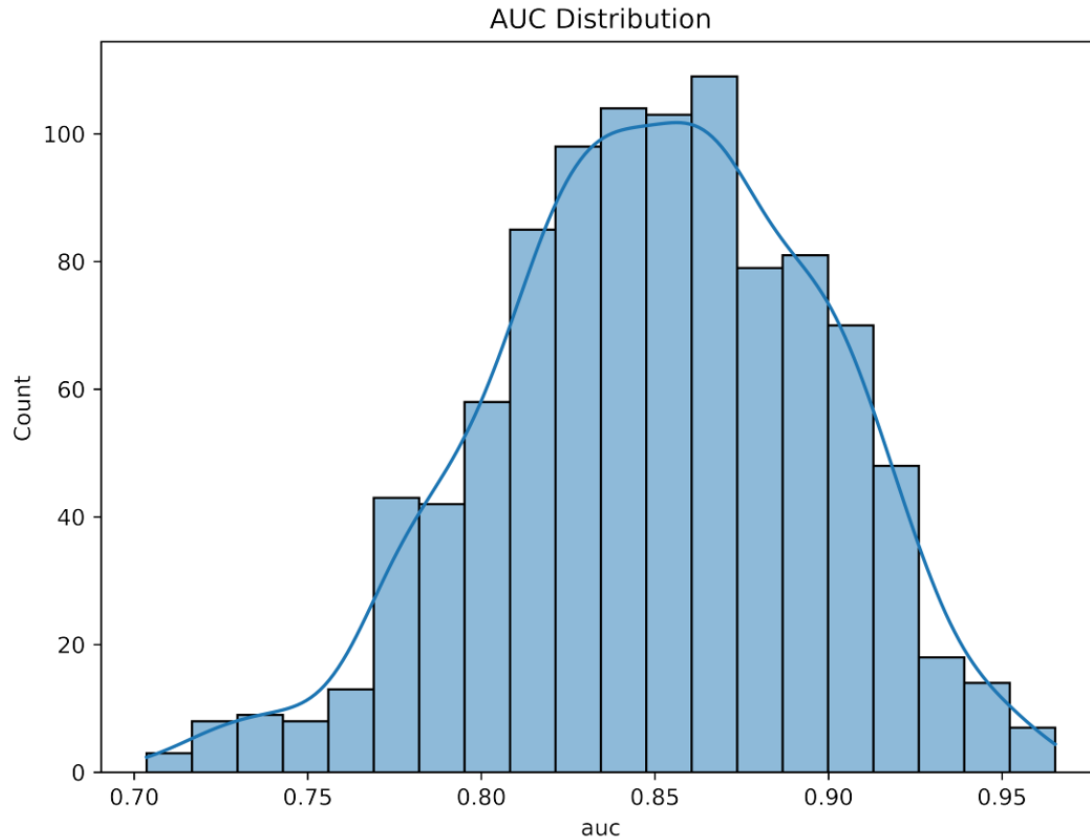
IMPLEMENTATION OF THE 3D RESNET-18 MODEL FOR DEEP FEATURE EXTRACTION

Prior to deep feature extraction, the pre-trained 3D ResNet-18 model implemented in PyTorch (version 2.1.2) was adaptively modified to ensure its suitability for this study. The original 3D ResNet-18 architecture is designed to process three-channel volumetric inputs, whereas the CT images used in this study are single-channel grayscale volumes. Therefore, the first convolutional layer of the network was modified to accept single-channel input, enabling proper processing of CT data while preserving the overall network architecture. Furthermore, to adapt the model for feature extraction rather than classification, the final fully connected layer was

removed. After this modification, the network outputs a 512-dimensional feature vector for each input sample. This design allows effective extraction of high-level semantic features while avoiding potential overfitting associated with task-specific fully connected layers. To ensure consistency with radiomics analysis, the regions used for deep learning feature extraction were aligned with the predefined regions of interest (ROIs), including both tumor and peritumoral regions. For each ROI, a total of 512 deep learning features were extracted and subsequently used for downstream analysis and model construction.



Supplementary Figure 1 Erosion and dilation algorithms in Python were used to expand different peritumoral regions from 3 mm to 20 mm. A: Peritumoral region after expansion by 3 mm; B: Peritumoral region after expansion by 5 mm; C: Peritumoral region after expansion by 10 mm; D: Peritumoral region after expansion by 20 mm.



Supplementary Figure 2 Robustness assessment of the combined model using bootstrapping with 1000 iterations. The histogram illustrates the distribution of area under the curve values obtained across 1000 bootstrap resamples of the validation set, with the overlaid curve representing the kernel density estimate. The results confirm the stability of the combined model's predictive performance. AUC: Area under the curve.

Supplementary Table 1 Univariable and multivariable analysis of baseline clinical and imaging factors associated with early recurrence after hepatocellular carcinoma ablation

Name	Univariable			Multivariable		
	OR	95%CI	<i>P</i> value	OR	95%CI	<i>P</i> value
Tumorsize	1.14	0.93-1.40	0.217			
Age	0.99	0.96-1.02	0.532			

Ablation method			
RFA			
MWA	0.83	0.41-1.69	0.611
Sex			
Female			
Male	1.42	0.62-3.29	0.408
HBV			
Positive			
Negative	0.91	0.46-1.79	0.782
Cirrhosis			
Positive			
Negative	0.61	0.27-1.38	0.235
N			
< 1.8			
1.8-6.3	1.06	0.55-2.04	0.863
> 6.3	1.56	0.09-26.09	0.757
L			
≥ 1.1			
< 1.1	0.7	0.37-1.35	0.29
ALT			
≤ 50			
> 50	0.87	0.41-1.82	0.708
AST			
> 40			
≤ 40	0.92	0.48-1.75	0.791
GGT			
≤ 60			
> 60	1.11	0.58-2.13	0.742

GLB						
≤ 35						
> 35	0.82	0.37-1.82	0.631			
HbsAg						
Positive						
Negative	1.51	0.63-3.60	0.35			
AFP						
< 40						
40-400	1.51	0.68-3.36	0.308			
> 400	2.66	0.93-7.62	0.068			
Np						
< 1.8						
1.8-6.3	0.7	0.30-1.64	0.416	0.72	0.29-1.77	0.476
> 6.3	0.39	0.16-0.99	0.046	0.29	0.10-0.80	0.017
Lp						
≥1.1						
< 1.1	1.33	0.68-2.59	0.409			
ALTp						
≤ 50						
> 50	0.75	0.35-1.63	0.472			
ASTp						
> 40						
≤ 40	2.29	0.86-6.07	0.095			
GGTp						
≤ 60						
> 60	0.98	0.51-1.88	0.947			

GLBp						
≤ 35						
> 35	1.15	0.55-2.39	0.708			
Capsule appearance						
Positive						
Negative	0.87	0.45-1.70	0.684			
Intratumor vascularity						
Positive						
Negative	2.28	1.14-4.54	0.02	1.67	0.78-3.57	0.19
Tumor growth patter						
Positive						
Negative	1.54	0.75-3.14	0.239			
Intratumor necrosis						
Positive						
Negative	2.13	1.10-4.12	0.024	2.55	1.17-5.57	0.018
PACE						
Positive						
Negative	0.88	0.39-1.95	0.746			
Tumor margin						
Positive						
Negative	0.89	0.45-1.74	0.732			

N: Neutrophil; L: Lymphocyte; ALT: Alanine transferase; AST: Aspartate transferase; GGT: Gammaglutamyl transferase; GLB: Globulin; HbsAg: Hepatitis B Surface Antigen; AFP: Alpha fetoprotein; Np: Postoperative neutrophil; Lp: Postoperative lymphocyte; ALTp: Postoperative alanine transferase; ASTp: Postoperative aspartate transferase; GGTP: Postoperative gammaglutamyl transferase; GLBp: Postoperative

globulin; PACE: Peritumoral arterial contrast enhancement; RFA: Radiofrequency ablation; MWA: Microwave ablation; PFS: Progression-free survival.

Supplementary Table 2 Feature stability assessed by selection frequency across five-fold cross-validation

Feature ID	Selection Frequency (out of 5 folds)
A_10mm_feature_272	5
P_10mm_feature_242	5
D_10mm_feature_492	5
D_10mm_feature_476	5
P_10mm_feature_351	5
D_10mm_feature_301	5
D_10mm_feature_280	5
D_10mm_feature_111	5
D_10mm_feature_383	5
A_10mm_feature_460	5
A_10mm_feature_494	4
D_10mm_feature_354	4
A_10mm_feature_358	4
D_10mm_feature_282	4
D_10mm_feature_19	4
D_10mm_feature_89	4
D_10mm_feature_418	4
A_10mm_feature_206	4
P_10mm_feature_373	4
D_10mm_feature_284	3
P_10mm_feature_490	3
D_10mm_feature_390	3

A_10mm_feature_360	3
A_10mm_feature_392	3
D_10mm_feature_33	3
A_10mm_feature_357	3
A_10mm_feature_328	3
D_10mm_feature_106	3
P_10mm_feature_347	3
D_10mm_feature_274	3
P_10mm_feature_280	3

A: Arterial phase; P: Portal phase; D: Delay phase.

Supplementary Table 3 Comparative performance of six machine learning algorithms across different feature sets in the training and validation cohorts

Feature set	Algorithm	Dataset	AUC (95%CI)	Acc	Sen	Spe	Prec	F1
Clic	SVM	Train	0.576 (0.563-0.588)	0.632	0.636	0.609	0.609	0.329
		Val	0.507 (0.489-0.524)	0.612	0.627	0.5	0.5	0.235
	LR	Train	0.603 (0.588-0.618)	0.606	0.674	0.508	0.508	0.512
		Val	0.582 (0.560-0.603)	0.612	0.692	0.5	0.5	0.519
	RF	Train	0.605 (0.588-0.621)	0.632	0.636	0.609	0.609	0.329
		Val	0.615 (0.591-0.640)	0.612	0.627	0.5	0.5	0.235
	KNN	Train	0.605 (0.589-0.621)	0.632	0.636	0.609	0.609	0.329
		Val	0.615 (0.592-0.639)	0.612	0.627	0.5	0.5	0.235
	XGBoost	Train	0.604 (0.594-0.614)	0.632	0.636	0.609	0.609	0.329
		Val	0.598 (0.584-0.613)	0.612	0.627	0.5	0.5	0.235
	LightGBM	Train	0.605 (0.589-0.621)	0.632	0.636	0.609	0.609	0.329
		Val	0.615 (0.592-0.639)	0.612	0.627	0.5	0.5	0.235
Tumor	SVM	Train	0.790 (0.761-0.820)	0.723	0.736	0.694	0.694	0.613

3 mm	LR	Val	0.763 (0.720-0.805)	0.731	0.745	0.7	0.7	0.609
		Train	0.786 (0.768-0.804)	0.729	0.815	0.635	0.635	0.691
	RF	Val	0.762 (0.736-0.788)	0.642	0.743	0.531	0.531	0.586
		Train	0.992 (0.959-1.000)	0.955	0.948	0.966	0.966	0.942
	KNN	Val	0.619 (0.586-0.652)	0.612	0.667	0.5	0.5	0.458
		Train	0.722 (0.711-0.734)	0.652	0.64	0.75	0.75	0.308
	XGBoost	Val	0.701 (0.683-0.720)	0.701	0.684	0.8	0.8	0.444
		Train	0.937 (0.900-0.976)	0.845	0.835	0.865	0.865	0.789
	LightGBM	Val	0.685 (0.632-0.739)	0.731	0.767	0.666	0.666	0.64
		Train	0.939 (0.901-0.977)	0.865	0.867	0.86	0.86	0.824
	SVM	Val	0.702 (0.646-0.757)	0.642	0.698	0.542	0.542	0.52
		Train	0.781 (0.762-0.800)	0.735	0.736	0.733	0.733	0.617
	LR	Val	0.661 (0.633-0.688)	0.701	0.723	0.65	0.65	0.565
		Train	0.729 (0.710-0.747)	0.677	0.742	0.591	0.591	0.609
	RF	Val	0.679 (0.653-0.706)	0.657	0.75	0.548	0.548	0.596
		Train	0.836 (0.820-0.852)	0.781	0.744	0.912	0.912	0.646
	KNN	Val	0.613 (0.594-0.632)	0.567	0.603	0.333	0.333	0.171
		Train	0.778 (0.754-0.801)	0.71	0.679	0.905	0.905	0.458
	XGBoost	Val	0.489 (0.450-0.528)	0.612	0.632	0.5	0.5	0.278
		Train	0.877 (0.844-0.909)	0.819	0.822	0.815	0.815	0.759
	LightGBM	Val	0.554 (0.508-0.600)	0.552	0.617	0.4	0.4	0.348
		Train	0.944 (0.906-0.982)	0.832	0.832	0.833	0.833	0.776
5 mm	SVM	Val	0.568 (0.515-0.620)	0.567	0.65	0.444	0.444	0.453
		Train	0.756 (0.738-0.774)	0.71	0.718	0.689	0.689	0.579
	LR	Val	0.714 (0.687-0.741)	0.657	0.714	0.56	0.56	0.549
		Train	0.721 (0.703-0.739)	0.677	0.747	0.588	0.588	0.615
	RF	Val	0.748 (0.723-0.773)	0.672	0.88	0.548	0.548	0.676
		Train	0.916 (0.898-0.934)	0.806	0.769	0.921	0.921	0.7

10 mm	KNN	Val	0.702 (0.680-0.724)	0.657	0.688	0.579	0.579	0.489
		Train	0.633 (0.621-0.644)	0.626	0.626	0.625	0.625	0.256
	XGBoost	Val	0.645 (0.626-0.664)	0.612	0.623	0.5	0.5	0.188
		Train	0.996 (0.946-1.000)	0.974	0.959	1	1	0.967
	LightGBM	Val	0.693 (0.626-0.760)	0.672	0.721	0.583	0.583	0.56
		Train	0.994 (0.949-1.000)	0.961	0.958	0.967	0.967	0.951
	SVM	Val	0.657 (0.602-0.712)	0.627	0.7	0.519	0.519	0.528
		Train	0.818 (0.802-0.833)	0.729	0.711	0.794	0.794	0.563
	LR	Val	0.804 (0.779-0.829)	0.701	0.691	0.75	0.75	0.474
		Train	0.691 (0.690-0.692)	0.4	0.713	0.4	0.4	0.571
	RF	Valn	0.716 (0.714-0.718)	0.388	0.606	0.388	0.388	0.559
		Train	0.906 (0.892-0.921)	0.774	0.73	0.966	0.966	0.615
	KNN	Val	0.647 (0.627-0.667)	0.657	0.655	0.667	0.667	0.343
		Train	1.000 (1.000-1.000)	1	1	1	1	1
	XGBoost	Val	0.606 (0.583-0.629)	0.627	0.629	0.6	0.6	0.194
		Train	0.999 (0.951-1.000)	0.981	0.969	1	1	0.975
20 mm	LightGBM	Val	0.634 (0.577-0.692)	0.612	0.66	0.5	0.5	0.435
		Train	0.913 (0.903-0.923)	0.665	0.641	1	1	0.278
	SVM	Val	0.576 (0.564-0.589)	0.612	0.612	0.376	0	0
		Train	0.824 (0.801-0.848)	0.787	0.783	0.796	0.796	0.703
	LR	Val	0.719 (0.683-0.755)	0.657	0.688	0.579	0.579	0.489
		Train	0.763 (0.746-0.780)	0.716	0.769	0.641	0.641	0.651
	RF	Val	0.755 (0.730-0.780)	0.731	0.848	0.618	0.618	0.7
		Train	0.983 (0.958-1.000)	0.903	0.868	0.98	0.98	0.865
	KNN	Val	0.572 (0.547-0.598)	0.567	0.611	0.385	0.385	0.256
		Train	1.000 (1.000-1.000)	1	1	1	1	1
	XGBoost	Val	0.457 (0.419-0.495)	0.552	0.608	0.375	0.375	0.286
		Train	0.935 (0.925-0.946)	0.677	0.65	1	1	0.324

	Val	0.590 (0.577-0.603)	0.582	0.603	0.25	0.25	0.067
LightGBM	Train	0.811 (0.801-0.822)	0.658	0.639	0.909	0.909	0.274
	Val	0.550 (0.534-0.566)	0.522	0.574	0	0	0

The best-performing values for each metric are highlighted in bold. SVM: Support vector machine; LR: Logistic regression; RF: Random forest; KNN: K-nearest neighbors; LightGBM: Light gradient boosting machine; XGBoost: Extreme gradient boosting; Train: Training set; Val: Validation set; Acc: Accuracy; Prec: Precision; Sen: Sensitivity; Spe: Specificity; F1: F1-score; AUC: Area under the curve.

Supplementary Table 4 The DeLong test comparisons among peritumoral models in the internal validation cohorts

Model 1	AUC of model 1	Model 2	AUC of model 2	<i>P</i> value
3-mm peritumoral model	0.679 (0.653-0.706)	5-mm peritumoral model	0.748 (0.723-0.773)	0.402
3-mm peritumoral model	0.679 (0.653-0.706)	10-mm peritumoral model	0.804(0.779-0.829)	0.118
3-mm peritumoral model	0.679 (0.653-0.706)	20-mm peritumoral model	0.755 (0.730-0.780)	0.291
5-mm peritumoral model	0.748 (0.723-0.773)	10-mm peritumoral model	0.803 (0.779-0.829)	0.469
5-mm peritumoral model	0.748 (0.723-0.773)	20-mm peritumoral model	0.755 (0.730-0.780)	0.925
10-mm peritumoral model	0.804 (0.779-0.829)	20-mm peritumoral model	0.755 (0.730-0.780)	0.543

The 10-mm peritumoral model showed the highest numerical area under the curve among the tested peritumoral models, but the pairwise DeLong tests showed no statistically significant differences between the 10-mm model and the other peritumoral models in the internal validation cohort. AUC: Area under the curve.