Table S1 VASARI scoring standard (according to the National Cancer Institute version; https://wiki.nci.nih.gov/display/cip/vasari)

Feature number	Name	Description	Options
F1	Tumor location	Location of lesion geographic epicenter (not all areas of involvement).	0 = – 1= Frontal 2 =Temporal 3=Insular 4=Parietal 5=Occipital 6=Brainstem 7=Cerebellum
F2	Side of tumor epicenter	Side of lesion epicenter.	0= – 1=Right 2=Center/Bilateral 3=Left
F3	Eloquent brain	Does the geographic center or the enhancing component involve eloquent cortex (motor, language, vision) or key underlying white matter?	0= – 1=None 2=Speech motor 3=Speech receptive 4=Motor 5=Vision
F4	Enhancement quality	[None, mild, moderate, marked] Qualitative degree of contrast enhancement is defined as having all or portions of the tumor demonstrating significantly higher signal on the postcontrast T1-weigthed images compared to precontrast.	0= – 1=None 2=Mild/Minimal 3=Marked/Avid
F5	Proportion enhancing	[Indeterminate, none (0%), <5%, 6–33%, 34–67%, 68–95%, >95%, all (100%)] What proportion of the entire tumor is enhancing? (assuming that the entire abnormality may be composed of (1) an enhancing component, (2) a nonenhancing component, (3) a necrotic component, or (4) an edema component).	0= – 1= N/A 2=None (0%) 3= <5% 4= 6–33% 5= 34–67% 6= 68–95% 7= >95% 8=All (100%) 9= Indeterminate
F6	Proportion nCET	[Indeterminate, none (0%), <5%, 6–33%, 34–67%, 68–95%, >95%, all (100%)] What proportion of the entire tumor is nonenhancing? Nonenhancing tumor is defined as regions of T2-weighted hyperintensity (less than the intensity of cerebrospinal fluid, with corresponding T1-weighted hypointensity) that are associated with mass effect and architectural distortion, including blurring of the gray–white interface (assuming that the entire abnormality may be composed of (1) an enhancing component, (2) a nonenhancing component, (3) a necrotic component, or (4) an edema component).	0= – 1= N/A 2=None (0%) 3= <5% 4= 6–33% 5= 34–67% 6= 68–95% 7= >95% 8=All (100%) 9= Indeterminate
F7	Proportion necrosis	[Indeterminate, none (0%), <5%, 6–33%, 34–67%, 68–95%, >95%, (100%)] All necrosis is defined as a region within the tumor that does not enhance or shows markedly diminished enhancement, is high on T2-weighted and proton-density images, is low on T1-weighted images, and has an irregular border (assuming that the entire abnormality may be composed of (1) an enhancing component, (2) a nonenhancing component, (3) a necrotic component, or (4) an edema component).	0= – 1= N/A 2=None (0%) 3= <5% 4= 6–33% 5= 34–67% 6= 68–95% 7= >95% 8=All (100%) 9= Indeterminate
F8	Cyst(s)	Cysts are well defined, rounded, and often eccentric regions of very high T2-weighted signal and low T1-weighted signal essentially matching CSF signal intensity, with very thin, regular, smooth, and nonenhancing or regularly enhancing walls, possibly with thin, regular, internal septations.	0= – 1= No 2= Yes
F9	Multifocal or multicentric	Multifocal is defined as having at least 1 region of tumor, either enhancing or nonenhancing, that is not contiguous with the dominant lesion and is outside the region of signal abnormality (edema) surrounding the dominant mass. This can be defined as those resulting from dissemination or growth by an established route, spread via commissural or other pathways, or via CSF channels or local metastases. Meanwhile, multicentric is defined as widely separated lesions in different lobes or different hemispheres that cannot be attributed to one of the previously mentioned pathways. Gliomatosis refers to generalized neoplastic transformation of the white matter of most of a hemisphere.	0 = – 1= N/A 2= Multifocal 3=Multicentric 4= Gliomatosis
F10	T1/FLAIR ratio	Tumor feature summary [mixed, expansive, or infiltrative]. Expansive = size of precontrast T1 abnormality (exclusive of signal intensity) approximates size of FLAIR abnormality; mixed = size of T1 abnormality moderately less than the FLAIR envelope; infiltrative = size of precontrast T1 abnormality much smaller than the size of the FLAIR abnormality (use T2 if FLAIR is not provided).	0= – 1= Expansive (T1≈FLAIR) 2= Mixed (T1<FLAIR) 3= Infiltrative (T1<<FLAIR)
F11	Thickness of enhancing margin	The scoring is not applicable if there is no contrast enhancement. If most of the enhancing rim is thin and regular and has homogenous enhancement, the grade is thin. If most of the rim demonstrates nodular and/or thick enhancement, the grade is thick. If there is only solid enhancement and no rim, the grade is none.	0= – 1= N/A 2= None 3= Thin 4= Thick/solid
F12	Definition of the enhancing margin	The scoring is not applicable (N/A) if there is no contrast enhancement. Assess if most of the outside margin of the enhancement is well defined or poorly defined.	0= – 1= N/A 2= Well–defined 3= Poorly–defined
F13	Definition of the nonenhancing margin (e.g., grade III)	If most of the outside nonenhancing margin of the tumor is well defined and smooth (geographic), versus if the margin is ill-defined and irregular.	0= – 1= N/A 2= Smooth 3= Irregular
F14	Proportion of edema	[Indeterminate, none (0%), <5%, 6–33%, 34–67%, 68–95%, >95%, all (100%)]. What proportion of the entire abnormality is vasogenic edema? Edema should be greater in signal than in nCET and somewhat lower in signal than in CSF. Pseudopods are characteristic of edema (assuming that the entire abnormality may be composed of (1) an enhancing component, (2) a nonenhancing component, (3) a necrotic component, or (4) an edema component).	0= – 1= N/A 2=None (0%) 3= <5% 4= 6–33% 5= 34–67% 6= 68–95% 7= >95% 8=All (100%) 9=Indeterminate
F15	Crosses edema	Edema spans white matter commissures extending into the contralateral hemisphere. (exclusive of herniated ipsilateral tissue).	0= – 1= N/A 2= No 3= Yes
F16	Hemorrhage	Intrinsic hemorrhage in the tumor matrix. Any intrinsic foci of low signal on T2-weighted imaging or high signal on T1-weighted imaging. (Use Bo image if necessary for confirmation.)	0= – 1= N/A 2= No 3= Yes
F17	Diffusion	Predominantly facilitated or restricted diffusion in the enhancing or nCET portion of the tumor (based on ADC map). Equivocal is neither. If there is no ADC, use no images. The proportion of tissue is not relevant.	0= – 1= No image 2= Facilitated 3= Restricted 4=Neither/equivocal
F18	Pial invasion	Enhancement of the overlying pia in continuity with enhancing or nonenhancing tumor.	0= – 1= No 2= Yes
F19	Ependymal invasion	Invasion of any adjacent ependymal surface in continuity with enhancing or nonenhancing tumor matrix.	0= – 1= No 2= Yes
F20	Cortical involvement	Nonenhancing or enhancing tumor extending into the cortical mantle or the cortex no longer distinguishable relative to subjacent tumor.	0= – 1= No 2= Yes
F21	Deep WM invasion	Enhancing or nCET tumor extending into the internal capsule or brainstem.	0= – 1= No 2= Yes
F22	nCET tumor crosses midline	nCET crossing into the contralateral hemisphere through white matter commissures (exclusive of herniated ipsilateral tissue).	0= – 1= N/A 2= No 3= Yes
F23	Enhancing tumor crosses midline	Enhancing tissue crossing into the contralateral hemisphere through white matter commisures (exclusive of herniated ipsilateral tissue).	0= – 1= N/A 2= No 3= Yes
F24	Satellites	An area of enhancement within the region of signal abnormality surrounding the dominant lesion but not contiguous with any part with the major tumor mass.	0= – 1= No 2= Yes
F25	Calvarial remodeling	Erosion of the inner table of the skull (possibly a secondary sign of slow growth).	0= – 1= No 2= Yes
F26	Extent of resection of enhancing tumor	[Indeterminate, none (0%), <5%, 6–33%, 34–67%, 68–33%, 34–67%, 68–95%, >95%, all (100%)]. Use the first postoperative scan (contrast- enhanced MR imaging) assessed for residual tumor. Estimate the proportion of enhancing tumor removed. A total resection of the component should be scored 100%. A subtotal resection of enhancing tissue should be scored accordingly.	0= – 1= N/A 2=None (0%) 3= <5% 4= 6–33% 5= 34–67% 6= 68–95% 7= >95% 8=All (100%) 9=Indeterminate
F27	Extent resection of nCET	[Indeterminate, none (0%), <5%, 6–33%, 34–67%, 68–95%, >95%, all (100%)]. Use the first postoperative scan (contrast-enhanced MR imaging) assessed for tumor residual. Estimate the proportion of non-enhancing tumor removed. A total resection of component should be scored 100%. A subtotal resection of enhancing tissue should be scored accordingly.	0= – 1= N/A 2=None (0%) 3= <5% 4= 6–33% 5= 34–67% 6= 68–95% 7= >95% 8=All (100%) 9=Indeterminate
F28	Extent resection of vasogenic edema	[Indeterminate, none (0%), <5%, 6–33%, 34–67%, 68–95%, >95%, all (100%)]Use the first postoperative scan (contrast-enhanced MR imaging) assessed for residual tumor. Estimate the proportion of edema removed. A total resection of enhancing nidus should be scored 100%. A subtotal resection of enhancing tissue should be scored accordingly.	0= – 1= N/A 2=None (0%) 3= <5% 4= 6–33% 5= 34–67% 6= 68–95% 7= >95% 8=All (100%) 9= Indeterminate
F29, F30	Lesion size	Largest perpendicular (x–y) cross-sectional diameter of T2 signal abnormality (longest dimension × perpendicular dimension) measured on a single axial image only.	0= – 1= <0.5cm 2= 0.5 cm 3= 1.0 cm 4= 1.5 cm 5= 2.0 cm 6= 2.5 cm 7= 3.0 cm 8= 3.5 cm 9= 4.0 cm 10= 4.5 cm 11= 5.0 cm 12 = 5.5 cm 13= 6.0 cm 14= 6.5 cm 15= 7.0 cm 16= 7.5 cm 17= 8.0 cm 18= >8.0 cm

VASARI, visually accessible Rembrandt images; CSF, cerebrospinal fluid; FLAIR, fluid attenuated inversion recovery; ADC, apparent diffusion coefficient.

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Table S2 MRI image acquisition protocol parameters from 3 centers

Parameters	A	B	C
Scanner type	GE Signa HDxt 3.0T (GE Medical Systems, Chicago, IL, USA)	Siemens Skyra 3.0T (Siemens Healthineers, Erlangen, Germany)	GE Discovery MR750 3.0T (GE Medical Systems, Chicago, IL, USA)
Magnetic field strength	3.0T	3.0T	3.0T
T1C (T1 contrast enhanced)			
Repetition time (ms)	225	459	549
Echo time (ms)	4.8	3	5.72
Flip angle (º)	90	90	90
Image slice thickness (mm)	2	2	2
Image slice spacing (mm)	1	0.5	1
T2f (T2-FLAIR)			
Repetition time (ms)	8,000	7,000	8,000
Echo time (ms)	101	79	100
Flip angle (º)	150	180	110
Image slice thickness (mm)	5	5	5
Image slice spacing (mm)	5	2	2

MRI, magnetic resonance imaging; GE, General Electric Company; T1C, T1-contrast enhanced; T2f, T2 fluid attenuated inversion recovery.

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Table S3 Clinical variables

Index	Label (ATRX mutant =1, ATRX wild type =0)	Age (years)	Gender	WHO grade	VASARI score
000-1	0	34	F	4	77
000-2	0	34	M	4	78
000-3	0	64	M	4	77
000-4	0	50	F	3	75
000-5	0	53	M	4	80
000-6	0	57	M	3	66
000-7	0	65	M	4	84
000-8	0	65	F	3	67
000-9	0	69	F	3	68
000-10	0	50	F	3	62
000-11	0	67	F	3	84
000-12	0	56	M	3	76
000-13	0	64	M	3	78
000-14	0	70	F	4	66
000-15	0	55	M	3	74
000-16	0	55	F	4	78
000-17	0	57	M	4	81
000-18	0	45	M	4	71
000-19	0	51	M	4	66
000-20	0	53	F	3	78
000-21	0	65	F	3	80
000-22	0	46	F	3	80
000-23	0	60	F	4	72
000-24	0	34	M	4	69
000-25	0	36	M	4	58
000-26	0	33	F	4	78
000-27	0	79	M	3	84
000-28	0	43	F	4	76
000-29	0	56	F	4	64
000-30	0	45	F	3	79
000-31	0	39	M	4	72
000-32	0	46	M	4	75
000-33	0	49	M	4	84
000-34	0	67	F	3	58
000-35	0	58	F	4	65
000-36	0	59	M	4	70
000-37	0	58	F	3	66
000-38	0	49	F	3	76
000-39	0	40	M	3	65
000-40	0	27	F	3	66
000-41	0	40	M	3	67
000-42	0	41	M	3	69
000-43	0	66	F	3	72
000-44	0	65	M	3	67
000-45	0	48	F	3	83
000-46	0	42	F	3	77
000-47	0	57	M	3	75
000-48	0	34	F	4	67
000-49	0	65	F	3	78
000-50	0	64	M	3	65
000-51	0	54	F	4	66
000-52	0	66	M	4	67
000-53	0	43	M	3	78
000-54	0	44	M	4	80
000-55	0	54	F	4	81
000-56	0	55	M	3	67
000-57	0	43	M	4	77
000-58	0	45	F	3	78
000-59	0	60	M	3	67
000-60	0	55	M	4	69
000-61	0	65	F	3	77
000-62	0	44	M	4	68
000-63	0	56	M	3	64
000-64	0	67	M	4	71
000-65	0	65	F	3	62
000-66	0	66	M	4	72
000-67	0	67	M	3	74
000-68	0	70	M	3	83
000-69	0	50	F	3	88
000-70	0	51	M	3	85
000-71	0	61	F	4	66
000-72	0	67	M	3	69
000-73	0	56	M	3	81
000-74	0	60	M	4	69
000-75	0	64	M	3	74
000-76	0	70	F	4	69
000-77	0	76	M	4	69
000-78	0	51	M	3	77
000-79	0	41	M	3	72
000-80	0	57	F	4	69

Table S3 *(continued)*

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Table S3 *(continued)*

Index	Label (ATRX mutant =1, ATRX wild type =0)	Age (years)	Gender	WHO grade	VASARI score
000-81	0	41	F	3	71
000-82	0	54	F	3	79
000-83	0	61	M	3	76
000-84	0	43	F	3	65
000-85	0	44	M	3	78
000-86	0	69	F	3	69
000-87	0	54	M	4	71
000-88	0	56	M	4	75
000-89	0	54	F	3	83
000-90	0	50	M	4	78
000-91	0	43	M	3	72
000-92	0	21	F	3	62
000-93	0	67	M	4	73
000-94	0	36	F	3	69
000-95	0	61	M	4	78
000-96	0	52	M	3	70
000-97	0	23	M	4	69
000-98	0	58	F	4	72
000-99	0	70	M	4	75
000-100	0	57	M	4	69
000-101	0	51	M	4	71
000-102	0	74	F	4	80
000-103	0	52	F	3	70
000-104	0	76	F	4	83
000-105	0	72	F	4	79
000-106	0	56	M	3	58
000-107	0	56	M	3	62
000-108	0	68	M	4	71
000-109	0	66	F	4	75
000-110	0	52	F	4	80
000-111	0	57	M	3	66
000-112	0	74	M	4	70
000-113	0	78	M	4	69
000-114	0	63	M	4	74
100-1	1	64	M	4	69
100-2	1	53	M	4	69
100-3	1	61	F	4	69
100-4	1	41	M	4	66
100-5	1	53	M	4	76
100-6	1	45	M	4	78
100-7	1	34	F	4	78
100-8	1	66	M	4	65
100-9	1	71	M	4	75
100-10	1	52	M	4	73
100-11	1	66	M	4	64
100-12	1	36	M	4	75
100-13	1	50	M	4	66
100-14	1	54	M	4	77
100-15	1	49	M	4	76
100-16	1	30	F	4	69
100-17	1	67	M	4	65
100-18	1	55	M	4	78
100-19	1	49	M	4	66
100-20	1	50	M	4	68
100-21	1	72	M	4	70
100-22	1	57	M	4	77
100-23	1	46	F	4	69
100-24	1	57	M	4	71
100-25	1	30	M	4	80
100-26	1	45	F	4	68
100-27	1	47	M	4	77
100-28	1	55	M	4	78
100-29	1	51	F	4	63
100-30	1	48	F	4	76
100-31	1	58	M	4	75
100-32	1	52	F	4	66
100-33	1	70	F	4	66
100-34	1	66	M	4	67
100-35	1	52	M	3	79
100-36	1	18	F	4	78
100-37	1	49	M	4	64
100-38	1	73	F	4	72
100-39	1	73	F	4	77
100-40	1	51	M	3	65
100-41	1	46	F	4	74
100-42	1	37	F	4	71
100-43	1	56	M	4	66
100-44	1	64	F	4	84

Table S3 *(continued)*

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Table S3 *(continued)*

Index	Label (ATRX mutant =1, ATRX wild type =0)	Age (years)	Gender	WHO grade	VASARI score
100-45	1	76	F	4	70
100-46	1	63	F	4	78
100-47	1	54	F	3	73
100-48	1	50	F	4	67
100-49	1	50	M	3	73
100-50	1	85	M	4	74
100-51	1	51	M	4	70
100-52	1	49	M	3	78
100-53	1	74	M	4	65
100-54	1	33	F	4	65
100-55	1	51	M	4	55
100-56	1	54	M	3	74
100-57	1	55	M	3	65
100-58	1	68	F	3	59
100-59	1	55	F	4	69
100-60	1	59	M	3	71
100-61	1	53	F	3	69
100-62	1	54	M	3	71
100-63	1	40	F	3	68
100-64	1	48	M	3	68
100-65	1	51	M	3	71
100-66	1	25	F	3	73
100-67	1	48	F	3	68
100-68	1	63	F	3	54
100-69	1	53	F	4	73
100-70	1	56	M	4	69
100-71	1	64	F	4	70
100-72	1	39	F	3	67
100-73	1	61	M	4	71
100-74	1	58	M	3	72
100-75	1	52	M	3	67
100-76	1	44	M	3	65
100-77	1	58	M	3	65
100-78	1	53	F	3	68
100-79	1	58	M	4	69
100-80	1	46	F	4	81
100-81	1	63	F	4	77
100-82	1	56	M	3	73
100-83	1	54	F	3	69
100-84	1	77	M	3	74
100-85	1	25	F	3	76
100-86	1	66	M	4	76
100-87	1	67	F	4	65
100-88	1	73	M	4	84
100-89	1	71	M	4	67
100-90	1	50	M	3	69
100-91	1	55	M	4	77
100-92	1	71	F	4	71
100-93	1	53	M	4	71
100-94	1	52	M	4	69
100-95	1	26	F	3	74
100-96	1	75	M	4	68
100-97	1	53	F	4	65
100-98	1	60	F	4	72
100-99	1	50	M	4	84
100-100	1	16	F	4	77
100-101	1	16	M	3	67
100-102	1	40	M	3	80
100-103	1	41	F	4	81
100-104	1	48	F	3	63
100-105	1	46	M	3	70
100-106	1	38	M	4	82
100-107	1	50	M	3	68
100-108	1	53	F	4	69
100-109	1	26	F	4	76
100-110	1	33	F	3	65
100-111	1	44	M	4	77
100-112	1	46	M	3	52
100-113	1	17	F	4	75
100-114	1	53	M	4	77
100-115	1	54	F	4	80
100-116	1	40	M,	4	84
100-117	1	64	F	4	75
100-118	1	40	M	3	60
100-119	1	63	M	4	83
100-120	1	57	F	3	59

ATRX, alpha-thalassemia X-linked intellectual disability; WHO, World Health Organization; VASARI, visually accessible Rembrandt images; F, female; M, male.

Table S4 The result of Delong test

Corresponding to different models	Training set	Validation set
Edema DL——edema radio	0.51	0.284
Edema DL——edema hybrid	0.266	0.153
Edema DL——tumor DL	0.401	0.206
Edema DL——tumor radio	0.998	0.67
Edema DL——tumor hybrid	0.427	0.074
Edema DL——overall DL	z	0.081
Edema DL——overall radio	0.137	0.142
Edema DL——overall hybrid	0.338	0.072
Edema radio——edema hybrid	0.569	0.469
Edema radio——tumor DL	0.823	0.863
Edema radio——tumor radio	0.467	0.566
Edema radio——tumor hybrid	0.854	0.52
Edema radio——overall DL	0.649	0.689
Edema radio——overall radio	0.993	0.337
Edema radio——overall hybrid	0.709	0.127
Edema hybrid——tumor DL	0.733	0.941
Edema hybrid——tumor radio	0.099	0.443
Edema hybrid——tumor hybrid	0.708	0.665
Edema hybrid——overall DL	0.912	0.877
Edema hybrid——overall radio	0.843	0.336
Edema hybrid——overall hybrid	0.846	0.338
Tumor DL——tumor radio	0.345	0.442
Tumor DL——tumor hybrid	0.964	0.353
Tumor DL——overall DL	0.706	0.611
Tumor DL——overall radio	0.835	0.706
Tumor DL——overall hybrid	0.873	0.48
Tumor radio——tumor hybrid	0.365	0.157
Tumor radio——overall DL	0.241	0.32
Tumor radio——overall radio	0.506	0.177
Tumor radio——overall hybrid	0.288	0.081
Tumor hybrid——overall DL	0.725	0.632
Tumor hybrid ——overall radio	0.863	0.911
Tumor hybrid ——overall hybrid	0.848	0.91
Overall DL——overall radio	0.676	0.857
Overall DL——overall hybrid	0.931	0.6
Overall radio——overall hybrid	0.726	0.333

DL, deep learning.

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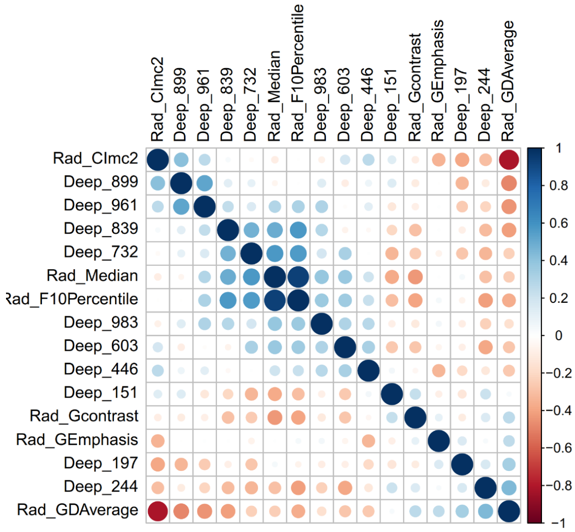

Figure S1 The feature correlation coefficient analysis.

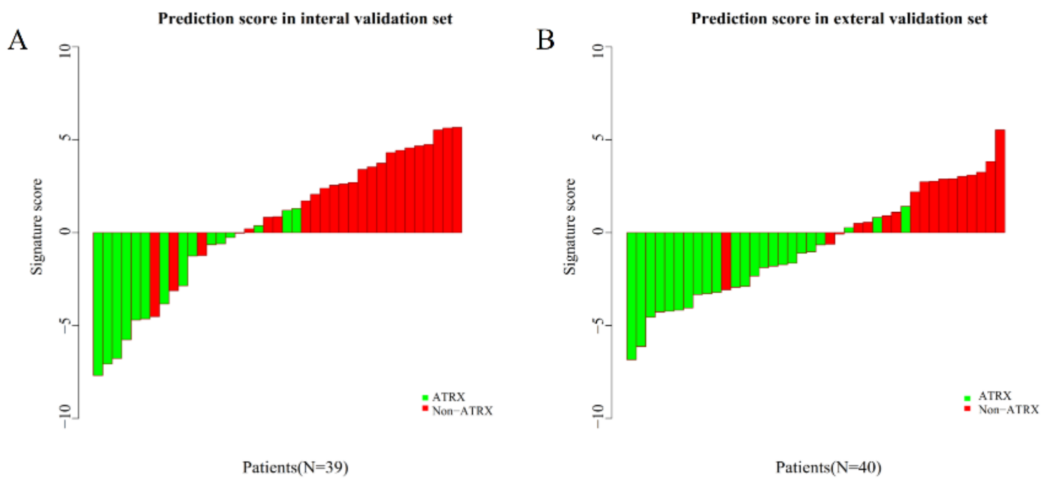

Figure S2 The feature correlation coefficient analysis. (A) Overall hybrid model classification performance on the validation set; (B) overall hybrid model classification performance on the test set.

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Appendix 1 Image preprocessing

First, we rigidly aligned each T1c volume to T2f using advanced normalization tools (ANTs). In order to eliminate the difference in brightness on MR images caused by factors such as the scanner itself and many unknown problems, N4 bias field correction was performed using SimpleITK. This employs a hybrid white stripe [22] approach for intensity normalization and uses the ANTs and White Stripe packages in R to complete a statistically principled process of image normalization that preserves intertissue grade and matches the intensity of the tissue without disrupting the natural balance of tissue intensities [23]. At last, isotropic resolution is resampled by using a linear interpolator to reinterpolate all images to 1 mm ×1 mm ×1 mm pixel in the normalized axes.

For the specific formula of radiomics characteristics, see the official Pyradiomics website (https://pyradiomics.readthedocs.io/en/latest). The feature calculation method was used to extract first-order statistics, shape and size, texture, and other features. The specific calculation formulae are listed below follows:

First-order statistics features

First-order statistics features describe the gray-level distribution of all voxels within the ROI.

Let X be a set of all voxels included in the ROI, Np the number of voxels in X, P(i) the first-order histogram with Ng discrete intensity levels, p(i) the normalized first-order histogram equal to P(i)/Np, and c the optional value, which shifts the intensities to prevent negative values in X.

1. Energy

$$energy = \sum_{i=1}^{N_p} (\mathbf{X}(i) + c)^2$$

2. Total energy

$$totalenergy = V_{voxel} \sum_{i=1}^{N_p} (\mathbf{X}(i) + c)^2$$

3. Entropy

$$entropy = -\sum_{i=1}^{N_g} p(i) \log_2 \big(p(i) + \epsilon \big)$$

ϵ is an arbitrarily small positive number ($\approx 2.2 \times 10^{-16}$)

4. Minimum

$$minimum = \min(\mathbf{X})$$

5. 10th percentile

The 10th percentile of X

6. 90th percentile

The 90th percentile of X

7. Maximum

$$maximum = \max(\mathbf{X})$$

8. Mean

$$mean = \frac{1}{N_p} \sum_{i=1}^{N_p} \mathbf{X}(i)$$

9. Median

The median gray-level intensity within the ROI.

10. Interquartile range

$$interquartilerange = \mathbf{P}_{75} - \mathbf{P}_{25}$$

11. Range

$$range = \max(\mathbf{X}) - \min(\mathbf{X})$$

12. Mean absolute deviation

$$MAD = \frac{1}{N_p} \sum_{i=1}^{N_p} | \mathbf{X}(i) - \bar{X} |$$

13. Robust mean absolute deviation (rMAD)

$$rMAD = \frac{1}{N_{10-90}} \sum_{i=1}^{N_{10-90}} | \mathbf{X}_{10-90}(i) - \bar{X}_{10-90} |$$

14. Root mean squared (RMS)

$$RMS = \sqrt{\frac{1}{N_p} \sum_{i=1}^{N_p} (\mathbf{X}(i) + c)^2}$$

15. Skewness

$$skewness = \frac{\mu_3}{\sigma^3} = \frac{\frac{1}{N_p} \sum_{i=1}^{N_p} (\mathbf{X}(i) - \bar{X})^3}{\left(\sqrt{\frac{1}{N_p} \sum_{i=1}^{N_p} (\mathbf{X}(i) - \bar{X})^2} \right)^3}$$

16. Kurtosis

$$kurtosis = \frac{\mu_4}{\sigma^4} = \frac{\frac{1}{N_p} \sum_{i=1}^{N_p} (\mathbf{X}(i) - \bar{X})^4}{\left(\frac{1}{N_p} \sum_{i=1}^{N_p} (\mathbf{X}(i) - \bar{X})^2 \right)^2}$$

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17. Variance

$$variance = \frac{1}{N_p} \sum_{i=1}^{N_p} (\mathbf{X}(i) - \bar{X})^2$$

18. Uniformity

$$uniformity = \sum_{i=1}^{N_g} p(i)^2$$

Shape and size features:

This group of features describe the 3-dimensional size and shape of the ROI. Features were derived from a triangle mesh generated using a marching cubes algorithm based on the ROI.

Let Nv be the number of voxels included in the ROI, Nf the number of faces defining the Mesh, V the volume of the mesh in millimeters cubed, and A the surface area of the mesh in millimeters squared.

1. Mesh volume

$$V_i = \frac{Oa_i \cdot (Ob_i \times Oc_i)}{6}$$

$$V = \sum_{i=1}^{N_f} V_i$$

2. Voxel volume

$$V_{voxel} = \sum_{k=1}^{N_v} V_k$$

3. Surface area

$$A_i = \frac{1}{2} | \mathrm{a}_i \mathrm{b}_i \times \mathrm{a}_i \mathrm{c}_i |$$

$$A = \sum_{i=1}^{N_f} A_i$$

4. Surface area to volume ratio

$$surfacetovolumeratio = \frac{A}{V}$$

5. Sphericity

$$sphericity = \frac{\sqrt[3]{36\pi V^2}}{A}$$

6. Maximum 3D diameter

Maximum 3D diameter is defined as the largest pairwise Euclidean distance between the tumor surface mesh vertices.

7. Maximum 2D diameter (slice)

Maximum 2D diameter (slice) is defined as the largest pairwise Euclidean distance between tumor surface mesh vertices in the row–column (generally the axial) plane.

8. Maximum 2D diameter (column)

Maximum 2D diameter (column) is defined as the largest pairwise Euclidean distance between tumor surface mesh vertices in the row–slice (usually the coronal) plane.

9. Maximum 2D diameter (row)

Maximum 2D diameter (row) is defined as the largest pairwise Euclidean distance between tumor surface mesh vertices in the column–slice (usually the sagittal) plane.

10. Major axis length

$$majoraxis = 4\sqrt{\lambda_{major}}$$

11. Minor axis length

$$minoraxis = 4\sqrt{\lambda_{minor}}$$

12. Least axis length

$$leastaxis = 4\sqrt{\lambda_{least}}$$

13. Elongation

$$elongation = \sqrt{\frac{\lambda_{minor}}{\lambda_{major}}}$$

14. Flatness

$$flatness = \sqrt{\frac{\lambda_{least}}{\lambda_{major}}}$$

Textural features

Textural features reflect information about the spatial arrangement of voxel intensities and therefore could describe the homogeneity of the ROI. In our study, textural features were derived from 4 statistical feature matrices: 22 from the gray-level co-occurrence matrix (GLCM), 16 from the gray-level run-length texture matrix (GLRLM), 16 from the gray-level size zone matrix (GLSZM), 14 from the gray-level dependence matrix (GLDM), and 5 from neighboring gray-scale difference matrix (NGTDM).

Gray-level co-occurrence matrix (GLCM)

1. Autocorrelation

$$autocorrelation = \sum_{i=1}^{N_g} \sum_{j=1}^{N_g} p(i,j)ij$$

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2. Joint average

$$jointaverage = \mu_x = \sum_{i=1}^{N_g} \sum_{j=1}^{N_g} p(i,j)i$$

3. Cluster prominence

$$clusterprominence = \sum_{i=1}^{N_g} \sum_{j=1}^{N_g} \left(i + j - \mu_x - \mu_y\right)^4 p(i,j)$$

4. Cluster shade

$$clustershade = \sum_{i=1}^{N_g} \sum_{j=1}^{N_g} \left(i + j - \mu_x - \mu_y\right)^3 p(i,j)$$

5. Cluster tendency

$$clustertendency = \sum_{i=1}^{N_g} \sum_{j=1}^{N_g} \left(i + j - \mu_x - \mu_y\right)^2 p(i,j)$$

6. Contrast

$$contrast = \sum_{i=1}^{N_g} \sum_{j=1}^{N_g} (i-j)^2 p(i,j)$$

7. Correlation

$$correlation = \frac{\sum_{i=1}^{N_g} \sum_{j=1}^{N_g} p(i,j)ij - \mu_x \mu_y}{\sigma_x(i)\sigma_y(j)}$$

8. Difference average

$$differenceaverage = \sum_{k=0}^{N_g-1} k p_{x-y}(k)$$

9. Difference entropy

$$differenceentropy = \sum_{k=0}^{N_g-1} p_{x-y}(k) \log_2\left(p_{x-y}(k) + \epsilon\right)$$

10. Difference variance

$$differencevariance = \sum_{k=0}^{N_g-1} (k - DA)^2 p_{x-y}(k)$$

11. Joint energy

$$jointenergy = \sum_{i=1}^{N_g} \sum_{j=1}^{N_g} \left(p(i,j)\right)^2$$

12. Joint entropy

$$jointentropy = -\sum_{i=1}^{N_g} \sum_{j=1}^{N_g} p(i,j) \log_2\left(p(i,j) + \epsilon\right)$$

13. Informational measure of correlation (IMC) 1

$$IMC1 = \frac{HXY - HXY1}{\max\{HX, HY\}}$$

14. Informational measure of correlation (IMC) 2

$$IMC2 = \sqrt{1 - e^{-2(HXY2 - HXY)}}$$

15. Inverse difference moment (IDM)

$$IDM = \sum_{k=0}^{N_g-1} \frac{p_{x-y}(k)}{1+k^2}$$

16. Inverse difference moment normalized (IDMN)

$$IDMN = \sum_{k=0}^{N_g-1} \frac{p_{x-y}(k)}{1 + \left(\frac{k^2}{N_g^2}\right)}$$

17. Inverse difference (ID)

$$ID = \sum_{k=0}^{N_g-1} \frac{p_{x-y}(k)}{1+k}$$

18. Inverse difference normalized (IDN)

$$IDN = \sum_{k=0}^{N_g-1} \frac{p_{x-y}(k)}{1 + \left(\frac{k}{N_g}\right)}$$

19. Inverse variance

$$inversevariance = \sum_{k=1}^{N_g-1} \frac{p_{x-y}(k)}{k^2}$$

20. Maximum probability

$$maximumprobability = \max\left(p(i,j)\right)$$

21. Sum entropy

$$sumentropy = \sum_{k=2}^{2N_g} p_{x+y}(k) \log_2\left(p_{x+y}(k) + \epsilon\right)$$

22. Sum of squares

$$sumsquares = \sum_{i=1}^{N_g} \sum_{j=1}^{N_g} (i - \mu_x)^2 p(i,j)$$

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Gray-level run-length texture matrix (GLRLM)

1. Short run emphasis (SRE)

$$SRE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_r}\frac{\mathbf{P}(i,j\mid\theta)}{j^2}}{N_r(\theta)}$$

2. Long run emphasis (LRE)

$$LRE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_r}\mathbf{P}(i,j\mid\theta)\,j^2}{N_r(\theta)}$$

3. Gray-level nonuniformity (GLN)

$$GLN = \frac{\sum_{i=1}^{N_g}\left(\sum_{j=1}^{N_r}\mathbf{P}(i,j\mid\theta)\right)^2}{N_r(\theta)}$$

4. Gray-level nonuniformity normalized (GLNN)

$$GLNN = \frac{\sum_{i=1}^{N_g}\left(\sum_{j=1}^{N_r}\mathbf{P}(i,j\mid\theta)\right)^2}{N_r(\theta)^2}$$

5. Run length nonuniformity (RLN)

$$RLN = \frac{\sum_{j=1}^{N_r}\left(\sum_{i=1}^{N_g}\mathbf{P}(i,j\mid\theta)\right)^2}{N_r(\theta)}$$

6. Run length nonuniformity normalized (RLNN)

$$RLNN = \frac{\sum_{j=1}^{N_r}\left(\sum_{i=1}^{N_g}\mathbf{P}(i,j\mid\theta)\right)^2}{N_r(\theta)^2}$$

7. Run percentage (RP)

$$RP = \frac{N_r(\theta)}{N_p}$$

8. Gray-level variance (GLV)

$$GLV = \sum_{i=1}^{N_g}\sum_{j=1}^{N_r}p(i,j\mid\theta)(i-\mu)^2$$

9. Run variance (RV)

$$RV = \sum_{i=1}^{N_g}\sum_{j=1}^{N_r}p(i,j\mid\theta)(j-\mu)^2$$

10. Run entropy (RE)

$$RE = -\sum_{i=1}^{N_g}\sum_{j=1}^{N_r}p(i,j\mid\theta)\log_2(p(i,j\mid\theta)+\epsilon)$$

11. Low gray-level run emphasis (LGLRE)

$$LGLRE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_r}\frac{\mathbf{P}(i,j\mid\theta)}{i^2}}{N_r(\theta)}$$

12. High gray-level run emphasis (HGLRE)

$$HGLRE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_r}\mathbf{P}(i,j\mid\theta)i^2}{N_r(\theta)}$$

13. Short run low gray-level emphasis (SRLGLE)

$$SRLGLE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_r}\frac{\mathbf{P}(i,j\mid\theta)}{i^2 j^2}}{N_r(\theta)}$$

14. Short run high gray-level emphasis (SRHGLE)

$$SRHGLE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_r}\frac{\mathbf{P}(i,j\mid\theta)i^2}{j^2}}{N_r(\theta)}$$

15. Long run low gray-level emphasis (LRLGLE)

$$LRLGLRE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_r}\frac{\mathbf{P}(i,j\mid\theta)\,j^2}{i^2}}{N_r(\theta)}$$

16. Long run high gray-level emphasis (LRHGLE)

$$LRHGLRE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_r}\mathbf{P}(i,j\mid\theta)i^2 j^2}{N_r(\theta)}$$

Gray-level size zone matrix (GLSZM)

1. Small area emphasis (SAE)

$$SAE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_s}\frac{\mathbf{P}(i,j)}{j^2}}{N_z}$$

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2. Large area emphasis (LAE)

$$LAE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_s}\mathbf{P}(i,j)\,j^2}{N_z}$$

3. Gray-level nonuniformity (GLN)

$$GLN = \frac{\sum_{i=1}^{N_g}\left(\sum_{j=1}^{N_s}\mathbf{P}(i,j)\right)^2}{N_z}$$

4. Gray-level nonuniformity normalized (GLNN)

$$GLNN = \frac{\sum_{i=1}^{N_g}\left(\sum_{j=1}^{N_s}\mathbf{P}(i,j)\right)^2}{N_z^2}$$

5. Size–zone nonuniformity (SZN)

$$SZN = \frac{\sum_{j=1}^{N_s}\left(\sum_{i=1}^{N_g}\mathbf{P}(i,j)\right)^2}{N_z}$$

6. Size–zone nonuniformity normalized (SZNN)

$$SZNN = \frac{\sum_{j=1}^{N_s}\left(\sum_{i=1}^{N_g}\mathbf{P}(i,j)\right)^2}{N_z^2}$$

7. Zone percentage (ZP)

$$ZP = \frac{N_z}{N_p}$$

8. Gray-level variance (GLV)

$$GLV = \sum_{i=1}^{N_g}\sum_{j=1}^{N_s} p(i,j)(i-\mu)^2$$

9. Zone variance (ZV)

$$ZV = \sum_{i=1}^{N_g}\sum_{j=1}^{N_s} p(i,j)(j-\mu)^2$$

10. Zone entropy (ZE)

$$ZE = -\sum_{i=1}^{N_g}\sum_{j=1}^{N_s} p(i,j)\log_2(p(i,j)+\epsilon)$$

11. Low gray-level zone emphasis (LGLZE)

$$LGLZE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_s}\frac{\mathbf{P}(i,j)}{i^2}}{N_z}$$

12. High gray-level zone emphasis (HGLZE)

$$HGLZE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_s}\mathbf{P}(i,j)i^2}{N_z}$$

13. Small area low gray-level emphasis (SALGLE)

$$SALGLE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_s}\frac{\mathbf{P}(i,j)}{i^2 j^2}}{N_z}$$

14. Small area high gray-level emphasis (SAHGLE)

$$SAHGLE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_s}\frac{\mathbf{P}(i,j)i^2}{j^2}}{N_z}$$

15. Large area low gray-level emphasis (LALGLE)

$$LALGLE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_s}\frac{\mathbf{P}(i,j)\,j^2}{i^2}}{N_z}$$

16. Large area high gray-level emphasis (LAHGLE)

$$LAHGLE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_s}\mathbf{P}(i,j)i^2 j^2}{N_z}$$

Gray-level dependence matrix (GLDM)

1. Small dependence emphasis (SDE)

$$SDE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_d}\frac{\mathbf{P}(i,j)}{i^2}}{N_z}$$

2. Large dependence emphasis (LDE)

$$LDE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_d}\mathbf{P}(i,j)\,j^2}{N_z}$$

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3. Gray-level nonuniformity (GLN)

$$GLN = \frac{\sum_{i=1}^{N_g}\left(\sum_{j=1}^{N_d}\mathbf{P}(i,j)\right)^2}{N_z}$$

4. Dependence nonuniformity (DN)

$$DN = \frac{\sum_{j=1}^{N_d}\left(\sum_{i=1}^{N_g}\mathbf{P}(i,j)\right)^2}{N_z}$$

5. Dependence nonuniformity normalized (DNN)

$$DNN = \frac{\sum_{j=1}^{N_d}\left(\sum_{i=1}^{N_g}\mathbf{P}(i,j)\right)^2}{N_z^2}$$

6. Gray-level variance (GLV)

$$GLV = \sum_{i=1}^{N_g}\sum_{j=1}^{N_d} p(i,j)(i-\mu)^2, \text{ where} \mu = \sum_{i=1}^{N_g}\sum_{j=1}^{N_d} ip(i,j)$$

7. Dependence variance (DV)

$$DV = \sum_{i=1}^{N_g}\sum_{j=1}^{N_d} p(i,j)(j-\mu)^2, \text{ where} \mu = \sum_{i=1}^{N_g}\sum_{j=1}^{N_d} jp(i,j)$$

8. Dependence entropy (DE)

$$DependenceEntropy = -\sum_{i=1}^{N_g}\sum_{j=1}^{N_d} p(i,j)\log_2(p(i,j)+\epsilon)$$

9. Low gray-level emphasis (LGLE)

$$LGLE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_d}\frac{\mathbf{P}(i,j)}{i^2}}{N_z}$$

10. High gray-level emphasis (HGLE)

$$HGLE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_d}\mathbf{P}(i,j)i^2}{N_z}$$

11. Small dependence low gray-level emphasis (SDLGLE)

$$SDLGLE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_d}\frac{\mathbf{P}(i,j)}{i^2 j^2}}{N_z}$$

12. Small dependence high gray-level emphasis (SDHGLE)

Measures the joint distribution of small dependence with higher gray-level values.

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13. Large dependence low gray-level emphasis (LDLGLE)

$$LDLGLE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_d}\frac{\mathbf{P}(i,j)j^2}{i^2}}{N_z}$$

14. Large dependence high gray-level emphasis (LDHGLE)

$$LDHGLE = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_d}\mathbf{P}(i,j)i^2 j^2}{N_z}$$

Neighboring gray-scale difference matrix (NGTDM)

1. Coarseness

$$Coarseness = \frac{1}{\sum_{i=1}^{N_g} p_i s_i}$$

2. Contrast

$$Contrast = \left(\frac{1}{N_{g,p}(N_{g,p}-1)}\sum_{i=1}^{N_g}\sum_{j=1}^{N_g} p_i p_j (i-j)^2\right)\left(\frac{1}{N_{v,p}}\sum_{i=1}^{N_g} s_i\right), \text{where } p_i \neq 0, p_j \neq 0$$

3. Busyness

$$Busyness = \frac{\sum_{i=1}^{N_g} p_i s_i}{\sum_{i=1}^{N_g}\sum_{j=1}^{N_g}|ip_i - jp_j|}, \text{where } p_i \neq 0, p_j \neq 0$$

4. Complexity

$$Complexity = \frac{1}{N_{v,p}}\sum_{i=1}^{N_g}\sum_{j=1}^{N_g}|i-j|\frac{p_i s_i + p_j s_j}{p_i + p_j}, \text{where } p_i \neq 0, p_j \neq 0$$

5. Strength

$$Strength = \frac{\sum_{i=1}^{N_g}\sum_{j=1}^{N_g}(p_i + p_j)(i-j)^2}{\sum_{i=1}^{N_g} s_i}, \text{where } p_i \neq 0, p_j \neq 0$$

Features extracted from wavelet-filtered images

After wavelet decomposition, low-level information hidden from the human eye can be exposed. In our study, Coiflet 1 wavelet was used to decompose the original image. High- and low-pass filters were applied stepwise on the x, y, and z coordinates, which generated 8 decompositions from 1 patient's image. The 14 first-order statistics and 68 textural features described above were extracted from all of 8 decompositions. Thus, a total of 728 wavelet features were extracted from each sequence.

Features extracted from Laplacian of Gaussian–filtered images

Application of a Laplacian of Gaussian filter to the input image yields a derived image for each Σ value specified. A Laplacian of Gaussian image is obtained by convolving the image with the second derivative (Laplacian) of a Gaussian kernel. The Gaussian kernel is used to smooth the image and is defined as follows:

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$$G(x,y,z,\sigma) = \frac{1}{(\sigma\sqrt{2\pi})^3} e^{-\frac{x^2+y^2+z^2}{2\sigma^2}}$$

The Gaussian kernel is convolved with the Laplacian kernel ∇2G(x,y,z), which is sensitive to areas with rapidly changing intensities, enhancing edges. The width of the filter in the Gaussian kernel is determined by σ and can be used to emphasize more fine (low σ values) or coarse (high σ values) textures.

Appendix 2 The formula for imaging score of imaging signature

Imaging Score =DL_t1c_197 × (0.874) + DL_t2f_603 × 0.776 + DL_t2f_732 × 0.248 + DL_t2f_899 × 1.089+DL_t2f_961 × 0.791+DL_t1c_151 × (–0.633) + DL_t1c_446 × 0.1 + Radio_t1c_GLCM_Contrast × (–0.847) + Radio_t2f_GLSZM_Emphasis × (–0.8108) + DL_t2f_839 × 0.476 + DL_t2f_244 × (–0.256) + DL_t2f_983 × 0.746 + DL_t2f_Firstorder_Median × 0.440+Radio_t2f_GLCM_Imc2 × 0.976 + Radio_t2f_Firstorder_10Percentile × 1.17 + Radio_t2f_GLCM Average × 0.5937

(DL, deep learning; t2f, T2 fluid-attenuated inversion recovery; T1c, contrast-enhanced T1-weighted; GLCM, gray-level co-occurrence matrix; GLSZM, gray-level size zone matrix)

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