Shape Descriptors

Sphericity = $\frac{\sqrt[3]{36\pi V^2}}{S}$, with *V* being the volume and *S* the surface.

Irregularity = $\frac{\sum_{i=1}^{6} i \times d(i)}{\sum_{i=1}^{6} d(i)}$, with *d(i)* being the number of voxels having *i* neighbor voxels in the surrounding background.

Major axis = max(distance(*p1, p2*), with *p1* and *p2* being two different voxels within the tumor.

3D surface = number of voxels spatially connected with the surrounding background.

Histogram-Based (First-Order) Metrics

The histogram is a column vector *h* with each entry indexed by the gray level values and whose values are the number of voxels in the region of interest with that gray level value. Thus, gray level value *i* appears within the ROI h_i times.

Note: Materka (*1*) and others use the information-theoretic logarithm based 2 in the entropy calculations. We suggest the use of natural logarithm in all calculations.

Mean

$$\mu = \sum_{i=1}^{G_{max}} \{i \cdot h_i\}$$

Variance

$$\sigma^2 = \sum_{i=1}^{G_{max}} \{(i-\mu)^2 \cdot h_i\}$$

Skewness (Set to 0 when σ = 0.)

$$\mu^3 = \frac{1}{\sigma^3} \sum_{i=1}^{G_{max}} \{(i-\mu)^3 \cdot h_i\}$$

Excess kurtosis (Set to 0 when σ = 0. Note: "kurtosis" and "excess kurtosis" differ in that excess kurtosis = kurtosis – 3.)

$$\mu^4 = \frac{1}{\sigma^4} \sum_{i=1}^{G_{max}} \{(i-\mu)^4 \cdot h_i\} - 3$$

Energy

$$Ene = \sum_{i=1}^{G_{max}} \{[h_i]^2\}$$

$\text{Entropy}_{\text{HIST}}$ (Note: We will differentiate between the various entropy calculations in this document, specifying the distribution from which the entropy is computed.)

$$Ent = -\sum_{i=1}^{G_{max}} \{h_i \cdot ln[h_i]\}$$

Gray-Level-Cooccurrence Matrix, GLCM (Also Called Gray-Tone-Spatial-Dependence Matrix, GTSDM)

Let *p* be the normalized (sum all of matrix entries is one) gray level cooccurrence matrix. (Note: Haralick (*2*) ambiguously states that *Ng* is the "number of distinct gray levels in the quantized image." However, the equations indicated that *Ng* is not the number of distinct values present in the image but rather the maximum possible quantized value, called G_{max} in the following formulas.) For the metrics calculations we use the following:

$$p_x(i) = \sum_{j=1}^{G_{max}} \{p_{i,j}\} \; ; \; p_y(j) = \sum_{j=1}^{G_{max}} \{p_{i,j}\}$$

$$p_{x+y}(n) = \sum_{i+j=n} \{p_{i,j}\} \; ; \; n \in \{2,3 \dots, 2 \cdot G_{max}\}$$

$$p_{x-y}(n) = \sum_{|i-j|=n} \{p_{i,j}\} \; ; \; n \in \{0,1 \dots, G_{max} - 1\}$$

$$\mu_{x-y} = \sum_{n=0}^{G_{max}-1} \{n \cdot p_{x-y}(n)\}$$

Physics and Information theory dictates that $0 \cdot \log(0) = 0$ for entropy calculations. This differs from Haralick (*2*), where an arbitrary ε is recommended. GLCM metrics are no. 1 to 14, from Haralick (*2*).

Angular second moment (ASM) (This is called energy in Soh (*3*) and uniformity in Clausi (*4*).)

$$f_1 = \sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{G_{max}} \left\{ \left(p_{i,j}\right)^2 \right\} \right\}$$

$\text{Contrast}_{\text{GLCM}}$ (The first formula from Haralick (*2*) and the second version from Clausi (*4*) are equal to each other.)

$$f_2 = \sum_{n=0}^{G_{max}-1} \{n^2 \cdot p_{x-y}(n)\} = \sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{G_{max}} \{(i-j)^2 \cdot p_{i,j}\} \right\}$$

Correlation (The first version corresponds to equations from Haralick (*2*) and Soh (*3*), which are equal to each other. The second one is from Clausi (*4*); the two are equivalent.)

$$f_3 = \frac{\sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{G_{max}} \{i \cdot j \cdot p_{i,j}\} \right\} - \mu_x \cdot \mu_y}{\sigma_x \cdot \sigma_y} = \frac{\sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{G_{max}} \{(i-\mu_x) \cdot (j-\mu_y) \cdot p_{i,j}\} \right\}}{\sigma_x \cdot \sigma_y}$$

μ_x, μ_y, σ_x, *and* σ_y are only loosely hinted at in Haralick (*2*). Taking the means and variances of the p_x could be interpreted as taking the mean of the values of p_x as a set of numbers, rather than the distribution mean. This would be an incorrect interpretation, and computing the mean of the distribution is the correct interpretation. This is corroborated by Bharati (*5*). The following definitions are taken from Bharati (*5*):

$$\mu_x = \sum_{i=1}^{G_{max}} \left\{ i \cdot \sum_{j=1}^{G_{max}} \{p_{i,j}\} \right\} \; ; \; \mu_y = \sum_{j=1}^{G_{max}} \left\{ j \cdot \sum_{i=1}^{G_{max}} \{p_{i,j}\} \right\}$$

$$\sigma_x = \left(\sum_{i=1}^{G_{max}} \left\{ (i-\mu_x)^2 \cdot \sum_{j=1}^{G_{max}} \{p_{i,j}\} \right\} \right)^{1/2} \; ; \; \sigma_y = \left(\sum_{j=1}^{G_{max}} \left\{ (j-\mu_y)^2 \cdot \sum_{i=1}^{G_{max}} \{p_{i,j}\} \right\} \right)^{1/2}$$

Sum-of-squares variance (Ambiguous, as μ was not defined.)

$$f_4 = \sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{G_{max}} \{(i-\mu)^2 \cdot p_{i,j}\} \right\}$$

We use the following definition for μ:

$$\mu = \frac{\sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{G_{max}} \{p_{i,j}\} \right\}}{(G_{max})^2}$$

Inverse different moment (IDM) (is called homogeneity in Soh (*3*))

$$f_5 = \sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{G_{max}} \left\{ \frac{1}{1+(i-j)^2} \cdot p_{i,j} \right\} \right\}$$

Sum average (SAVE)

$$f_6 = \sum_{n=2}^{2 \cdot G_{max}} \{ n \cdot p_{x+y}(n) \}$$

Sum variance (SVAR) (The formula in Haralick (*2*) incorrectly uses f_8, an error that has propagated into many other papers and code implementations.)

$$f_7 = \sum_{n=2}^{2 \cdot G_{max}} \{ (n-f_6)^2 \cdot p_{x+y}(n) \}$$

GLCM sum entropy (SENT)

$$f_8 = -\sum_{n=2}^{2 \cdot G_{max}} \{ p_{x+y}(n) \cdot \ln[p_{x+y}(n)] \}$$

$\text{Entropy}_{\text{GLCM}}$

$$f_9 = -\sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{G_{max}} \{ p_{i,j} \cdot \ln[p_{i,j}] \} \right\}$$

Difference variance (DVAR) (The equation from the Murphy lab code was incorrect (mean was not subtracted) and is equal to $\text{Contrast}_{\text{GLCM}}$ (f_2 above). This error has propagated into several code implementations.)

$$f_{10} = -\sum_{n=0}^{G_{max}-1} \left\{ \left(n - \mu_{x-y}\right)^2 \cdot p_{x-y}(n) \right\}$$

GLCM difference entropy (DENT)

$$f_{11} = -\sum_{n=0}^{G_{max}-1} \left\{ p_{x-y}(n) \cdot \ln\left[p_{x-y}(n)\right] \right\}$$

Information Correlation (IC) (Set to infinity if the denominator is zero.)

$$f_{12} = \frac{f_9 - Ent_{xy,1}}{max\left\{Ent_x; Ent_y\right\}}$$

Autocorrelation

$$f_{13} = \sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{G_{max}} \left\{ i \cdot j \cdot p_{i,j} \right\} \right\}$$

Dissimilarity

$$f_{14} = \sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{G_{max}} \left\{ |i - j| \cdot p_{i,j} \right\} \right\}$$

Cluster prominence (CP)

$$f_{15} = \sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{G_{max}} \left\{ \left(i + j - \mu_x - \mu_y\right)^4 \cdot p_{i,j} \right\} \right\}$$

Maximum probability (MaxProba)

$$f_{16} = \max_{i,j}\left\{p_{i,j}\right\}$$

Inverse difference (ID) (Clausi (*4*))

$$f_{17} = \sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{G_{max}} \left\{ \frac{1}{1 + |i - j|} \cdot p_{i,j} \right\} \right\}$$

Neighborhood-Gray-Tone-Difference Matrix (NGTDM)

Let *s* be the NGTDM vector, indexed s_i, and p_i be the probability of a voxel value for voxels that are used in the computation of the NGTDM. N_g is the number of unique gray levels present in the image (not necessarily equal to the highest gray level value, G_{max}, since some values may not be present in the image). When a gray level is not present, the corresponding s_i is zero. (Note: no ε is added to the coarseness or texture strength computation. Rather, if the denominator is zero, the value is set to infinity.) For contrast and complexity, the normalization factor *n* is meant to be the number of voxels that are used in the computation of the neighborhood difference matrix. For busyness, Amadasun (*6*) does not have the absolute value within the denominator. This would lead to a denominator that is always zero if implemented according to the equation given in Amadsun (*6*). Materka (*1*) shows the absolute value in the denominator in the busyness equation, a form that we recommend.

Coarseness

$$g_1 = \left[\sum_{i=1}^{G_{max}} \{p_i \cdot s_i\}\right]^{-1}$$

Contrast$_{NGTDM}$ (Set to –1 if there is only a single gray level [no contrast can be computed].)

$$g_2 = \left[\frac{1}{N_g \cdot (N_g - 1)} \cdot \sum_{i=1}^{G_{max}} \left\{\sum_{j=1}^{G_{max}} \{p_i \cdot p_j \cdot (i-j)^2\}\right\}\right] \cdot \left[\frac{1}{n} \cdot \sum_{i=1}^{G_{max}} \{s_i\}\right]$$

Busyness

$$g_3 = \frac{\sum_{i=1}^{G_{max}} \{p_i \cdot s_i\}}{\sum_{i=1}^{G_{max}} \left\{\sum_{j=1}^{G_{max}} \{|i \cdot p_i - j \cdot p_j|\}\right\}} \; ; \; p_i \neq 0 \, ; p_j \neq 0$$

Complexity

$$g_4 = \sum_{i=1}^{G_{max}} \left\{\sum_{j=1}^{G_{max}} \left\{\frac{|i-j| \cdot (p_i \cdot s_i + p_j \cdot s_j)}{n \cdot (p_i + p_j)}\right\}\right\} \; ; \; p_i \neq 0 \, ; p_j \neq 0$$

Texture strength (TS)

$$g_5 = \frac{\sum_{i=1}^{G_{max}} \left\{\sum_{j=1}^{G_{max}} \{(p_i + p_j) \cdot (i-j)^2\}\right\}}{\sum_{i=1}^{G_{max}} \{s_i\}} \; ; \; p_i \neq 0 \, ; p_j \neq 0$$

Gray-Level-Zone-Size Matrix (GLZSM)

Let *p* be the gray-level-zone-size matrix (GLZSM) indexed by $p_{i,j}$ with rows *i* indicating gray levels and columns *j* indicating zone sizes. The largest zone size (the number of columns) will be denoted S_{max}. The total number of unique connected zones is n_z. The total number of voxels is n_v. The following metrics are taken from Tang (*7*).

Small-zone-size emphasis (SZSE)

$$Z_1 = \frac{1}{n_z} \cdot \sum_{i=1}^{G_{max}} \left\{\sum_{j=1}^{S_{max}} \left\{\frac{p_{i,j}}{j^2}\right\}\right\}$$

Large-zone-size emphasis (LZSE)

$$Z_2 = \frac{1}{n_z} \cdot \sum_{i=1}^{G_{max}} \left\{\sum_{j=1}^{S_{max}} \{p_{i,j} \cdot j^2\}\right\}$$

Low-gray-level-zone emphasis (LGLZE)

$$Z_3 = \frac{1}{n_z} \cdot \sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{S_{max}} \left\{ \frac{p_{i,j}}{i^2} \right\} \right\}$$

High-gray-level-zone emphasis (HGLZE)

$$Z_4 = \frac{1}{n_z} \cdot \sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{S_{max}} \left\{ p_{i,j} \cdot i^2 \right\} \right\}$$

Small-zone/low-gray emphasis (SZLGE)

$$Z_5 = \frac{1}{n_z} \cdot \sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{S_{max}} \left\{ \frac{p_{i,j}}{i^2 \cdot j^2} \right\} \right\}$$

Small-zone/high-gray emphasis (SZHGE)

$$Z_6 = \frac{1}{n_z} \cdot \sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{S_{max}} \left\{ \frac{p_{i,j} \cdot i^2}{j^2} \right\} \right\}$$

Large-zone/low-gray emphasis (LZLGE)

$$Z_7 = \frac{1}{n_z} \cdot \sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{S_{max}} \left\{ \frac{p_{i,j} \cdot j^2}{i^2} \right\} \right\}$$

Large-zone/high-gray emphasis (LZHGE)

$$Z_8 = \frac{1}{n_z} \cdot \sum_{i=1}^{G_{max}} \left\{ \sum_{j=1}^{S_{max}} \left\{ p_{i,j} \cdot i^2 \cdot j^2 \right\} \right\}$$

Gray-level nonuniformity (GLNU)

$$Z_9 = \frac{1}{n_z} \cdot \sum_{i=1}^{G_{max}} \left\{ \left[\sum_{j=1}^{S_{max}} \left\{ p_{i,j} \right\} \right]^2 \right\}$$

Zone-size nonuniformity (ZSNU)

$$Z_{10} = \frac{1}{n_z} \cdot \sum_{j=1}^{S_{max}} \left\{ \left[\sum_{i=1}^{G_{max}} \left\{ p_{i,j} \right\} \right]^2 \right\}$$

Zone-size percentage (SZP)

$$Z_{11} = \frac{n_z}{n_v}$$

SUPPLEMENTAL TABLE 1: Test-Retest Repeatability of Features Computed on FDG PET Component

Feature	Quantization		Bland-Altman analysis				ICC
	Method	Value	Mean (%)	SD (%)	LRL (%)	URL (%)	
Volume							
MAV	N/A		-1.4	11.1	-23.2	20.3	0.997
Shape descriptors							
Sphericity	N/A		1.1	4.8	-8.3	10.5	0.969
Irregularity			-0.5	4.8	-9.9	8.9	0.848
3D Surface			-2.1	9	-19.6	15.5	0.994
Major axis			-0.6	8.4	-17	15.9	0.993
1st order (histogram) metrics							
Maximum	N/A		3.5	19.3	-34.3	41.3	0.964
Mean			3.0	17.0	-30.4	36.3	0.97
Standard deviation (SD)			3.8	21.5	-38.4	46.1	0.961
Skewness			-1.1	33.7	-67.1	64.9	0.865
Kurtosis			0.8	19.1	-36.8	38.3	0.940
Energy			-1.2	23.8	-47.9	45.5	0.973
$Entropy_{HIST}$			0.1	4.0	-7.9	8.0	0.991
CH_{AUC}			-0.2	3.6	-7.3	6.9	0.812
2nd order metrics							
GLCM							
ASM	B	8	1.2	23.3	-44.4	46.7	0.934
		16	1.1	20.7	-39.5	41.6	0.945
		32	1	21.7	-41.5	43.6	0.832
		64	-0.5	18.6	-37	36.1	0.949
		128	-0.8	19	-38.1	36.5	0.958
	W	0.5	-11.3	41.8	-93.3	70.7	0.904
IDM	B	8	0.5	7.3	-13.8	14.9	0.973
		16	0	9.4	-18.5	18.5	0.973
		32	0	11.5	-22.6	22.6	0.97
		64	-0.8	16.8	-33.8	32.2	0.958
		128	-2.1	23.5	-48.1	44	0.935
	W	0.5	-5.0	16.4	-37.1	27.1	0.964
$Entropy_{GLCM}$	B	8	-0.8	7.5	-15.4	13.8	0.911
		16	-0.4	4.1	-8.4	7.7	0.941
		32	-0.3	3.6	-7.4	6.8	0.955
		64	-0.1	2.6	-5.1	4.9	0.984
		128	0	2.5	-4.9	4.8	0.992
	W	0.5	5.7	22.6	-38.7	50.1	0.969
Correlation	B	8	2.9	104.6	-202	207.9	0.978

		16	2.4	115.6	-224.2	229.1	0.977
		32	0.3	115.9	-226.9	227.6	0.978
		64	0.7	114.4	-223.5	225	0.977
		128	0.6	112.1	-219	220.3	0.977
	W	0.5	7.6	107.1	-202.3	217.5	0.969
ID	B	8	0.5	5.4	-10	10.9	0.972
		16	0	6.4	-12.5	12.5	0.973
		32	0.1	7.2	-14	14.2	0.973
		64	-0.4	9.3	-18.7	18	0.968
		128	-0.8	11.3	-23	21.3	0.964
	W	0.5	-3.6	11.9	-27.0	19.8	0.964
Dissimilarity	B	8	-0.6	10.4	-21.1	19.9	0.971
		16	-0.3	10.2	-20.2	19.6	0.97
		32	-0.4	9.9	-19.9	19.1	0.972
		64	-0.3	9.8	-19.6	19	0.972
		128	-0.3	9.9	-19.6	19	0.972
	W	0.5	10.0	31.7	-52.1	72.1	0.974
$Contrast_{GLCM}$	B	8	-0.8	17.6	-35.3	33.8	0.967
		16	-0.6	18.3	-36.4	35.1	0.963
		32	-0.7	18.2	-36.4	35.1	0.964
		64	-0.7	18.1	-36.2	34.9	0.965
		128	-0.6	18.2	-36.2	35	0.964
	W	0.5	14.9	47.4	-77.9	107.7	0.982
SOSV	B	8	-0.2	16.5	-32.6	32.2	0.914
		16	-0.3	17.9	-35.3	34.8	0.910
		32	-0.5	18.8	-37.2	36.3	0.905
		64	-0.4	18.9	-37.5	36.6	0.907
		128	0.1	1.8	-3.5	3.7	0.575
	W	0.5	11.4	39.1	-65.3	88.1	0.994
SAVE	B	8	0.1	9.1	-17.7	17.8	0.923
		16	0	10.2	-19.9	19.9	0.921
		32	-0.1	10.9	-21.5	21.3	0.917
		64	-0.1	11.1	-21.8	21.6	0.919
		128	-0.5	19.1	-37.9	37	0.906
	W	0.5	5.2	19.3	-32.7	43.1	0.984
SVAR	B	8	-1.4	15.5	-31.9	29.1	0.899
		16	-1.3	15.9	-32.5	29.9	0.892
		32	-1.3	16	-32.6	30	0.89
		64	-1.3	15.9	-32.4	29.8	0.892
		128	-0.1	11.2	-22.2	21.9	0.918
	W	0.5	12.5	46.6	-78.9	103.9	0.988
SENT	B	8	-0.7	6.1	-12.8	11.3	0.884
		16	-0.4	3.8	-7.9	7.1	0.910

		32	-0.4	3.5	-7.3	6.5	0.905
		64	-0.2	2.1	-4.4	4	0.959
		128	-1.3	15.9	-32.5	30	0.890
	W	0.5	4.3	19.5	-33.8	42.4	0.972
DVAR	B	8	-0.2	14.8	-29.2	28.8	0.970
		16	-0.6	16.1	-32.2	31	0.966
		32	-0.6	16.7	-33.3	32.2	0.963
		64	-0.7	16.7	-33.3	32	0.963
		128	-0.2	2.2	-4.5	4.1	0.965
	W	0.5	11.7	42.5	-71.7	95.1	0.983
DENT	B	8	-0.6	6.8	-13.9	12.8	0.941
		16	-0.3	4.5	-9.2	8.5	0.961
		32	-0.3	4.1	-8.4	7.8	0.949
		64	-0.2	3.0	-6.1	5.7	0.961
		128	-0.6	16.7	-33.4	32.2	0.963
	W	0.5	4.3	17.6	-30.2	38.9	0.970
IC	B	8	0.5	29.7	-57.7	58.6	0.981
		16	0.5	22.5	-43.5	44.6	0.961
		32	-0.6	15.3	-30.6	29.3	0.945
		64	-1	13.3	-27.1	25	0.960
		128	-0.2	2.6	-5.3	4.9	0.957
	W	0.5	-1.0	32.0	-63.6	61.7	0.944
Autocorrelation	B	8	0	17.9	-35	35	0.900
		16	-0.2	19.8	-39.1	38.7	0.895
		32	-0.4	21.1	-41.8	41	0.890
		64	-0.4	21.4	-42.3	41.6	0.892
		128	0	0.0	0	0	0.834
	W	0.5	9.8	37.2	-63.0	82.7	0.995
Prominence	B	8	-2.5	23.9	-49.4	44.5	0.853
		16	-2.3	25.4	-52.2	47.5	0.835
		32	-2.2	26.1	-53.4	48.9	0.823
		64	-2.4	26	-53.3	48.6	0.826
		128	-30.8	225.5	-472.8	411.1	0.875
	W	0.5	19.0	74.5	-127.0	165.1	0.993
MaxProba	B	8	-0.2	27	-53.1	52.8	0.956
		16	1.5	30.9	-59	62.1	0.924
		32	2.5	34.2	-64.5	69.5	0.833
		64	-2.1	34.3	-69.4	65.2	0.933
		128	-2.2	26.1	-53.4	48.9	0.824
	W	0.5	-7.3	35.5	-76.9	62.3	0.946
NGTDM							
Coarseness	B	8	0.9	16	-30.4	32.2	0.964
		16	1	14.5	-27.3	29.3	0.977

		32	0.8	15	-28.6	30.2	0.969
		64	1.4	14.3	-26.6	29.4	0.968
		128	-5.6	40.9	-85.7	74.5	0.851
	W	0.5	-0.6	37.7	-74.4	73.2	0.841
Contrast$_{NGTDM}$	B	8	-0.2	29.6	-58.2	57.8	0.649
		16	1.1	25.2	-48.2	50.4	0.883
		32	0.3	26.3	-51.2	51.9	0.927
		64	0.6	27.6	-53.5	54.7	0.985
		128	2.4	13.4	-23.9	28.7	0.970
	W	0.5	15.4	45.7	-74.2	105.1	0.669
Busyness	B	8	-4.7	22.2	-48.2	38.8	0.994
		16	-2.5	18.6	-38.9	33.9	0.993
		32	-1.3	17.5	-35.6	33	0.993
		64	-1.9	15	-31.3	27.6	0.992
		128	-0.8	29	-57.7	56.1	0.990
	W	0.5	-9.6	55.5	-118.4	99.3	0.361
Complexity	B	8	-0.2	14.7	-28.9	28.5	0.880
		16	-0.1	15.5	-30.4	30.3	0.948
		32	0.3	16.1	-31.3	31.9	0.962
		64	-0.3	16.5	-32.6	32	0.981
		128	-2.6	13.1	-28.3	23.1	0.993
	W	0.5	10.7	39.6	-66.9	88.3	0.924
TS	B	8	-1.4	14.7	-30.2	27.3	0.993
		16	-1.4	14.6	-29.9	27.1	0.993
		32	-1.3	14.6	-30	27.3	0.992
		64	-1.3	14.6	-29.8	27.2	0.992
		128	-1.1	17	-34.5	32.3	0.982
	W	0.5	6.6	29.6	-51.5	64.7	0.996
3rd order metrics							
GLZSM							
SZSE	B	8	1.6	12.9	-23.6	26.8	0.665
		16	0.6	5.9	-11	12.1	0.836
		32	0.3	3.6	-6.8	7.4	0.861
		64	0.2	2.8	-5.3	5.7	0.746
		128	0	2	-3.8	3.9	0.622
	W	0.5	-2.6	37.7	-76.6	71.3	0.910
LZSE	B	8	1.7	53.6	-103.4	106.8	0.961
		16	2.8	38.1	-71.9	77.5	0.416
		32	-0.7	21.7	-43.2	41.7	0.791
		64	-0.8	11.1	-22.6	21	0.878
		128	-0.3	7.4	-14.8	14.2	0.765
	W	0.5	-14.6	63.2	-138.5	109.3	0.943
ZSNU	B	8	-1.3	23.2	-46.8	44.1	0.980

		16	-1	16.8	-33.9	31.8	0.992
		32	-0.3	15.3	-30.4	29.7	0.991
		64	-1.1	13.7	-28	25.8	0.995
		128	-2.4	13.3	-28.5	23.6	0.995
	W	0.5	2.1	29.3	-55.3	59.5	0.988
GLNU	B	8	1.1	38	-73.4	75.6	0.933
		16	0.2	23.3	-45.5	46	0.982
		32	-0.2	16.5	-32.5	32	0.993
		64	-0.4	13.6	-27.1	26.3	0.996
		128	-1.1	13.9	-28.3	26.1	0.998
	W	0.5	9.2	46.8	-82.5	100.9	0.991
ZSP	B	8	-0.1	20.1	-39.5	39.3	0.951
		16	0.4	9.4	-18.1	18.8	0.954
		32	0.3	5.7	-11	11.6	0.920
		64	0.3	3.6	-6.8	7.4	0.839
		128	0.1	2.5	-4.9	5.1	0.693
	W	0.5	6.5	33.3	-58.7	71.8	0.945
LGLZE	B	8	-0.8	14.3	-28.9	27.2	0.709
		16	1.4	20.7	-39.2	42	0.763
		32	1.7	34.4	-65.8	69.2	0.733
		64	3.6	44.9	-84.5	91.6	0.669
		128	3.9	51.7	-97.3	105.2	0.684
	W	0.5	-1.7	27.4	-55.4	52.1	0.954
HGLZE	B	8	-0.6	16.4	-32.8	31.5	0.793
		16	0.2	17.8	-34.6	35	0.841
		32	0.1	19	-37.2	37.4	0.874
		64	-0.4	19.4	-38.3	37.6	0.884
		128	-0.1	20	-39.3	39.2	0.885
	W	0.5	7.4	39.4	-69.8	84.6	0.993
SZLGE	B	8	0	22.6	-44.3	44.3	0.379
		16	3.8	26.1	-47.5	55	0.602
		32	3	36.7	-68.9	74.9	0.599
		64	4.6	48.6	-90.7	99.8	0.428
		128	4.1	56.2	-106.1	114.3	0.392
	W	0.5	-3.1	47.7	-96.6	90.4	0.670
SZHGE	B	8	1	22.1	-42.2	44.3	0.863
		16	1	19.9	-38.1	40.1	0.859
		32	0.6	19.8	-38.3	39.5	0.876
		64	-0.3	19.5	-38.6	37.9	0.887
		128	0	20.2	-39.6	39.6	0.886
	W	0.5	3.6	63.7	-121.2	128.4	0.993
LZLGE	B	8	-1.1	66.5	-131.4	129.2	0.957
		16	1.2	58.5	-113.5	115.9	0.347

		32	0.9	53.2	-103.5	105.3	0.544
		64	1.7	51.8	-99.8	103.3	0.744
		128	5.8	54.2	-100.5	112	0.785
	W	0.5	-18.7	76.4	-168.5	131.1	0.945
LZHGE	B	8	4.4	46.4	-86.6	95.3	0.978
		16	2.5	32	-60.1	65.1	0.969
		32	-1	22.8	-45.7	43.6	0.940
		64	-0.5	22.4	-44.4	43.4	0.861
		128	-0.5	20.5	-40.7	39.7	0.863
	W	0.5	-3.0	53.7	-108.3	102.3	0.931

SUPPLEMENTAL TABLE 2: Test–Retest Repeatability of Features Computed on Low-Dose CT Component

Feature	Quantization		Bland-Altman analysis				ICC
	Method	Value	Mean (%)	SD (%)	LRL (%)	URL (%)	
Volume							
AV	N/A		-0.4	10.5	-21.0	20.3	0.997
Shape descriptors							
Sphericity	N/A		0.3	10.0	-19.4	20.0	0.946
Irregularity			1.3	3.3	-5.2	7.7	0.948
3D surface			-0.6	11.6	-23.4	22.2	0.988
Major axis			3.8	18.4	-32.3	39.9	0.972
1st order metrics (histogram)							
Maximum	N/A		4.7	38.6	-70.9	80.3	0.539
Mean			-4.2	43.6	-89.7	81.3	0.865
Standard deviation			-0.1	12.0	-23.7	23.5	0.866
Skewness			11.1	202.2	-385.2	407.4	0.213
Kurtosis			4.8	37.4	-68.6	78.1	0.034
Energy			0.6	12.3	-23.5	24.7	0.915
$Entropy_{HIST}$			-0.1	2.5	-5.1	4.8	0.914
CH_{AUC}			0.7	9.1	-17.0	18.5	0.851
2nd order metrics							
GLCM							
ASM	B	8	5.8	45.2	-82.7	94.4	0.543
		16	7.7	52.4	-95.1	110.5	0.356
		32	7.8	54.2	-98.4	114.0	0.219
		64	7.6	54.3	-98.7	114.0	0.159
		128	8.1	52.0	-93.8	110.0	0.163
	W	10	1.9	24.3	-45.7	49.4	0.921
IDM	B	8	1.7	10.8	-19.4	22.9	0.823
		16	1.9	17.5	-31.3	37.2	0.800
		32	3.8	23.4	-42.0	49.6	0.757
		64	4.5	27.6	-49.6	58.5	0.689

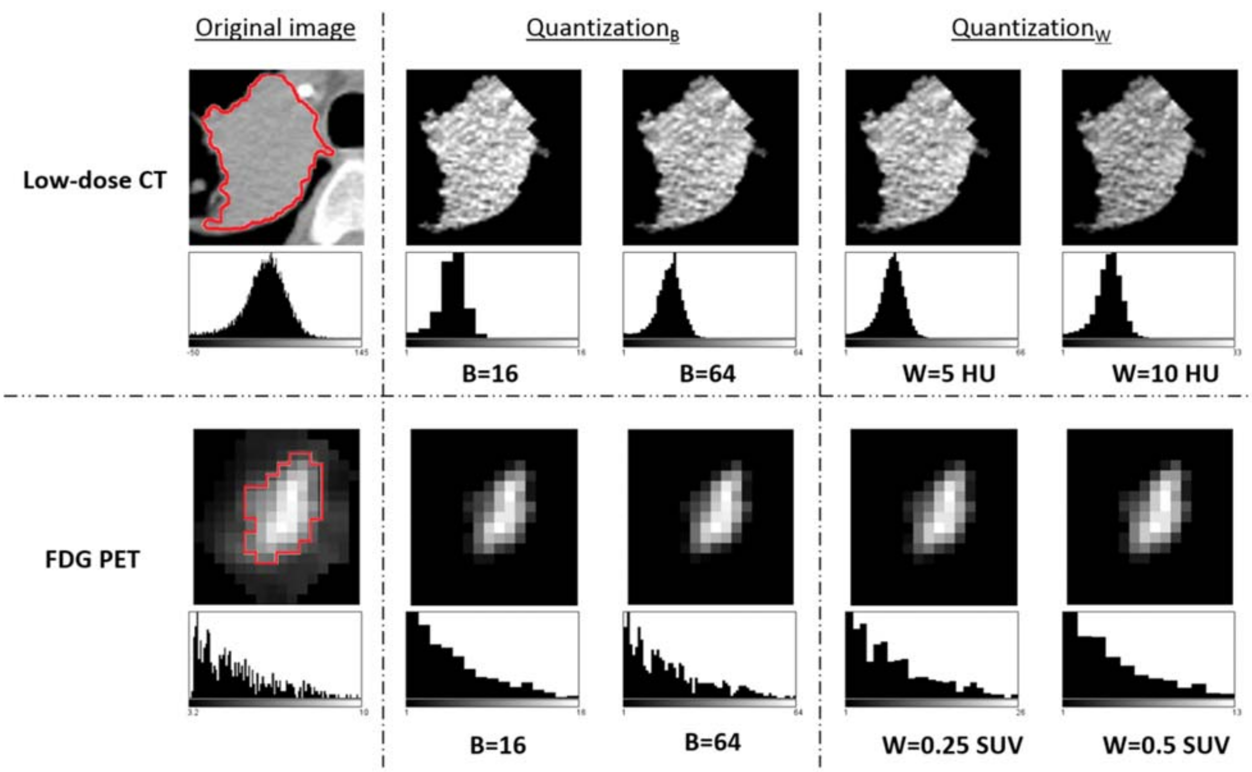
		128	5.0	29.9	-53.7	63.7	0.623
	W	10	1.3	8.2	-14.9	17.4	0.951
$Entropy_{GLCM}$	B	8	-4.9	31.8	-67.3	57.4	0.791
		16	-3.4	21.6	-45.6	38.9	0.777
		32	-2.5	15.5	-32.9	27.9	0.763
		64	-1.9	12.0	-25.4	21.6	0.742
		128	-1.5	9.4	-19.9	16.8	0.713
	W	10	-0.4	5.2	-10.6	9.9	0.934
Correlation	B	8	3.0	24.6	-45.2	51.3	0.829
		16	3.0	24.0	-44.2	50.1	0.840
		32	3.4	24.2	-44.0	50.7	0.845
		64	3.5	24.1	-43.8	50.7	0.847
		128	3.6	24.2	-43.9	51.0	0.848
	W	10	3.5	24.3	-44.1	51.1	0.842
ID	B	8	1.5	9.2	-16.6	19.5	0.811
		16	2.2	13.0	-23.3	27.7	0.795
		32	2.8	16.4	-29.4	34.9	0.770
		64	3.2	19.4	-34.7	41.2	0.738
		128	3.7	21.7	-38.8	46.2	0.708
	W	10	0.9	5.6	-10.2	11.9	0.951
Dissimilarity	B	8	-6.7	37.5	-80.1	66.8	0.856
		16	-5.9	33.2	-71.1	59.2	0.861
		32	-5.7	32.2	-68.8	57.3	0.863
		64	-5.6	32.1	-68.6	57.3	0.863
		128	-5.7	32.2	-68.8	57.4	0.863
	W	10	-1.7	10.9	-23.0	19.6	0.949
$Contrast_{GLCM}$	B	8	-9.0	48.1	-103.1	85.2	0.889
		16	-8.9	52.2	-111.1	93.4	0.887
		32	-9.2	53.9	-114.8	96.4	0.889
		64	-9.2	54.4	-115.9	97.5	0.889
		128	-9.3	54.7	-116.5	97.9	0.889
	W	10	-2.8	20.6	-43.2	37.5	0.937
SOSV	B	8	-6.0	46.2	-96.6	84.7	0.787
		16	-6.0	49.7	-103.4	91.4	0.791
		32	-6.2	51.9	-108.0	95.6	0.791
		64	-6.1	53.0	-109.9	97.7	0.791
		128	-6.2	53.4	-110.9	98.6	0.791
	W	10	0.1	1.8	-3.4	3.6	0.916
SAVE	B	8	-3.4	25.4	-53.3	46.5	0.760
		16	-3.5	27.7	-57.7	50.8	0.765
		32	-3.7	29.5	-61.5	54.1	0.764
		64	-3.7	30.3	-63.1	55.7	0.763
		128	-3.7	30.7	-63.9	56.4	0.764

	W	10	0.0	1.1	-2.2	2.3	0.918
SVAR	B	8	-7.3	49.8	-104.8	90.2	0.877
		16	-6.8	52.3	-109.4	95.7	0.877
		32	-6.9	53.1	-111.0	97.2	0.878
		64	-6.9	53.4	-111.5	97.7	0.878
		128	-7.0	53.5	-111.9	98.0	0.878
	W	10	0.9	5.6	-10.1	11.9	0.829
SENT	B	8	-4.2	28.7	-60.4	52.0	0.743
		16	-2.6	17.8	-37.6	32.3	0.747
		32	-1.8	12.6	-26.4	22.8	0.752
		64	-1.4	10.0	-21.0	18.2	0.749
		128	-1.2	8.3	-17.5	15.1	0.745
	W	10	0.1	0.4	-0.8	0.9	0.865
DVAR	B	8	-8.3	40.3	-87.3	70.8	0.886
		16	-8.4	47.7	-102.0	85.2	0.888
		32	-9.1	51.8	-110.6	92.5	0.889
		64	-9.2	53.1	-113.3	94.9	0.889
		128	-9.3	53.5	-114.1	95.5	0.890
	W	10	-1.4	9.8	-20.6	17.9	0.820
DENT	B	8	-5.1	27.8	-59.6	49.4	0.803
		16	-3.4	19.3	-41.3	34.4	0.812
		32	-2.8	15.7	-33.6	28.0	0.803
		64	-2.3	13.1	-28.0	23.4	0.791
		128	-2.0	10.9	-23.3	19.4	0.783
	W	10	-0.3	1.9	-4.1	3.5	0.822
IC	B	8	8.4	42.4	-74.8	91.5	0.797
		16	8.9	41.1	-71.8	89.5	0.848
		32	8.7	39.0	-67.7	85.0	0.841
		64	7.1	32.6	-56.8	71.1	0.880
		128	3.3	26.2	-48.2	54.7	0.957
	W	10	6.7	34.8	-61.5	74.8	0.846
Autocorrelation	B	8	-5.8	46.2	-96.3	84.7	0.784
		16	-5.8	49.8	-103.3	91.7	0.787
		32	-6.0	52.0	-108.0	96.0	0.787
		64	-5.9	53.1	-110.0	98.3	0.787
		128	-5.9	53.6	-111.1	99.2	0.787
	W	10	0.4	3.3	-6.1	6.8	0.856
CP	B	8	-8.0	72.5	-150.1	134.1	0.853
		16	-7.6	75.4	-155.2	140.1	0.849
		32	-7.8	75.9	-156.6	141.1	0.847
		64	-7.8	76.1	-156.9	141.3	0.847
		128	-7.8	76.2	-157.1	141.5	0.847
	W	10	1.4	7.8	-13.8	16.7	0.856

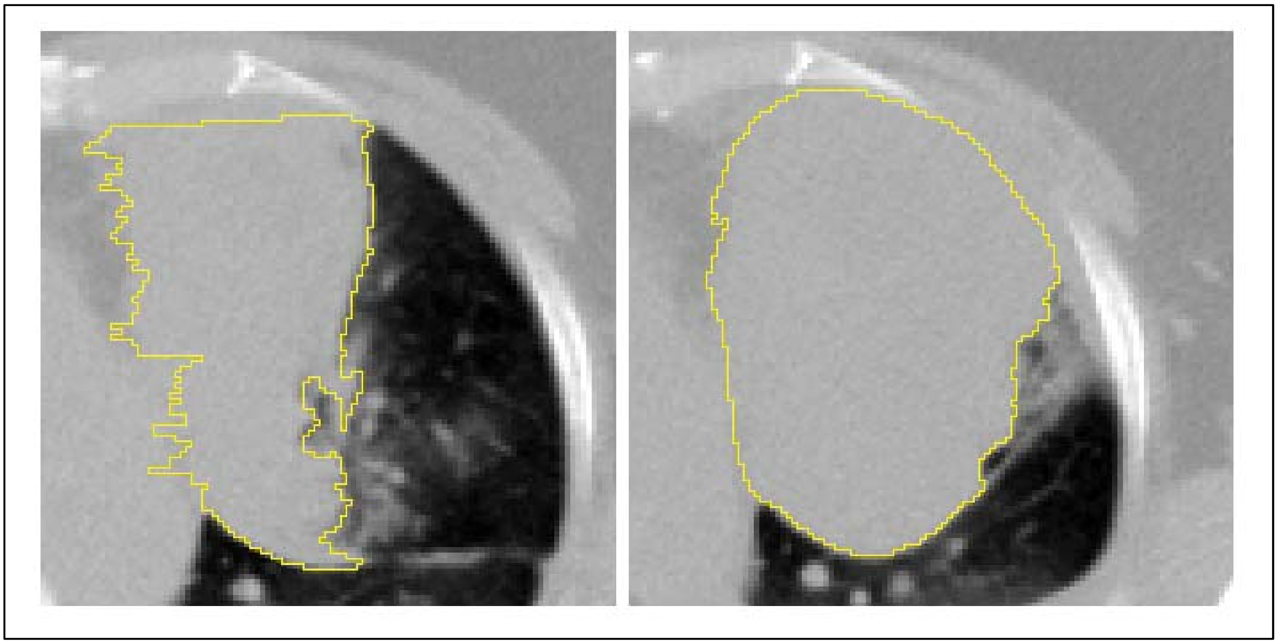
MaxProba	B	8	3.7	40.3	-75.2	82.6	0.677
		16	7.7	49.9	-90.1	105.6	0.557
		32	7.9	50.8	-91.7	107.5	0.330
		64	3.7	52.8	-99.7	107.2	0.173
		128	4.2	52.4	-98.4	106.8	0.255
	W	10	1.5	21.1	-39.9	42.8	0.879
NGTDM							
Coarseness	B	8	0.5	31.9	-62.0	63.0	-
		16	-2.3	20.9	-43.2	38.6	0.9883
		32	-2.8	20.1	-42.1	36.5	0.9888
		64	-2.9	19.8	-41.8	36.0	0.9861
		128	-2.7	20.8	-43.5	38.1	0.977
	W	10	-2.7	19.5	-41.0	35.6	0.9743
$Contrast_{NGTDM}$	B	8	-9.9	64.9	-137.1	117.2	0.8199
		16	-8.3	63.1	-132.1	115.4	0.8366
		32	-5.9	60.2	-123.9	112.2	0.8419
		64	-4.5	56.9	-116.0	107.1	0.8476
		128	-5.2	54.3	-111.6	101.1	0.8424
	W	10	1.6	18.3	-34.2	37.5	0.8823
Busyness	B	8	0.0	29.7	-58.2	58.1	0.9803
		16	3.4	22.4	-40.4	47.3	0.9701
		32	4.0	25.0	-45.1	53.1	0.949
		64	4.2	26.0	-46.8	55.2	0.9378
		128	4.1	26.1	-47.0	55.1	0.9335
	W	10	1.6	18.0	-33.6	36.8	0.9937
Complexity	B	8	-3.0	25.3	-52.6	46.5	0.6031
		16	0.0	12.3	-24.2	24.2	0.8403
		32	0.5	13.4	-25.8	26.7	0.8382
		64	0.5	14.3	-27.6	28.5	0.8148
		128	0.3	14.7	-28.5	29.1	0.7823
	W	10	-0.5	12.3	-24.5	23.5	0.7293
TS	B	8	-3.5	36.8	-75.6	68.5	0.9864
		16	-2.9	33.8	-69.2	63.4	0.9877
		32	-2.9	34.1	-69.8	63.9	0.9876
		64	-2.9	34.3	-70.1	64.3	0.9871
		128	-3.0	34.3	-70.2	64.3	0.9871
	W	10	1.7	17.9	-33.3	36.8	0.9931
3rd order metrics							
GLZSM							
SZSE	B	8	-0.5	3.9	-8.3	7.2	0.876
		16	-0.2	4.0	-8.0	7.6	0.842
		32	-0.4	5.1	-10.5	9.6	0.845
		64	-0.6	4.8	-10.1	8.9	0.784

		128	-0.6	3.6	-7.7	6.5	0.709
	W	10	-0.5	2.6	-5.6	4.6	0.910
LZSE	B	8	12.5	80.2	-144.8	169.8	0.044
		16	8.0	112.7	-213.0	228.9	0.050
		32	6.5	79.9	-150.2	163.2	-
		64	7.1	41.2	-73.7	88.0	-
		128	4.3	26.0	-46.6	55.2	0.013
	W	10	0.8	68.7	-133.8	135.5	0.323
ZSNU	B	8	-2.4	35.8	-72.6	67.9	0.973
		16	0.3	24.5	-47.8	48.3	0.997
		32	1.8	22.9	-43.1	46.6	0.989
		64	3.0	26.9	-49.8	55.7	0.976
		128	5.2	30.2	-54.1	64.5	0.964
	W	10	1.9	19.1	-35.5	39.3	0.994
GLNU	B	8	-5.9	50.3	-104.4	92.6	0.919
		16	-3.1	46.0	-93.2	87.1	0.968
		32	-2.2	38.3	-77.2	72.8	0.989
		64	-1.9	30.2	-61.0	57.3	0.993
		128	-0.6	23.9	-47.5	46.2	0.994
	W	10	0.4	20.7	-40.3	41.0	0.998
ZSP	B	8	-7.4	46.8	-99.2	84.4	0.911
		16	-5.2	40.8	-85.2	74.8	0.859
		32	-3.7	28.1	-58.7	51.3	0.785
		64	-2.8	17.4	-36.9	31.3	0.673
		128	-1.5	9.0	-19.0	16.1	0.608
	W	10	-0.9	11.9	-24.2	22.4	0.949
LGLZE	B	8	4.4	30.9	-56.2	65.1	0.677
		16	4.9	46.9	-86.9	96.7	0.494
		32	5.0	47.5	-88.1	98.1	0.384
		64	1.7	46.2	-89.0	92.3	0.480
		128	1.0	48.9	-94.8	96.9	0.673
	W	10	-2.3	19.6	-40.6	36.1	0.926
HGLZE	B	8	-3.6	35.3	-72.9	65.6	0.715
		16	-5.6	47.6	-98.8	87.6	0.764
		32	-6.2	51.6	-107.3	94.8	0.772
		64	-6.3	52.8	-109.8	97.3	0.774
		128	-6.3	53.3	-110.8	98.3	0.776
	W	10	1.1	16.3	-30.9	33.0	0.827
SZLGE	B	8	2.4	28.6	-53.7	58.5	0.635
		16	4.4	42.7	-79.4	88.1	0.552
		32	4.9	44.4	-82.1	91.8	0.443
		64	1.4	44.6	-86.1	88.8	0.533
		128	1.1	48.1	-93.1	95.4	0.704

	W	10	-2.7	18.9	-39.8	34.4	0.936
SZHGE	B	8	-3.1	35.5	-72.7	66.5	0.727
		16	-5.3	48.2	-99.7	89.1	0.767
		32	-6.4	54.1	-112.5	99.6	0.781
		64	-6.7	55.4	-115.3	102.0	0.780
		128	-6.5	54.9	-114.1	101.0	0.779
	W	10	0.7	17.6	-33.7	35.2	0.833
LZLGE	B	8	14.1	96.5	-175.0	203.1	-
		16	10.7	115.3	-215.2	236.6	-
		32	6.0	87.4	-165.2	177.3	-
		64	3.6	59.6	-113.3	120.5	-
		128	1.8	55.4	-106.8	110.4	-
	W	10	-0.3	61.7	-121.3	120.7	0.330
LZHGE	B	8	8.4	60.6	-110.4	127.1	0.588
		16	5.9	104.6	-199.1	210.8	0.629
		32	3.6	70.6	-134.8	141.9	-
		64	3.8	36.4	-67.6	75.2	-
		128	-1.3	42.0	-83.7	81.1	0.753
	W	10	0.8	71.0	-38.3	139.8	0.332



SUPPLEMENTAL FIGURE 1: The different quantization approaches with different values for B (number of bins) or W (bin width) and corresponding histograms in low-dose CT and FDG PET components. Red contours correspond to the tumor delineation.



SUPPLEMENTAL FIGURE 2: patient with clearly nonrepeatable volume delineation

REFERENCES

1. Materka A, Strzelecki M. *Texture Analysis Methods: A Review.* Brussels, Belgium: Institute of Electronics, Lodz University of Technology; 1998. Technical report no. COST B11.

2. Haralick RM, Shanmugam K, Dinstein I. Textural features for image classification. *IEEE Trans Syst Man Cybern*. 1973;SMC-3:610–621.

3. Soh L-K, Tsatsoulis C. Texture analysis of SAR sea ice imagery using gray level co-occurrence matrices. *IEEE Trans Geosci Remote Sens*. 1999;37:780–795.

4. Clausi DA. An analysis of co-occurrence texture statistics as a function of gray level quantization. *Can J Remote Sens*. 2002;28:45–62.

5. Bharati MH, Liu JJ, MacGregor JF. Image texture analysis: methods and comparisons. *Chemom Intell Lab Syst*. 2004;72:57–71.

6. Amadasun M, King R. Textural features corresponding to textural properties. *IEEE Trans Syst Man Cybern*. 1989;19:1264–1274.

7. Tang X. Texture information in run-length matrices. *IEEE Trans Image Process*. 1998;7:1602–1609.