

Supplementary data for the paper:

Automated enhancement of color microscopic image of stained specimen by low-rank and sparse matrix decomposition

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Images/specimens:

36 images of H&E-stained specimens; 6 images of SUDAN-stained specimens; 3 images of CD34-stained specimens.

Algorithms:

Robust principal component analysis (RPCA) algorithm applied to vectorized gray scale image in RGB color space: `RPCA_rgb`.

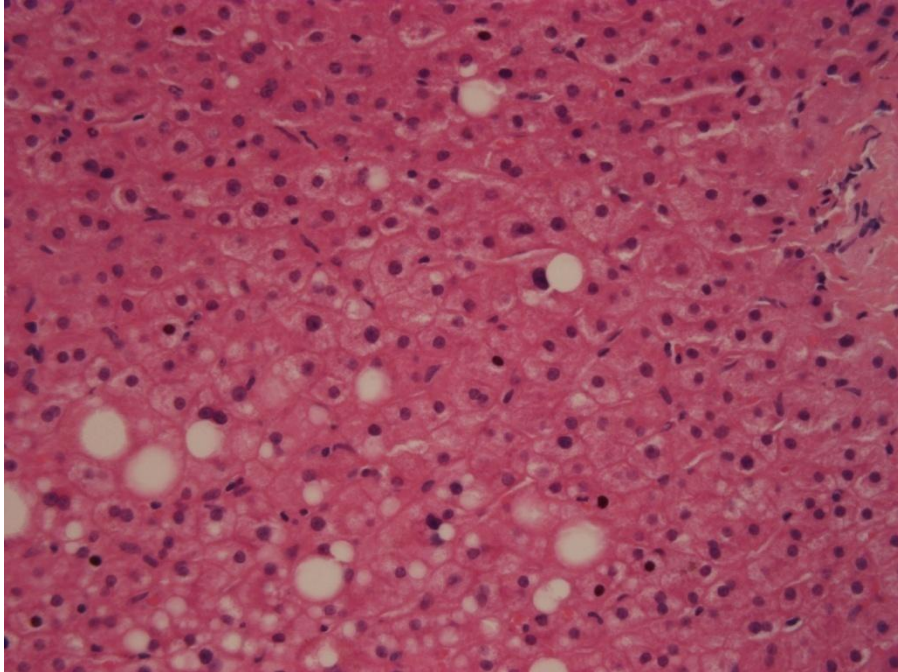
RPCA algorithm applied to luminance L^* component in CIE $L^* a^* b^*$ color space: `RPCA_L`.

Matlab `imadjust` algorithm applied to luminance L^* component in CIE $L^* a^* b^*$ color space.

Matlab `adapthisteq` algorithm applied to luminance L^* component in CIE $L^* a^* b^*$ color space.

Due to space efficiency images enhanced by `RPCA_L`, `imadjust` and `adapthisteq` are not shown. Only results of performance evaluation are presented.

Human liver. Diagnosis: fatty liver.



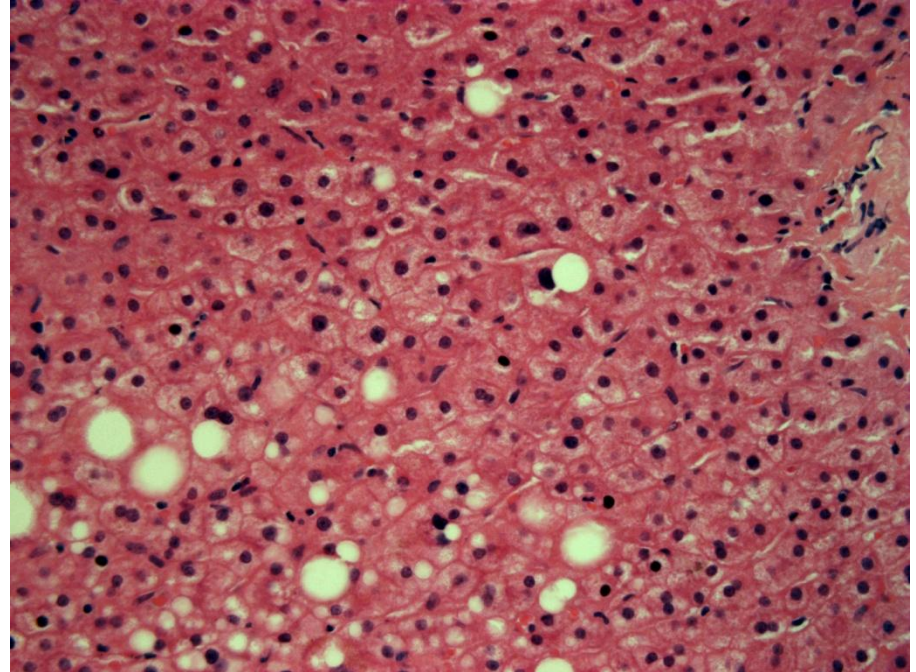
H&E-stained specimen:

MOS: 3.71

colorfulness: 0.3345

sharpness: 6.9688

contrast: 1.8364



RPCA_rgb enhanced image:

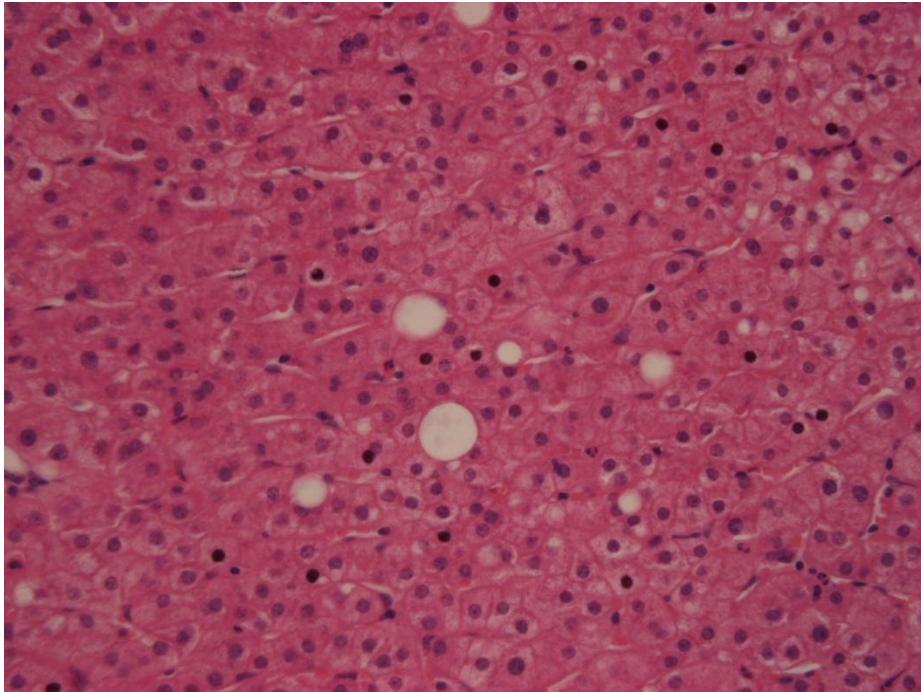
MOS: 4.71

colorfulness: 0.5444

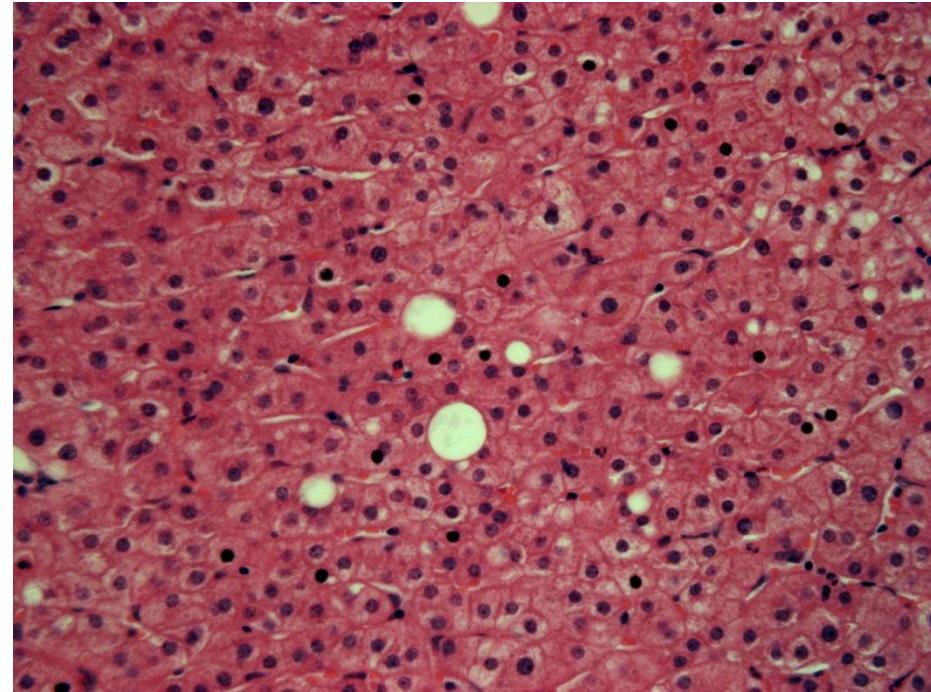
sharpness: 6.9971

contrast: 1.6447

Human liver. Diagnosis: fatty liver.

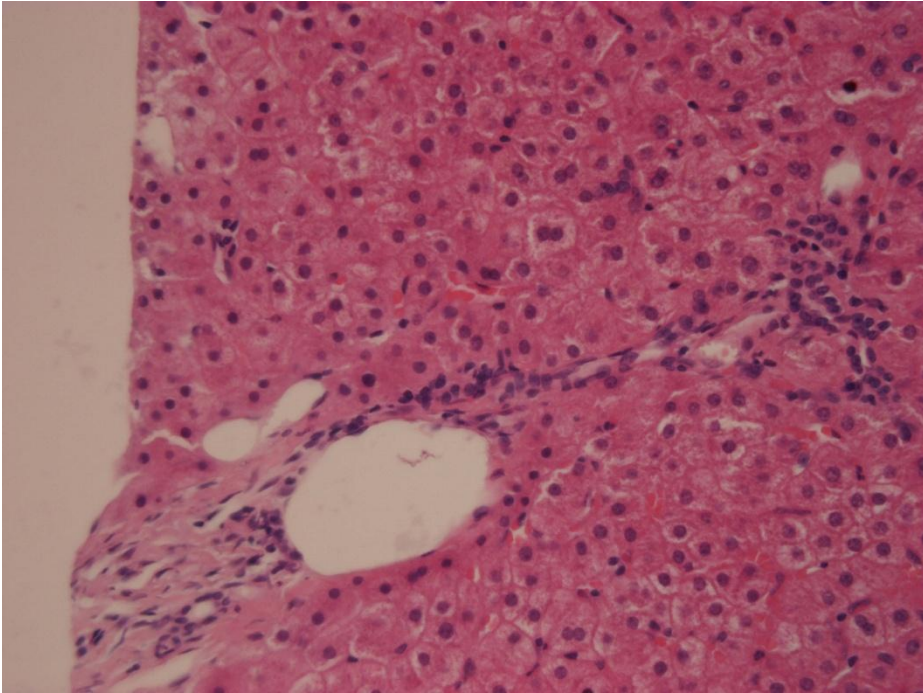


H&E-stained specimen:
MOS: 3.57
colorfulness: 0.3100
sharpness: 6.8558
contrast: 1.8261



RPCA_rgb enhanced image:
MOS: 4.32
colorfulness: 0.5123
sharpness: 6.9084
contrast: 1.6267

Human liver. Diagnosis: fatty liver.



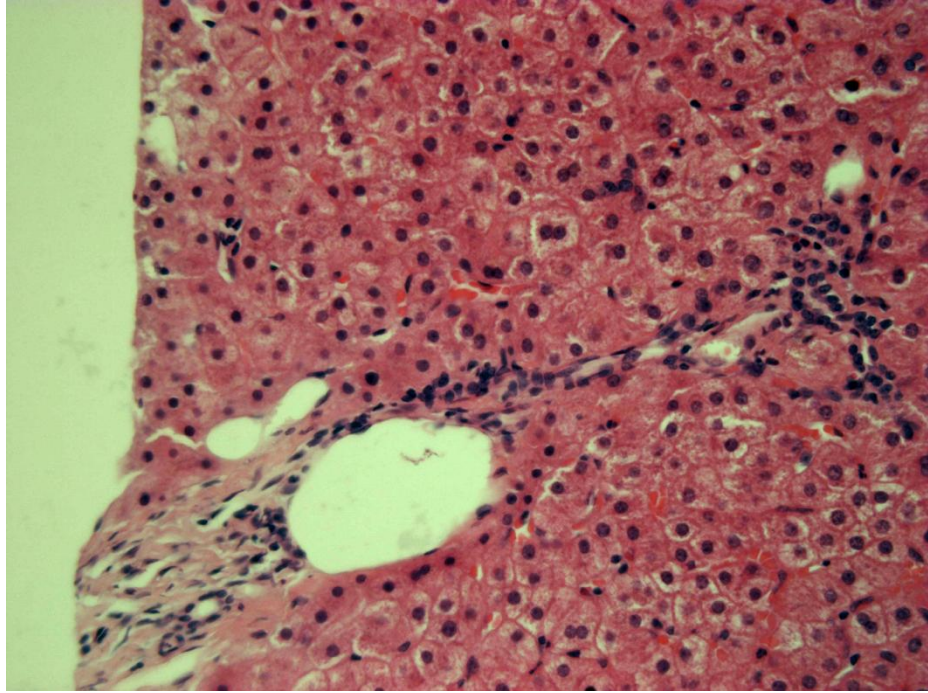
H&E-stained specimen:

MOS: 4.00

colorfulness: 0.4199

sharpness: 7.9051

contrast: 1.9260



RPCA_rgb enhanced image:

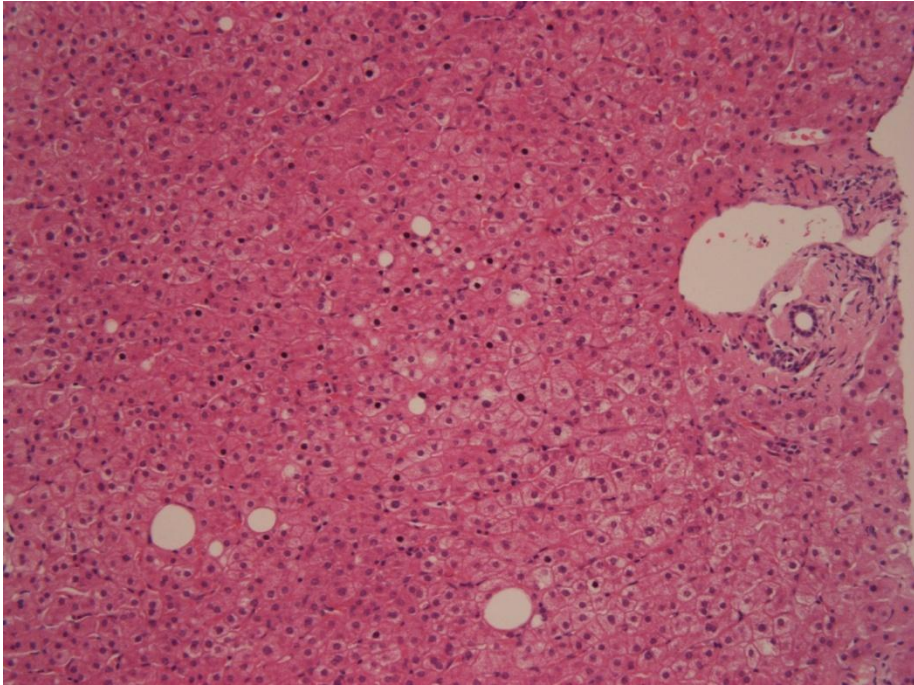
MOS: 4.57

colorfulness: 0.5047

sharpness: 12.3167

contrast: 1.3727

Human liver. Diagnosis: fatty liver.



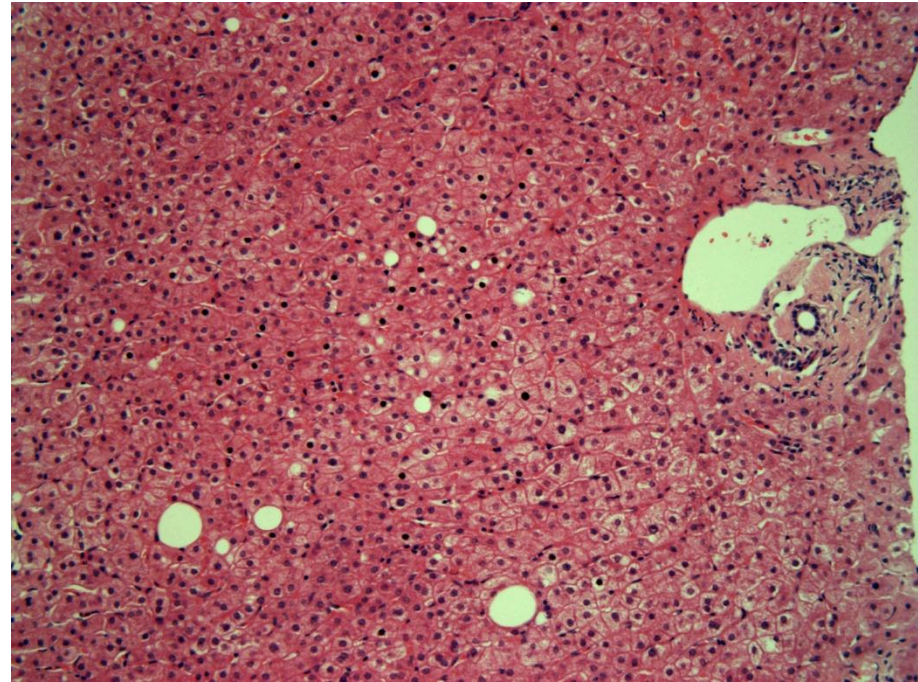
H&E-stained specimen:

MOS: 3.96

colorfulness: 0.4032

sharpness: 9.5972

contrast: 1.7062



RPCA_rgb enhanced image:

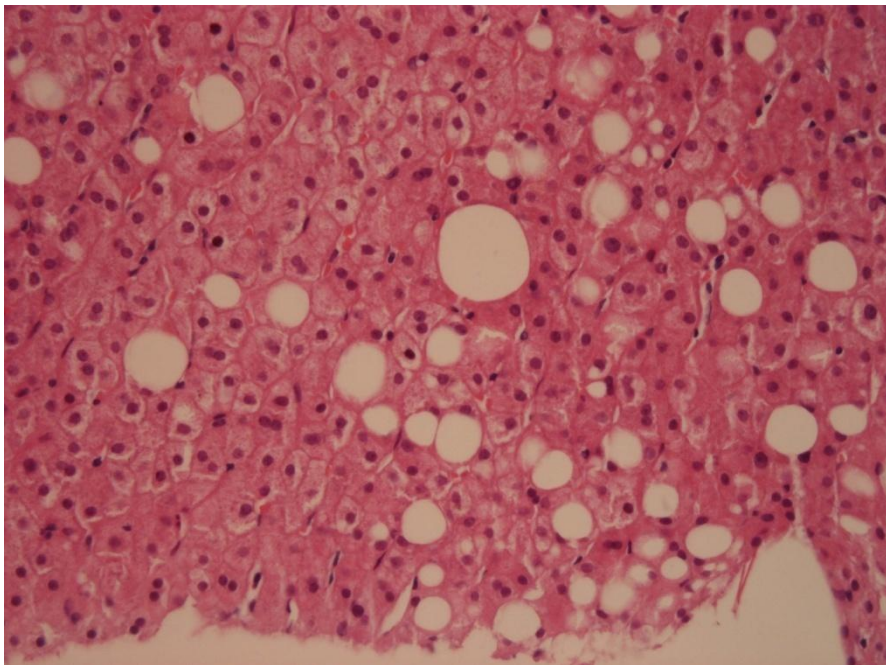
MOS: 4.43

colorfulness: 0.6209

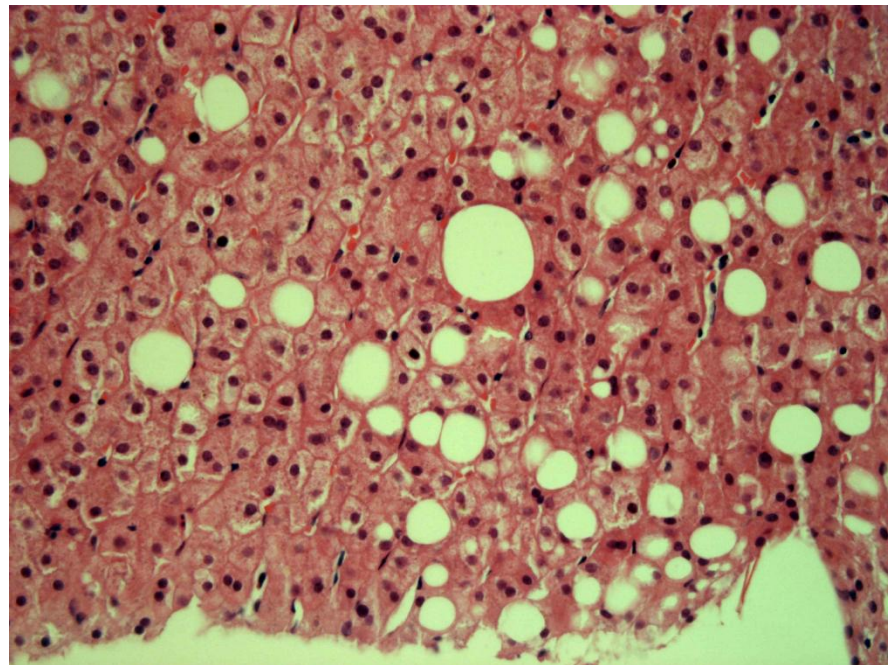
sharpness: 9.6264

contrast: 1.4970

Human liver. Diagnosis: fatty liver.

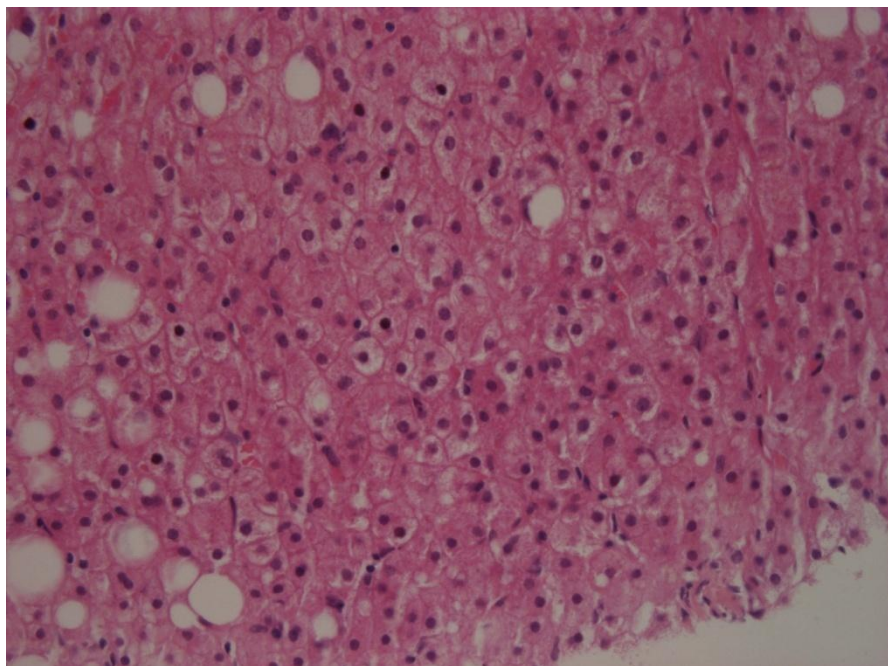


H&E-stained specimen:
MOS: 4.14
colorfulness: 0.3467
sharpness: 7.2180
contrast: 1.8904



RPCA_rgb enhanced image:
MOS: 4.29
colorfulness: 0.5778
sharpness: 7.2307
contrast: 1.7071

Human liver. Diagnosis: fatty liver.



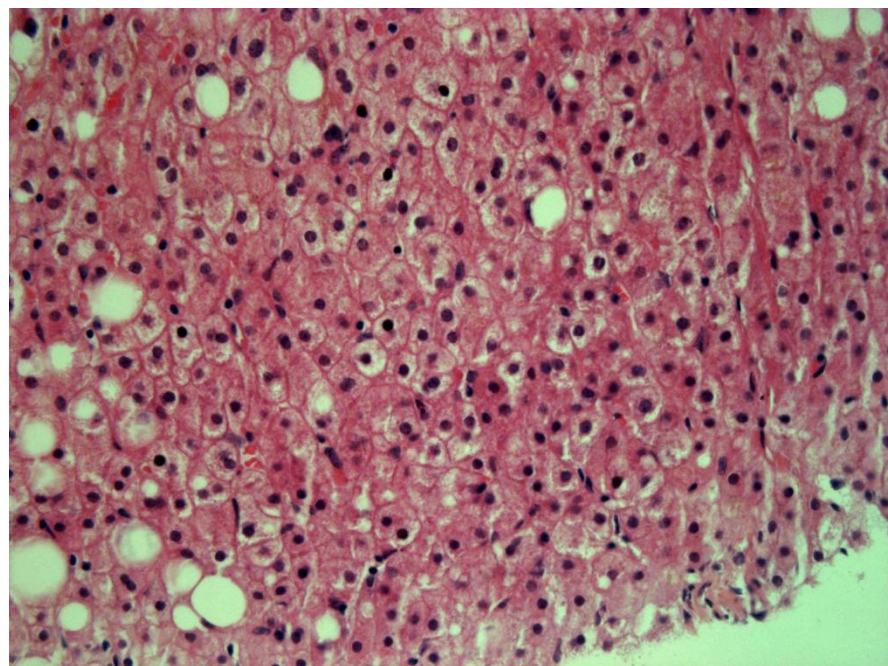
H&E-stained specimen:

MOS: 3.54

colorfulness: 0.3231

sharpness: 6.9846

contrast: 1.8188



RPCA _rgb enhanced image:

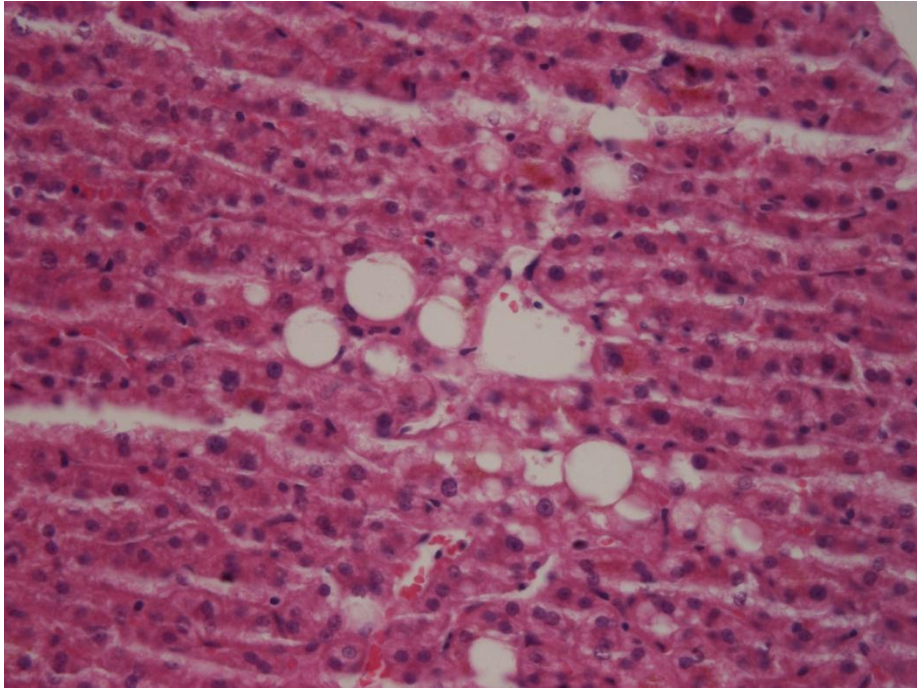
MOS: 4.54

colorfulness: 0.5791

sharpness: 6.9852

contrast: 1.6284

Human liver. Diagnosis: fatty liver.



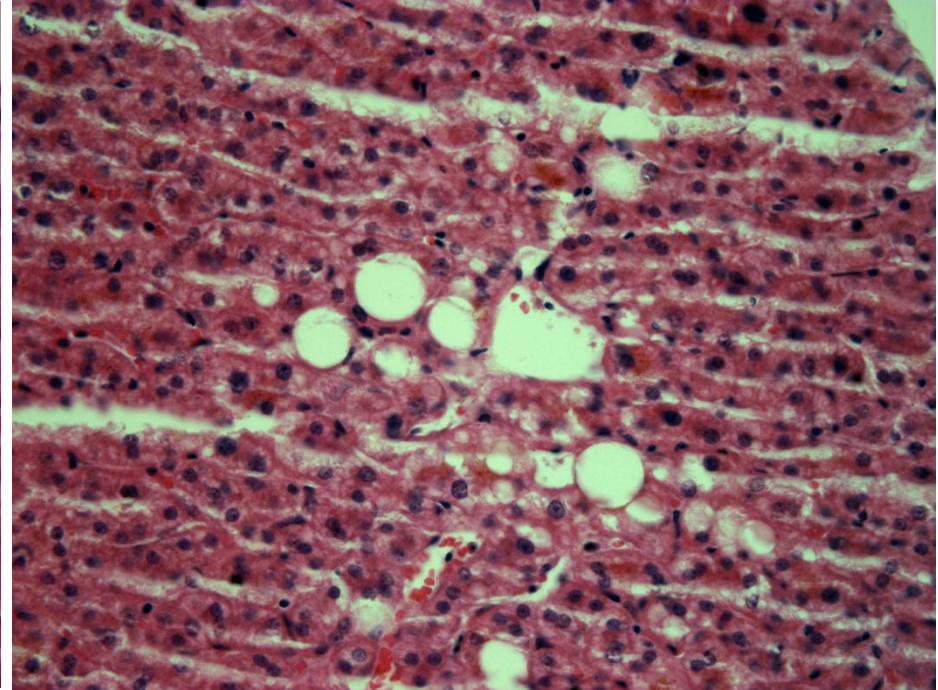
H&E-stained specimen:

MOS: 2.86

colorfulness: 0.4579

sharpness: 7.5574

contrast: 1.5911



RPCA_rgb enhanced image:

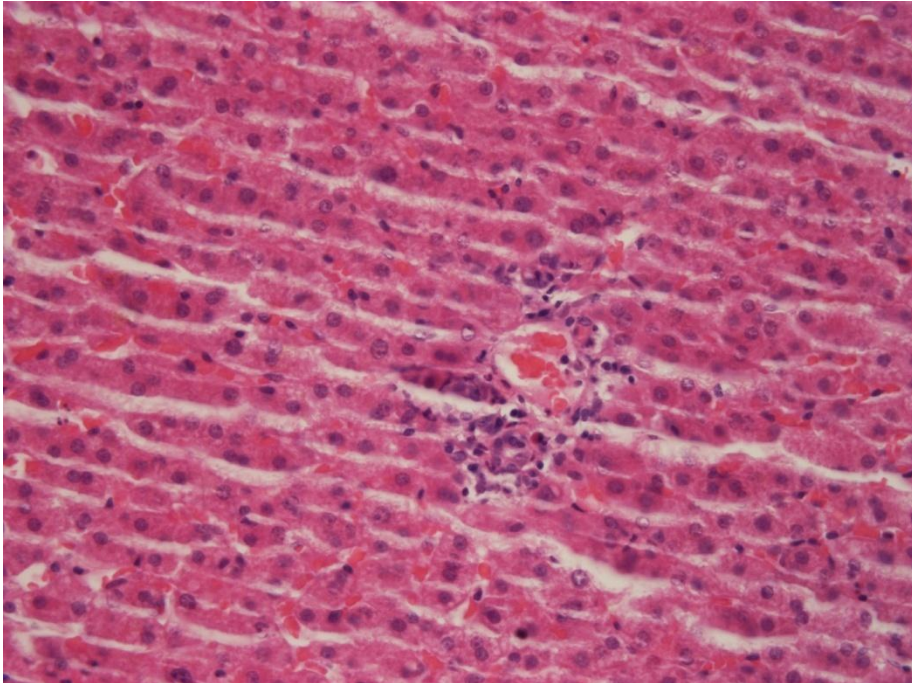
MOS: 3.86

colorfulness: 0.5747

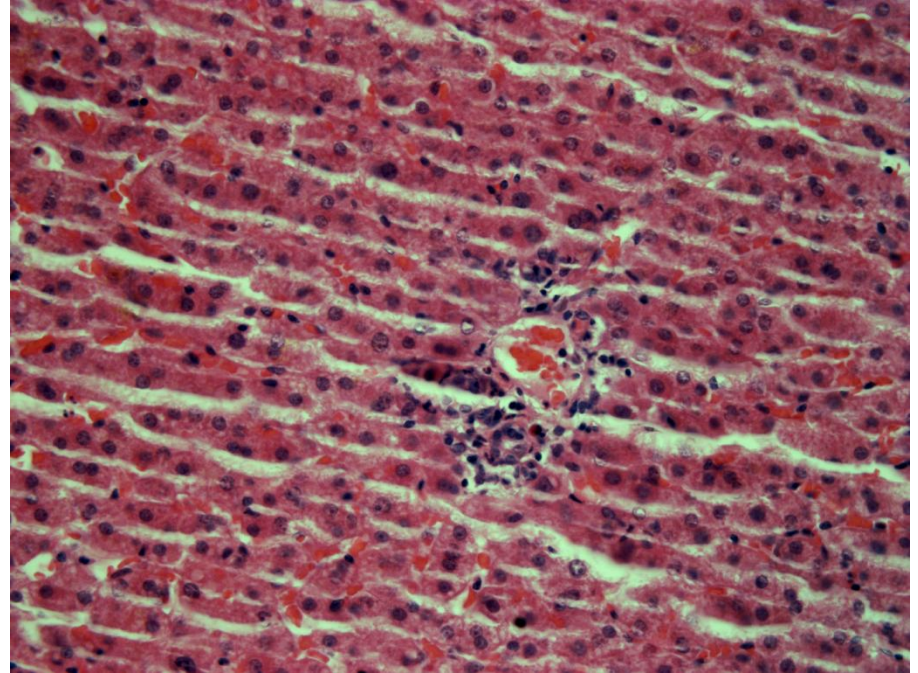
sharpness: 7.0108

contrast: 1.6005

Human liver. Diagnosis: fatty liver.

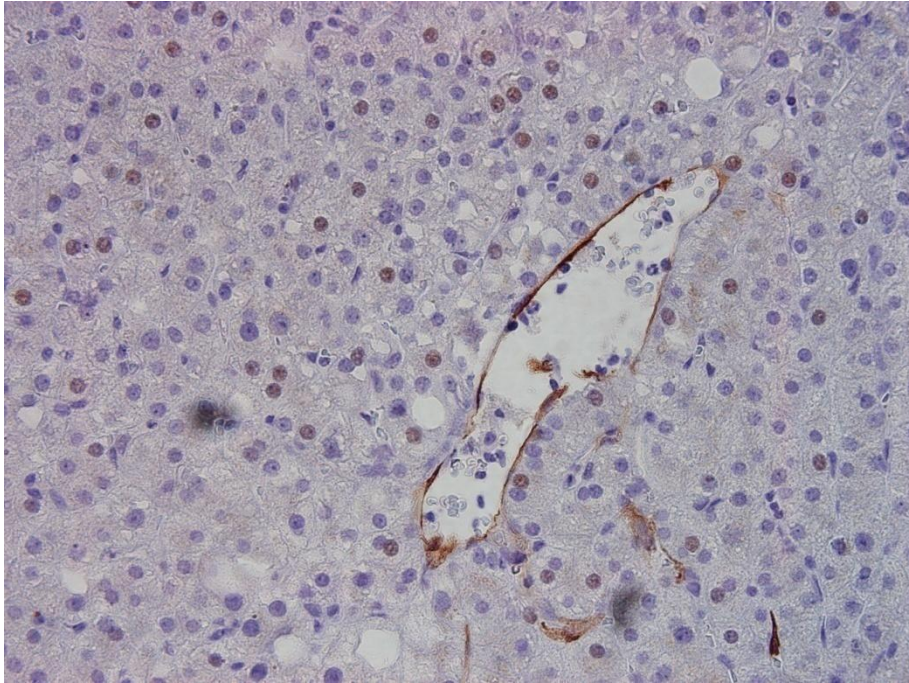


H&E-stained specimen:
MOS: 3.43
colorfulness: 0.4472
sharpness: 7.3485
contrast: 1.7839

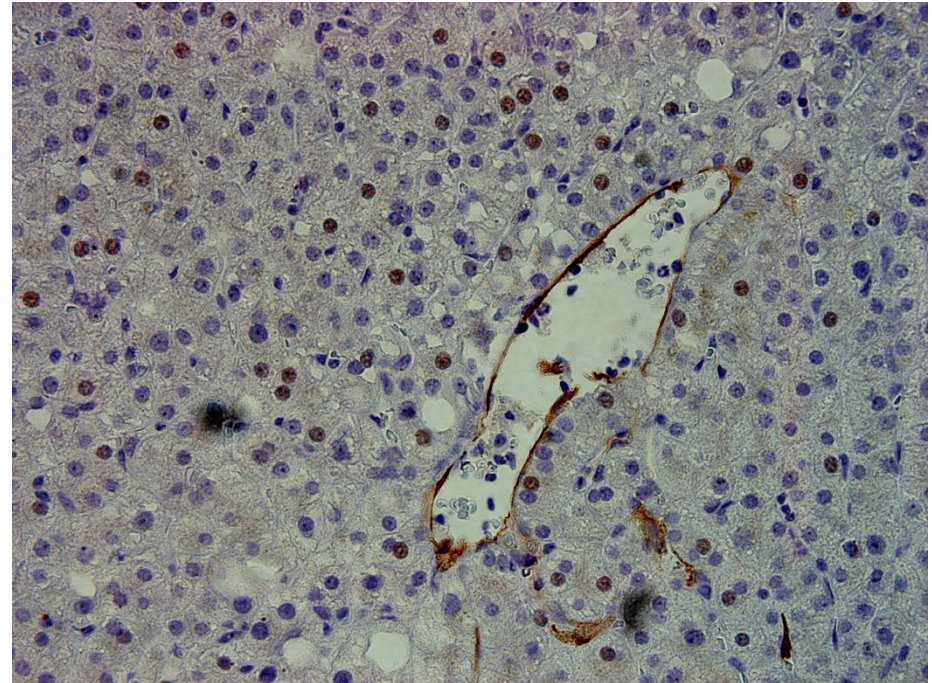


RPCA_rgb enhanced image:
MOS: 3.54
colorfulness: 0.5908
sharpness: 7.3545
contrast: 1.5836

Human liver. Diagnosis: fatty liver.

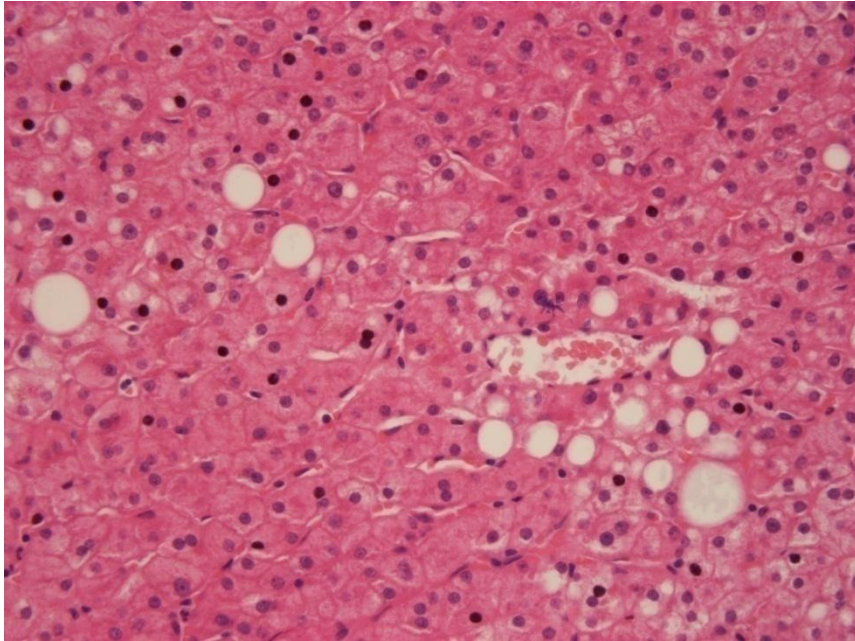


Anti-CD34 stained specimen:
MOS: 4.11
colorfulness: 0.4189
sharpness: 9.2807
contrast: 1.5552



RPCA_rgb enhanced image:
MOS: 4.68
colorfulness: 0.7187
sharpness: 9.4766
contrast: 1.3368

Human liver. Diagnosis: fatty liver.



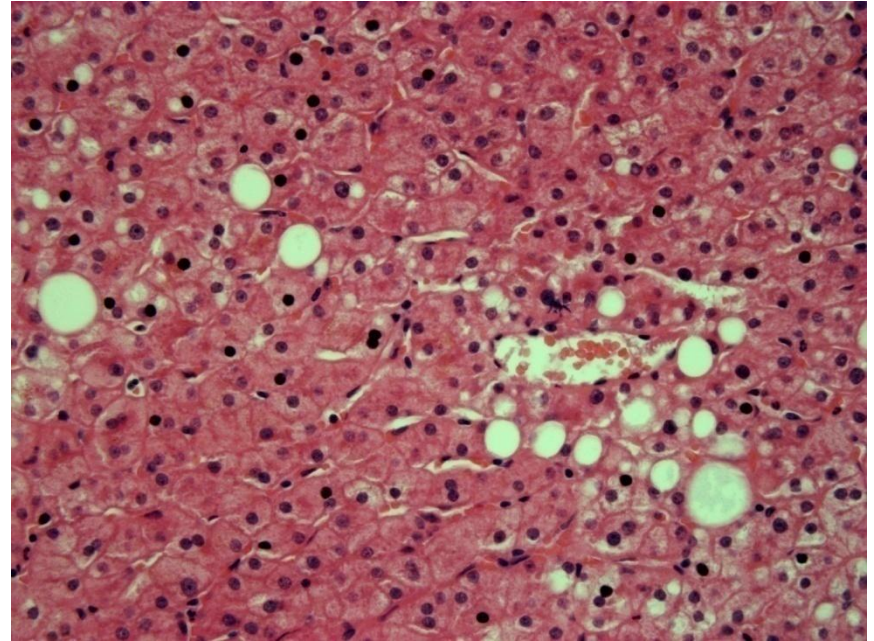
H&E stained specimen:

MOS: 3.54

colorfulness: 0.4035

sharpness: 6.7015

contrast: 1.8448



RPCA_rgb enhanced image:

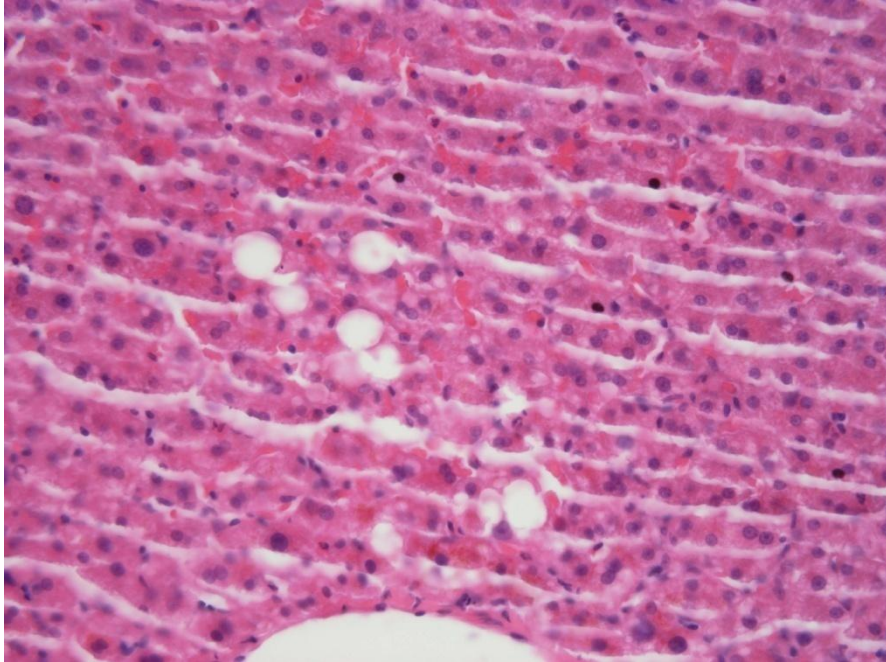
MOS: 4.14

colorfulness: 0.5574

sharpness: 6.7631

contrast: 1.6515

Human liver. Diagnosis: fatty liver.



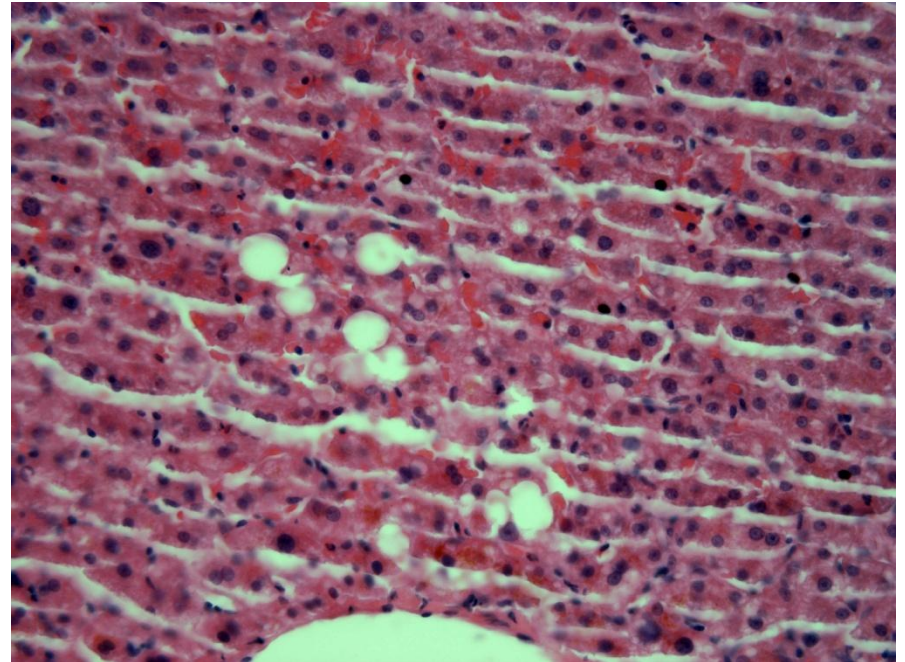
H&E-stained specimen:

MOS: 3.11

colorfulness: 0.4920

sharpness: 6.6053

contrast: 1.9070



RPCA_rgb enhanced image:

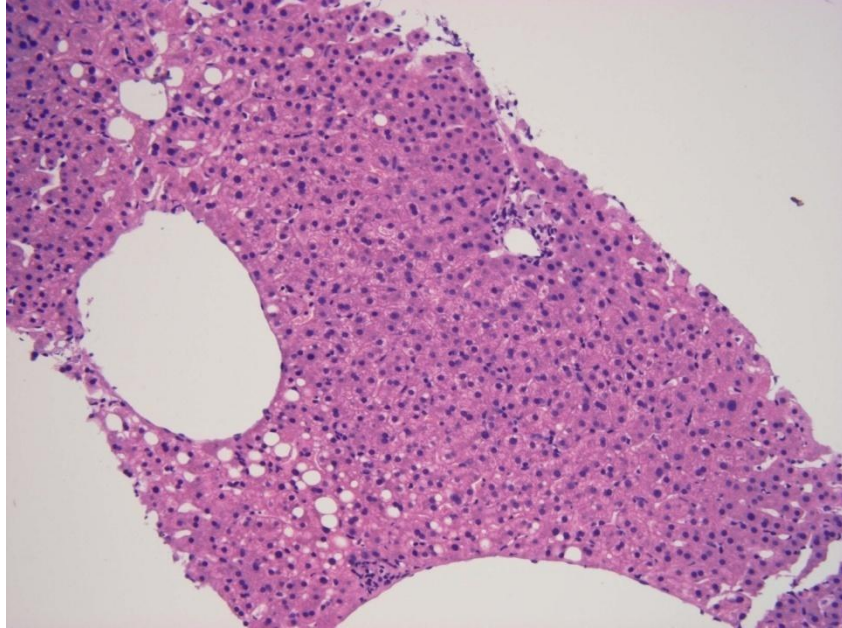
MOS: 3.29

colorfulness: 0.6345

sharpness: 6.6128

contrast: 1.7160

Human liver. Diagnosis: fatty liver.



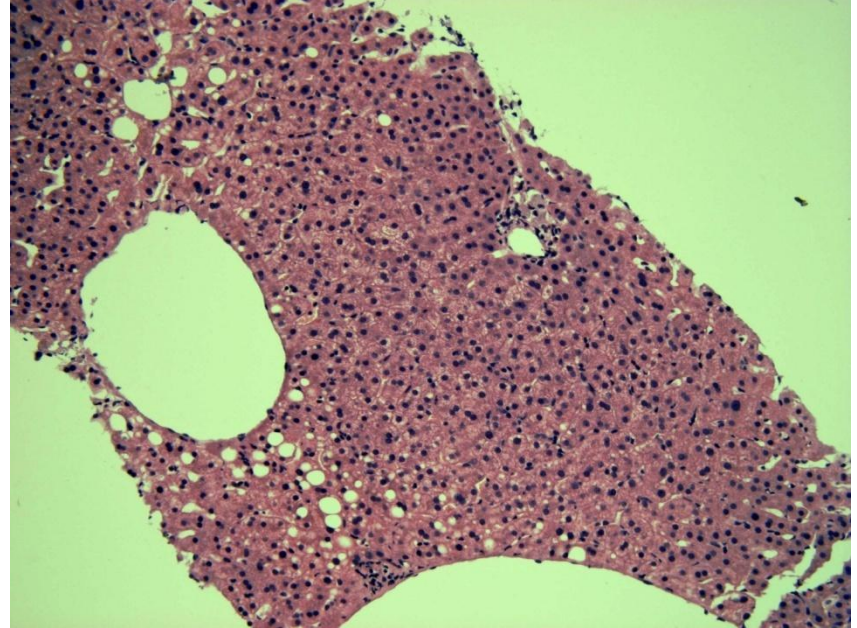
H&E-stained specimen:

MOS: 4.25

colorfulness: 0.6768

sharpness: 10.3880

contrast: 2.2593



RPCA_rgb enhanced image:

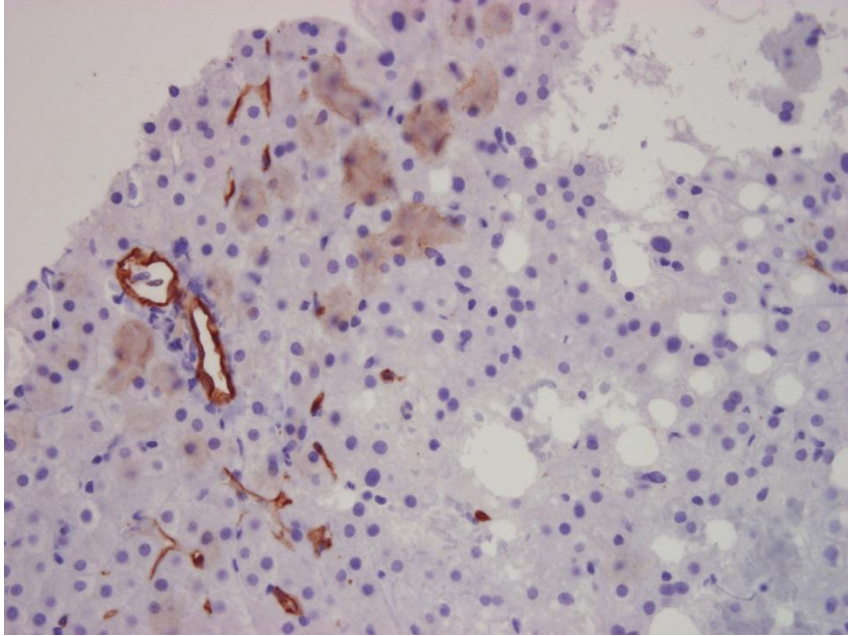
MOS: 3.82

colorfulness: 0.8362

sharpness: 10.4205

contrast: 2.1169

Human liver. Diagnosis: fatty liver.



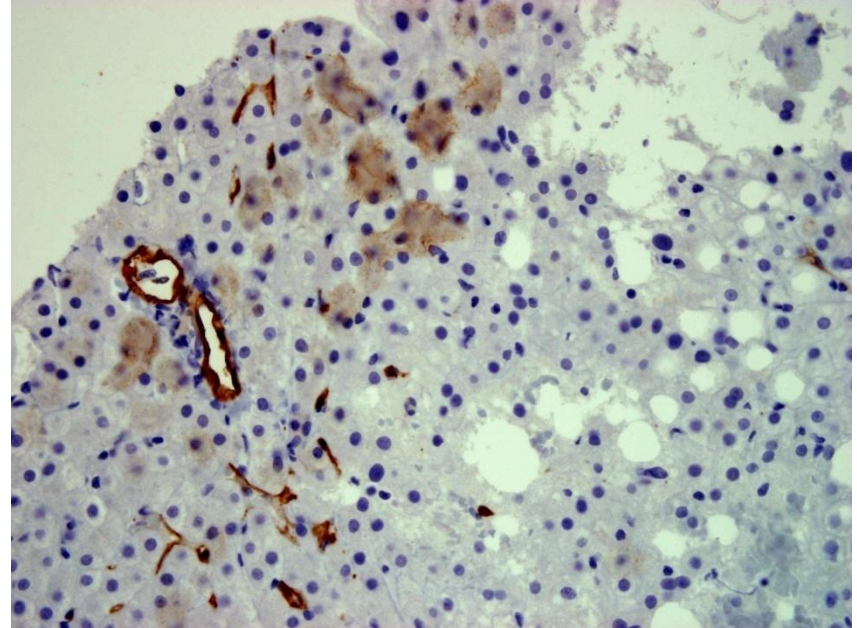
Anti-CD34 stained specimen:

MOS: 4.25

colorfulness: 0.3762

sharpness: 5.5268

contrast: 2.1389



RPCA_rgb enhanced image:

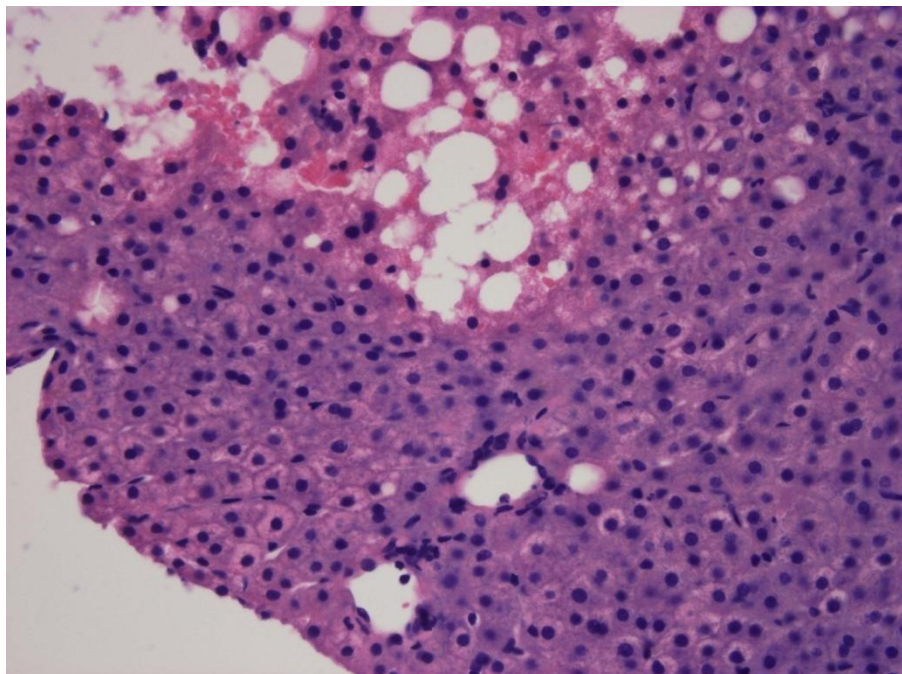
MOS: 4.89

colorfulness: 0.5972

sharpness: 5.6258

contrast: 1.9822

Human liver. Diagnosis: fatty liver.



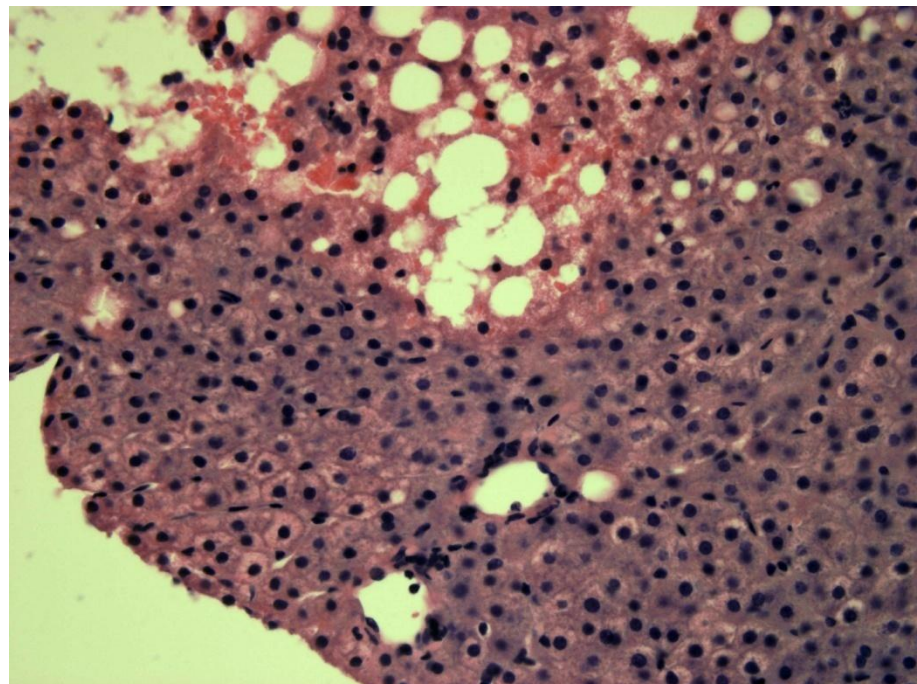
H&E-stained specimen:

MOS: 3.71

colorfulness: 0.5716

sharpness: 7.0963

contrast: 1.8676



RPCA_rgb enhanced image:

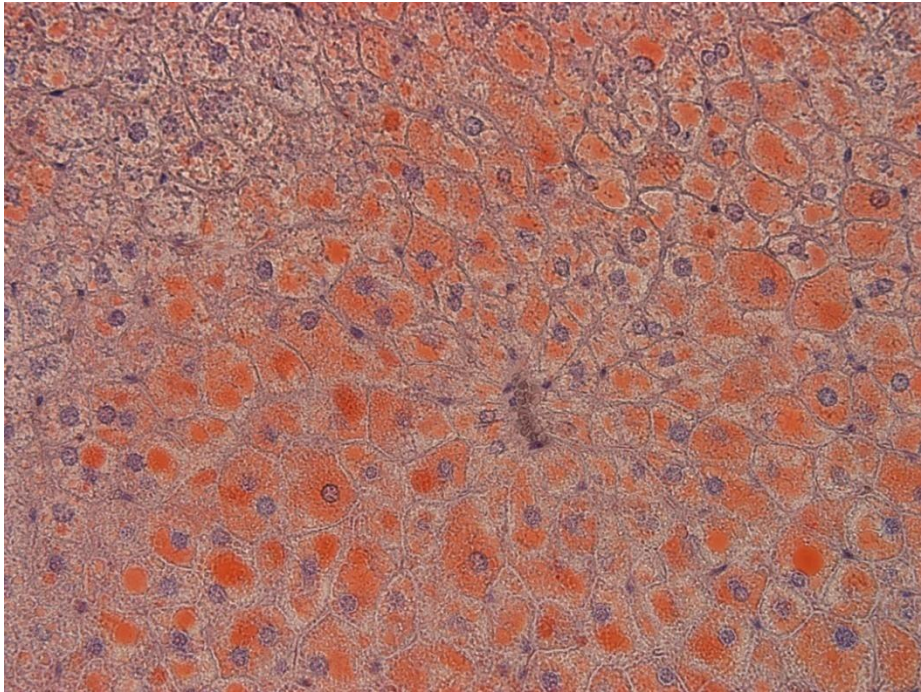
MOS: 3.14

colorfulness: 0.6981

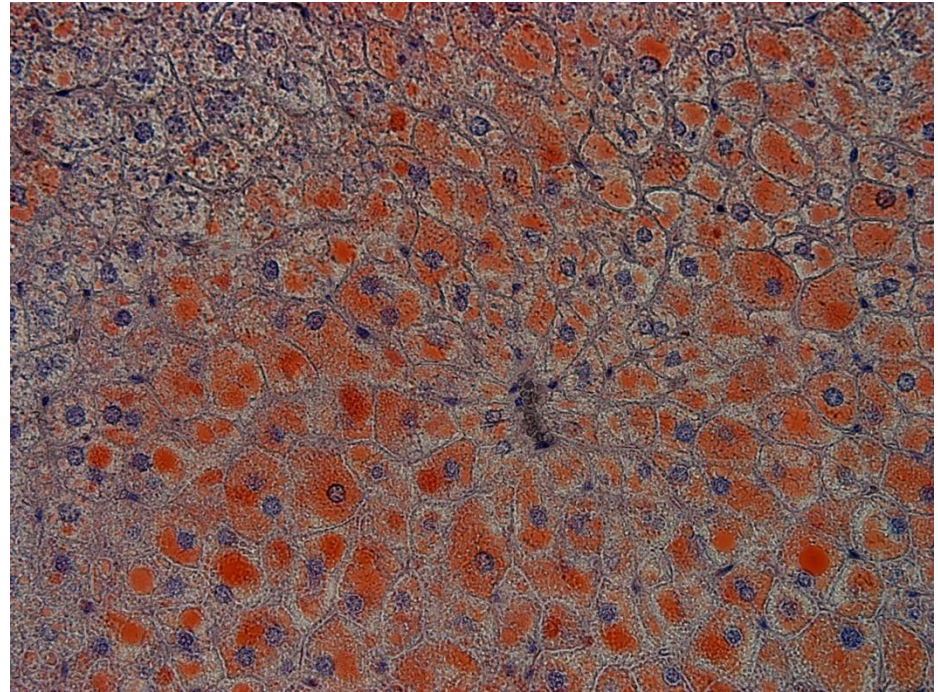
sharpness: 7.0969

contrast: 1.7483

Mosue liver. Diagnosis: fatty liver.

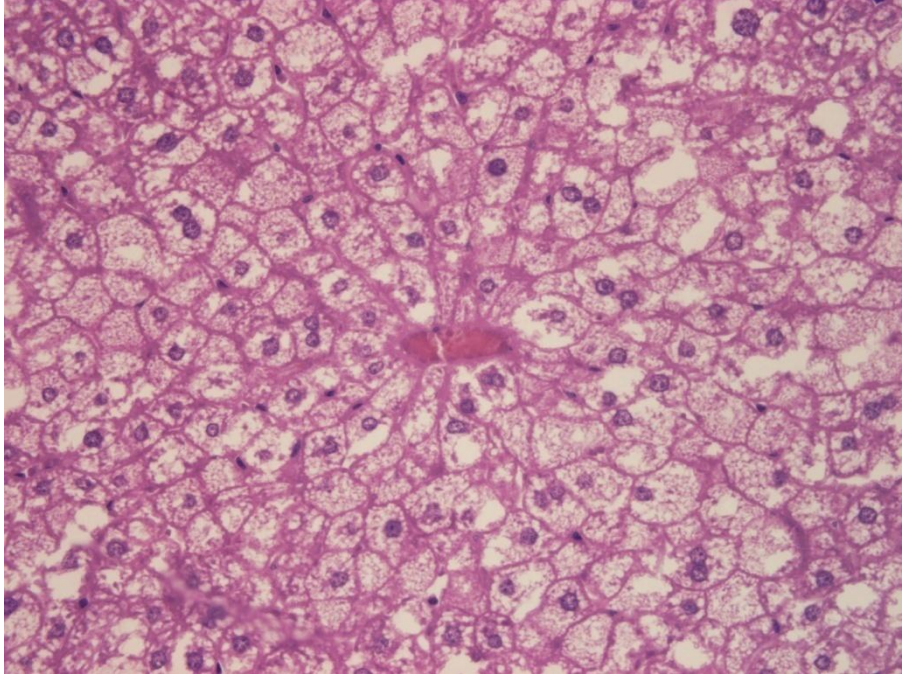


SUDAN III stained specimen:
MOS: 4.43
colorfulness: 0.6170
sharpness: 9.4648
contrast: 1.3669



RPCA_rgb enhanced image:
MOS: 4.43
colorfulness: 0.7409
sharpness: 9.4970
contrast: 1.1302

Mouse liver. Diagnosis: fatty liver.



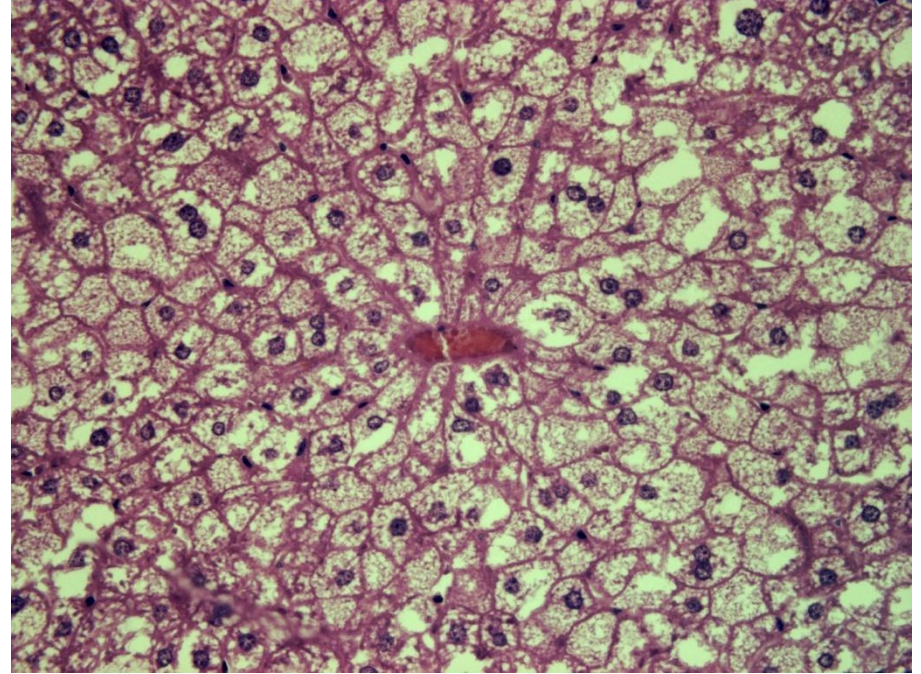
H&E stained specimen:

MOS: 4.29

colorfulness: 0.4993

sharpness: 9.1433

contrast: 1.7240



RPCA_rgb enhanced image:

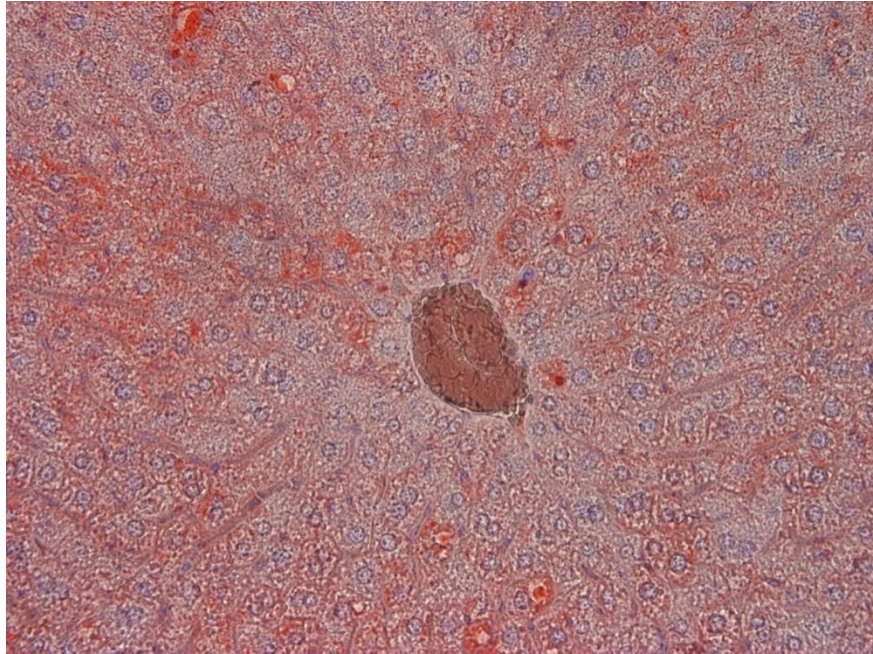
MOS: 4.29

colorfulness: 0.6672

sharpness: 9.1452

contrast: 1.5215

Mouse liver. Diagnosis: fatty liver.



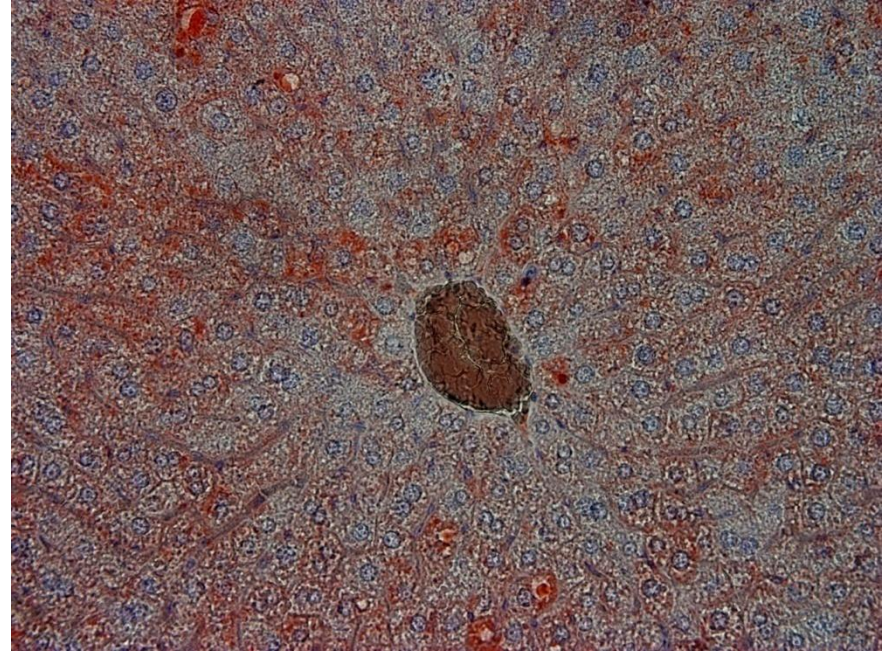
SUDAN III stained specimen:

MOS: 3.39

colorfulness: 0.4840

sharpness: 8.4629

contrast: 1.3956



RPCA_rgb enhanced image:

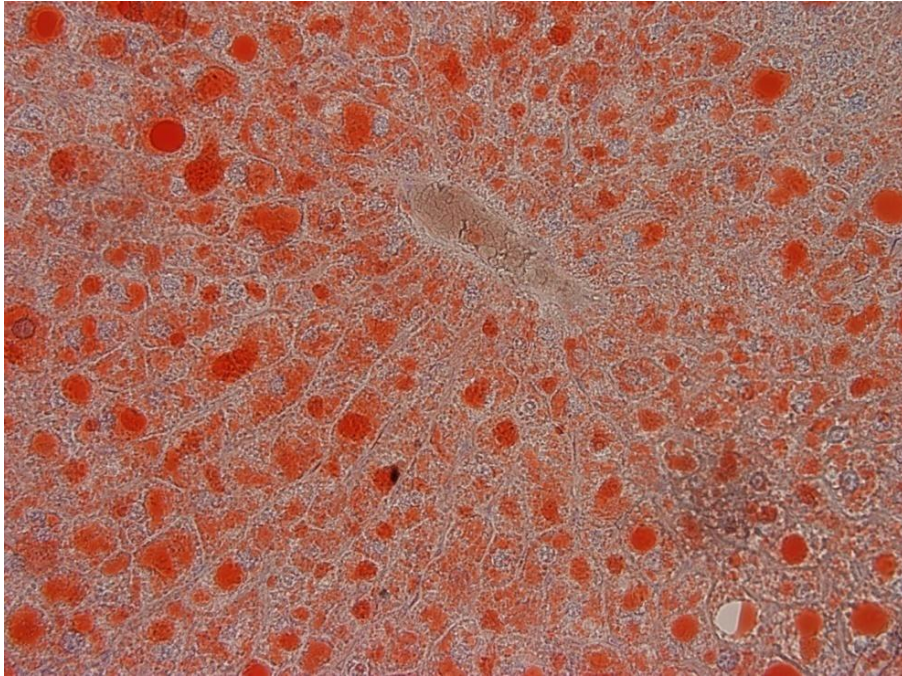
MOS: 3.86

colorfulness: 0.6020

sharpness: 8.4841

contrast: 1.1450

Mouse liver. Diagnosis: fatty liver.



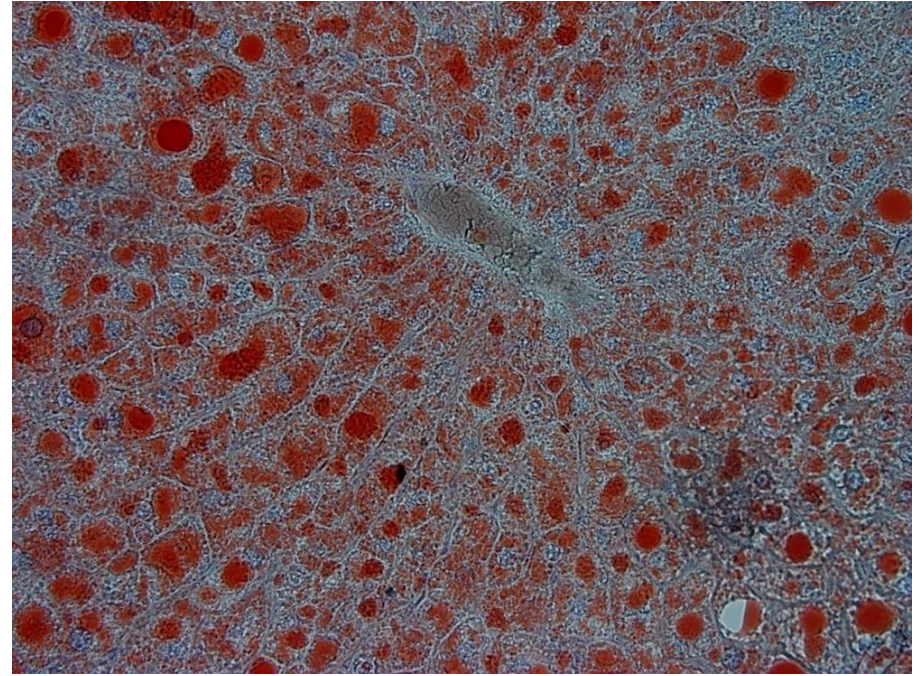
SUDAN III stained specimen:

MOS: 3.86

colorfulness: 0.6646

sharpness: 10.0464

contrast: 1.3956



RPCA_rgb enhanced image:

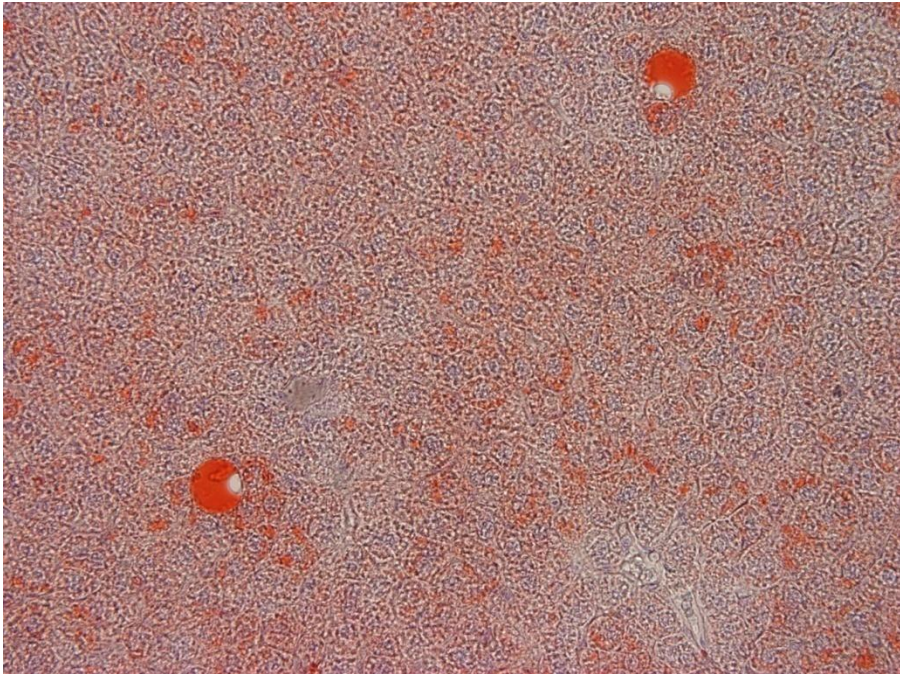
MOS: 3.79

colorfulness: 0.8117

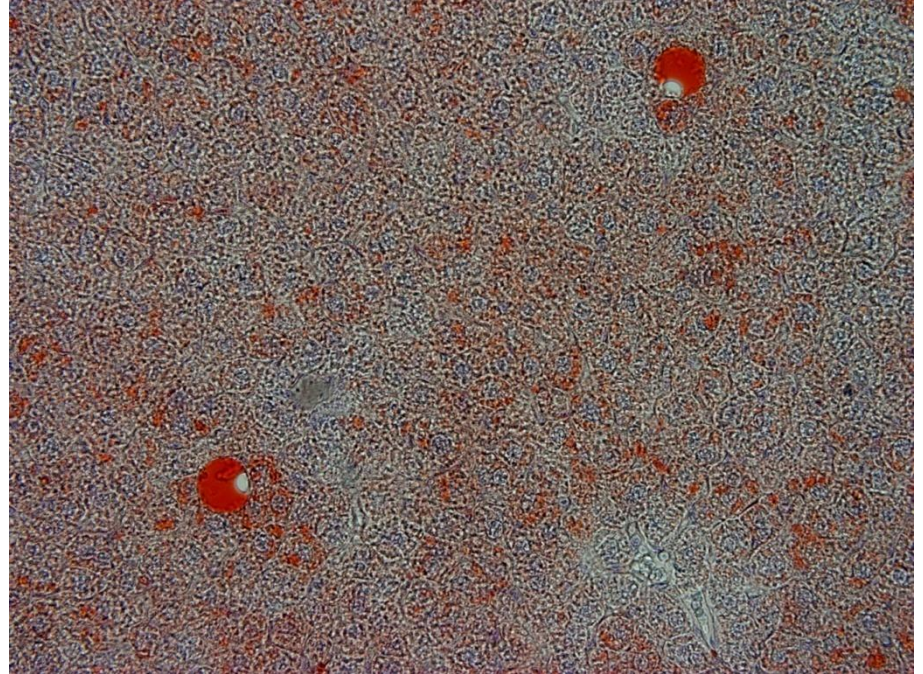
sharpness: 10.0763

contrast: 1.1847

Mouse liver. Diagnosis: fatty liver.

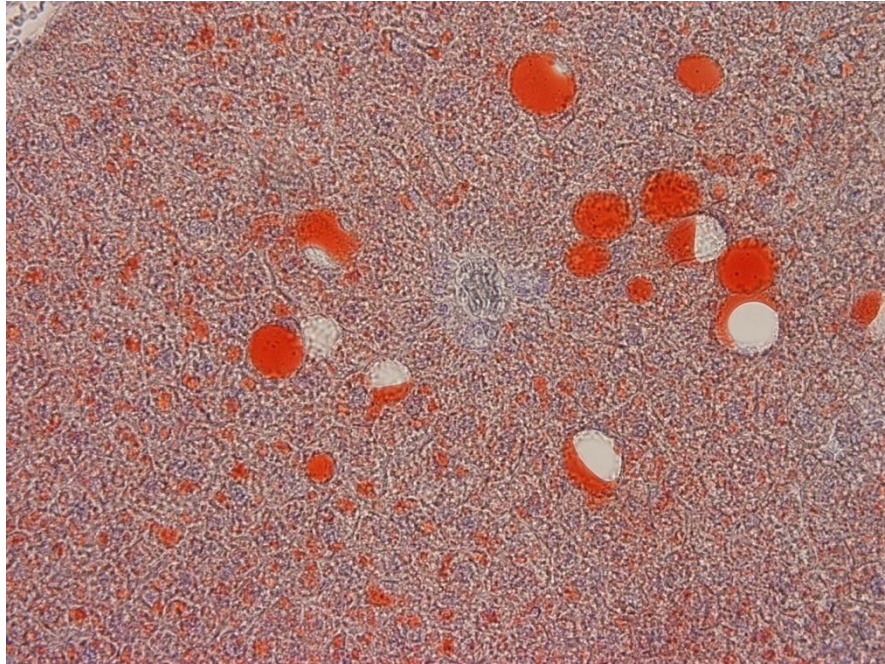


SUDAN III stained specimen:
MOS: 2.86
colorfulness: 0.5675
sharpness: 7.8090
contrast: 1.2740



RPCA_rgb enhanced image:
MOS: 2.86
colorfulness: 0.6751
sharpness: 7.8284
contrast: 1.0379

Mouse liver. Diagnosis: fatty liver.



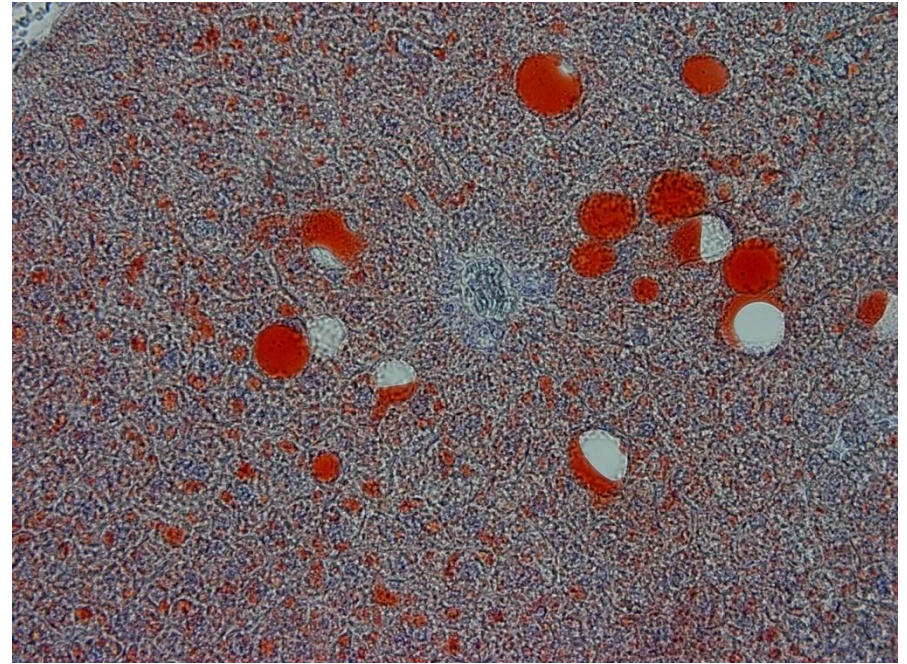
SUDAN III stained specimen:

MOS: 3.71

colorfulness: 0.6668

sharpness: 8.3855

contrast: 1.2784



RPCA_rgb enhanced image:

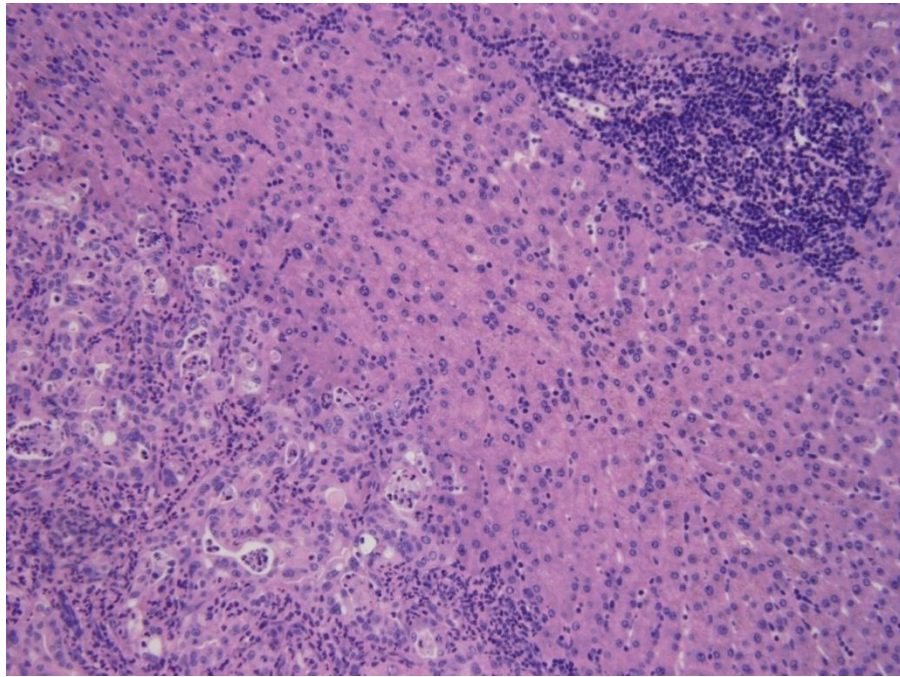
MOS: 3.57

colorfulness: 0.7801

sharpness: 8.4018

contrast: 1.0680

Human liver. Diagnosis: pancreatic adenocarcinoma.



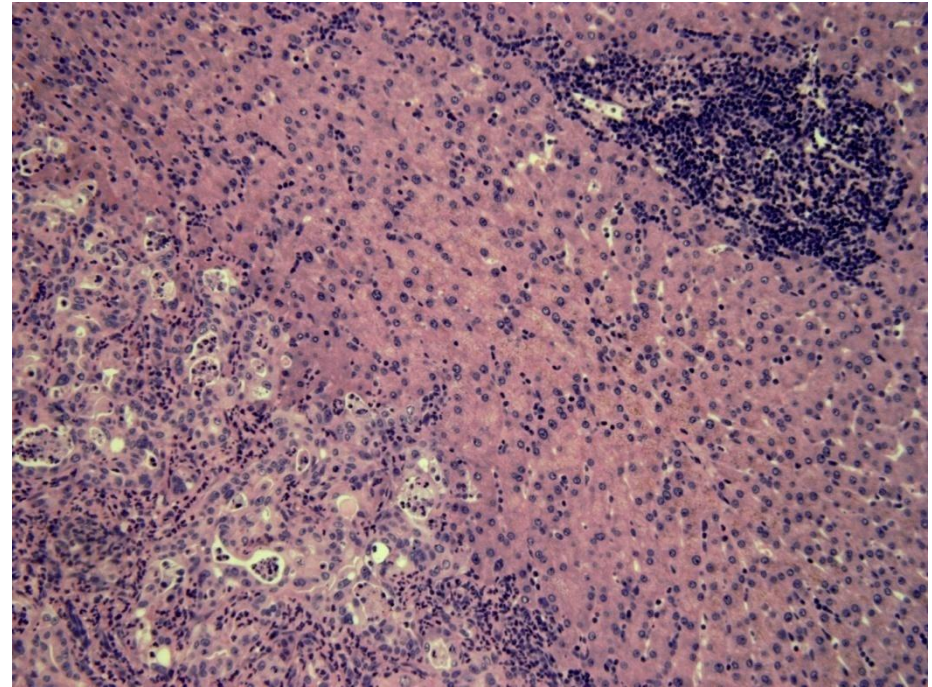
H&E stained image:

MOS: 3.96

colorfulness: 0.4253

sharpness: 11.5451

contrast: 1.6644



RPCA_rgb enhanced image:

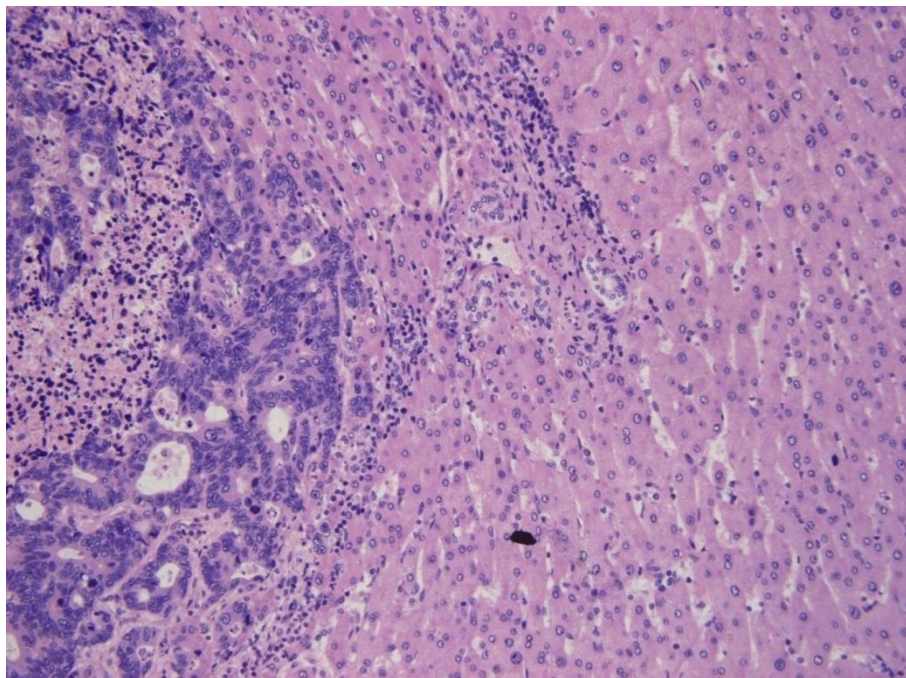
MOS: 4.32

colorfulness: 0.6205

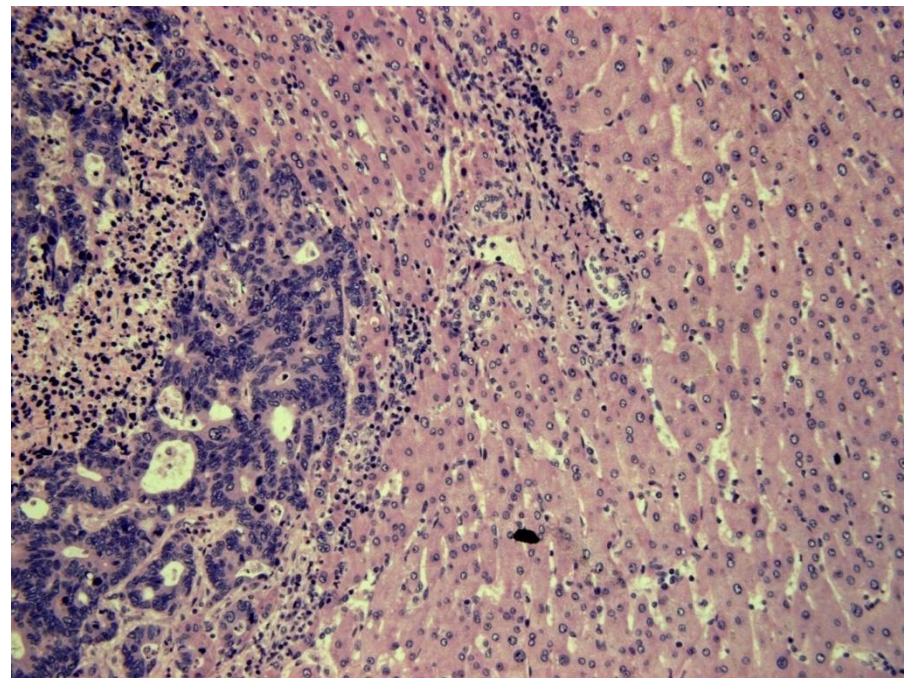
sharpness: 11.5678

contrast: 1.4756

Human liver. Diagnosis: metastasis of primary colon.

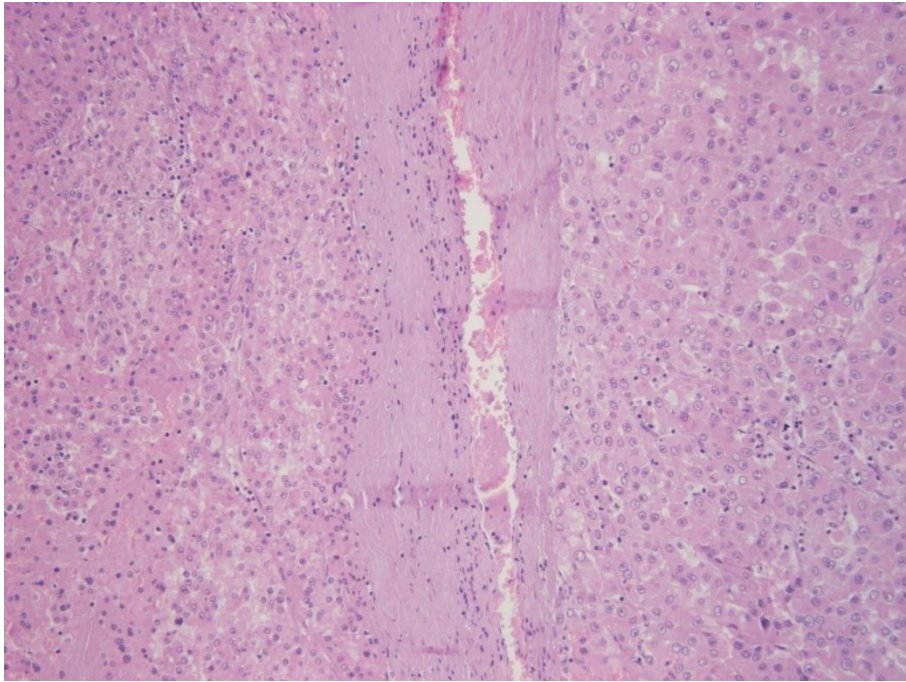


H&E stained image:
MOS: 4.43
colorfulness: 0.4429
sharpness: 11.5506
contrast: 1.6763

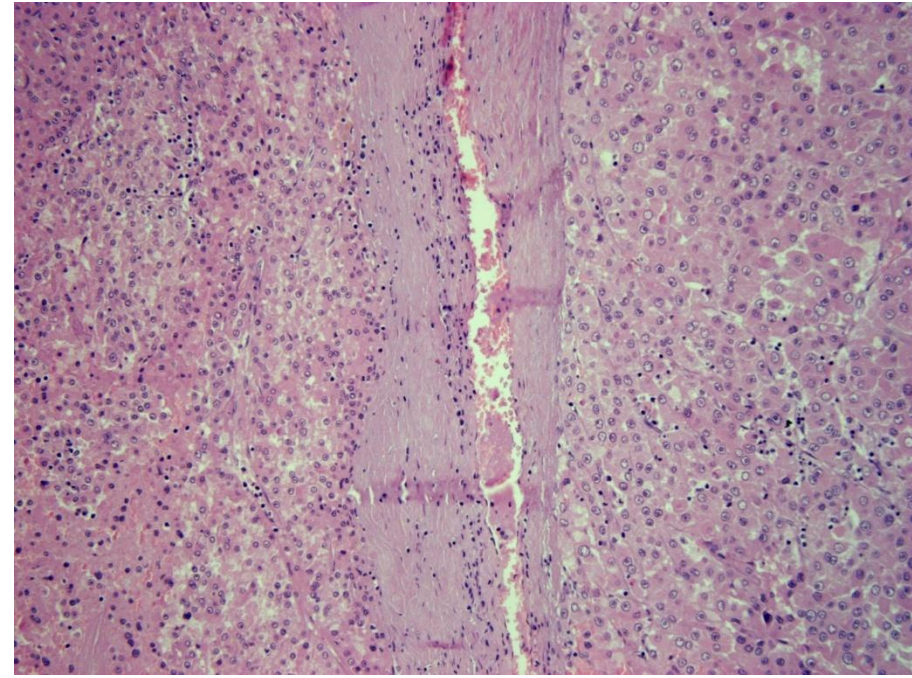


RPCA_rgb enhanced image:
MOS: 4.29
colorfulness: 0.6139
sharpness: 11.6814
contrast: 1.4975

Human liver. Diagnosis: hepatocellular carcinoma.

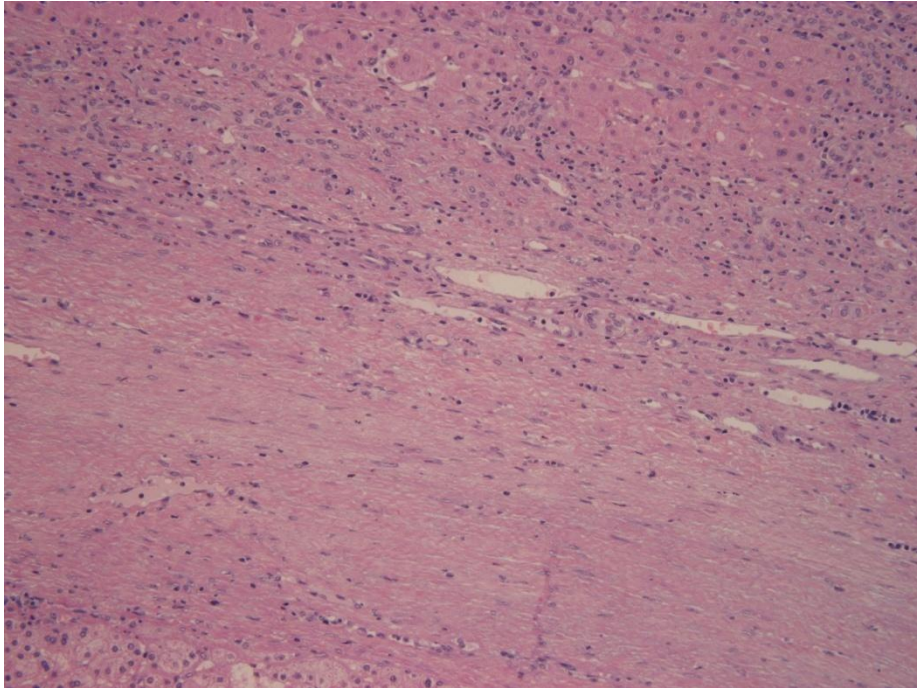


H&E stained image:
MOS: 3.57
colorfulness: 0.3938
sharpness: 11.2341
contrast: 1.4183



RPCA_rgb enhanced image:
MOS: 4.57
colorfulness: 0.5393
sharpness: 10.1647
contrast: 1.6571

Human liver. Diagnosis: hepatocellular carcinoma.



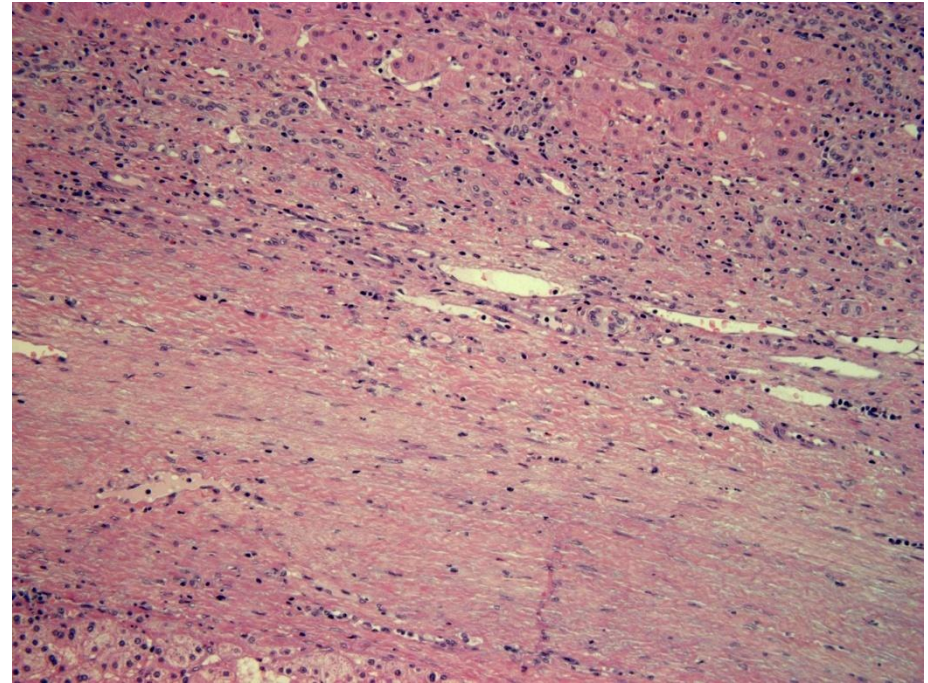
H&E stained image:

MOS: 3.71

colorfulness: 0.2937

sharpness: 9.3856

contrast: 1.7727



RPCA_rgb enhanced image:

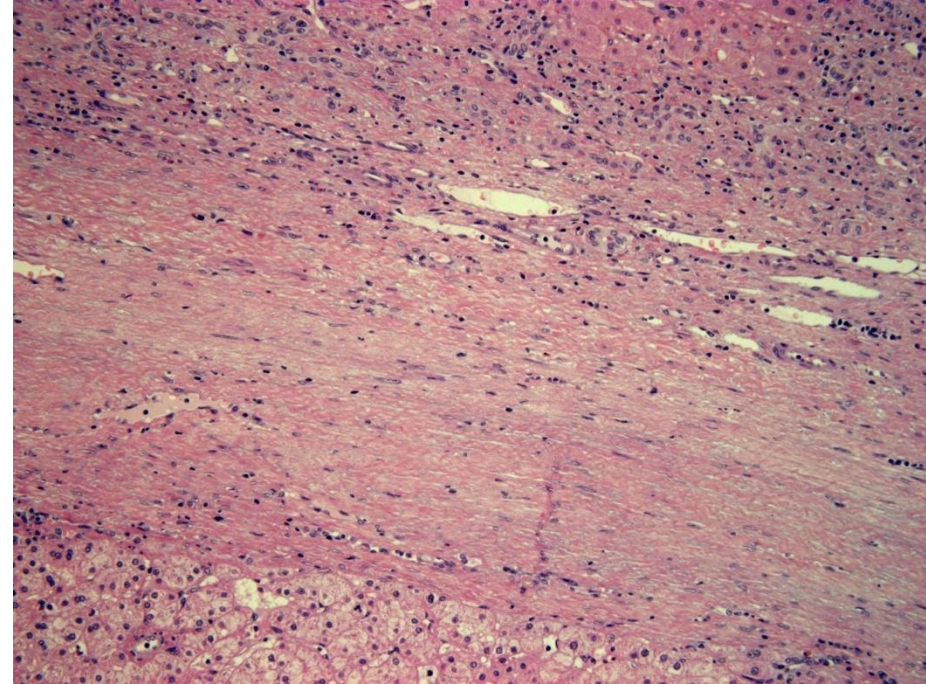
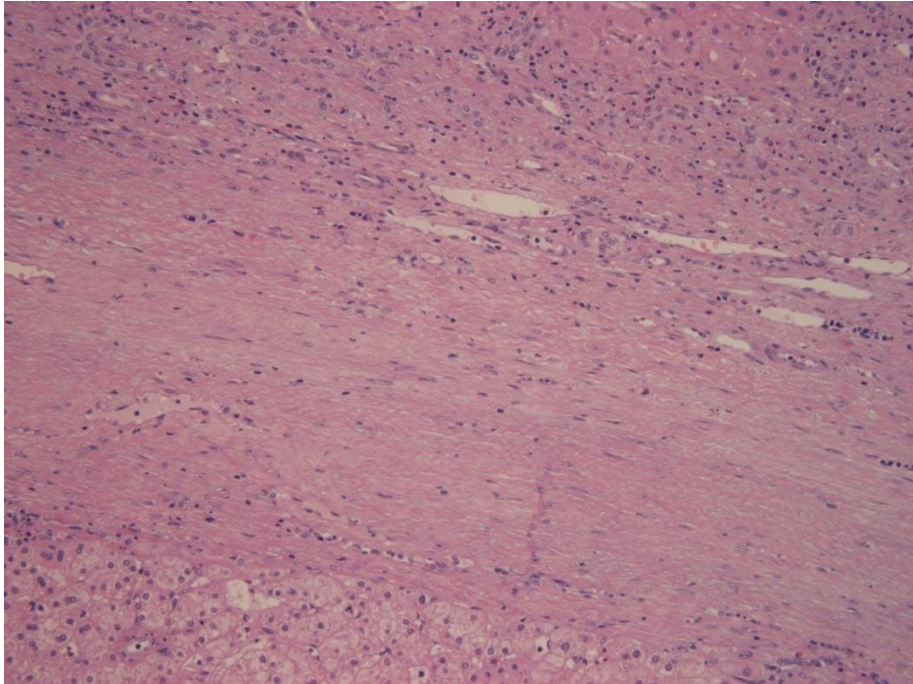
MOS: 4.57

colorfulness: 0.5153

sharpness: 9.5167

contrast: 1.5671

Human liver. Diagnosis: hepatocellular carcinoma.



H&E-stained image:

MOS: 3.86

colorfulness: 0.2891

sharpness: 9.2341

contrast: 1.7786

RPCA_rgb enhanced image:

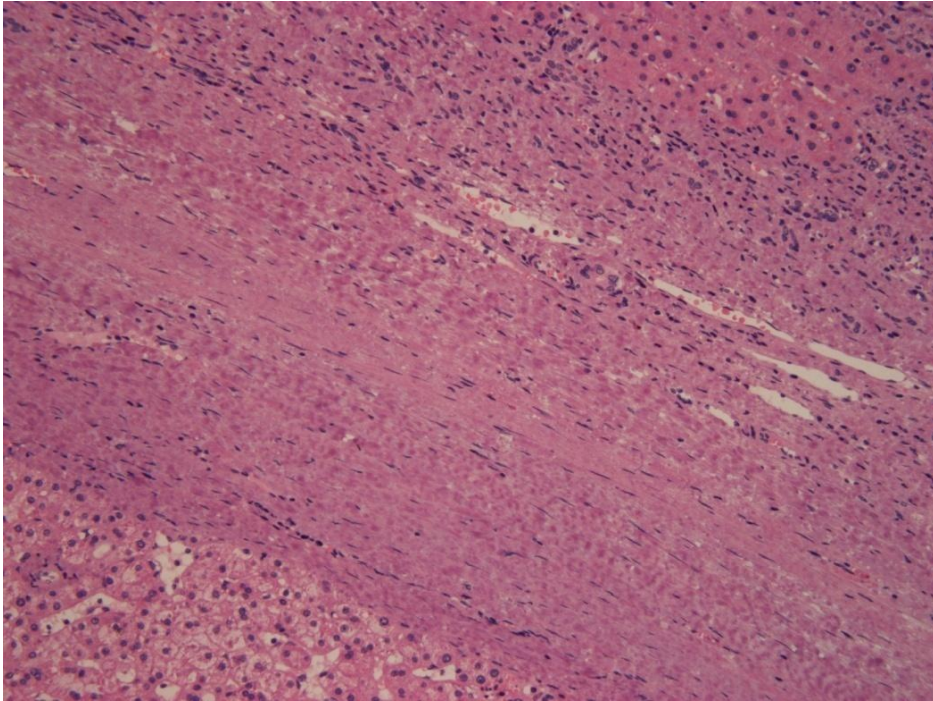
MOS: 4.71

colorfulness: 0.5167

sharpness: 9.3307

contrast: 1.5734

Human liver. Diagnosis: hepatocellular carcinoma.



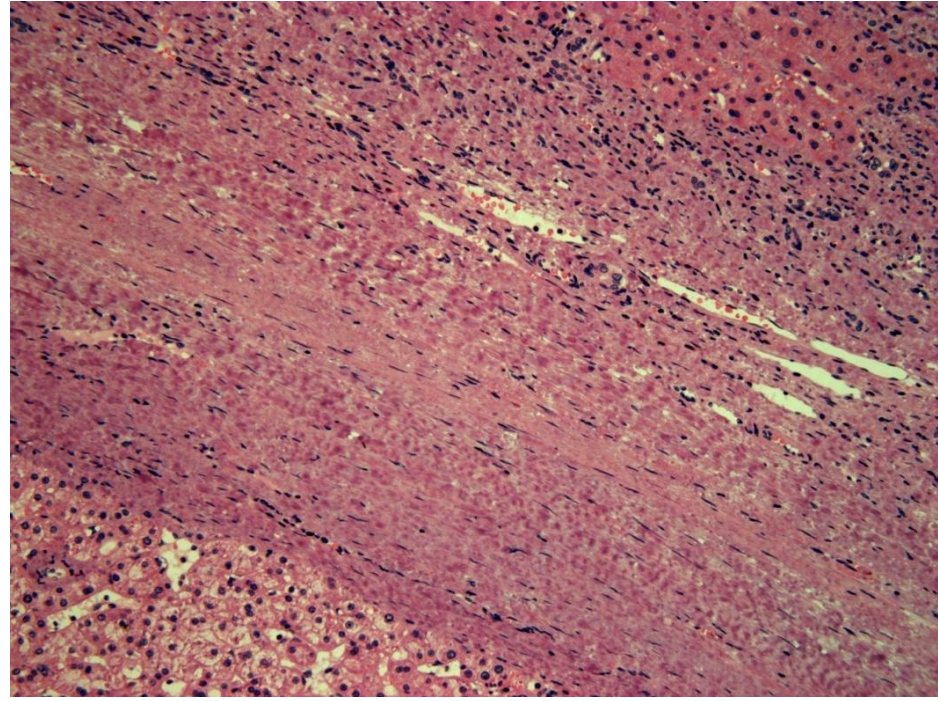
H&E-stained image:

MOS: 4.000

colorfulness: 0.3681

sharpness: 10.2586

contrast: 1.7025



RPCA_rgb enhanced image:

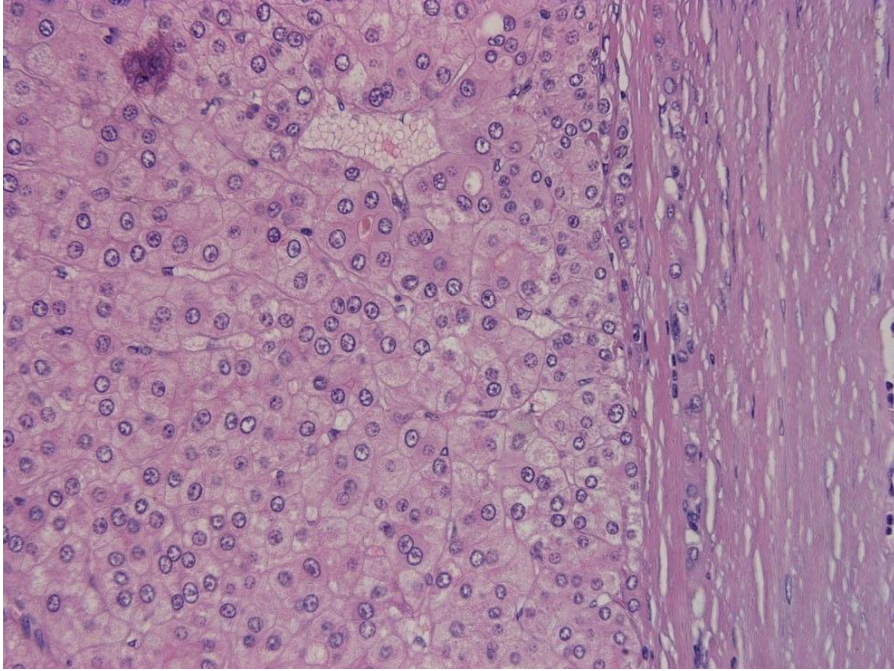
MOS: 4.68

colorfulness: 0.5534

sharpness: 10.4227

contrast: 1.5023

Human liver. Diagnosis: hepatocellular carcinoma.



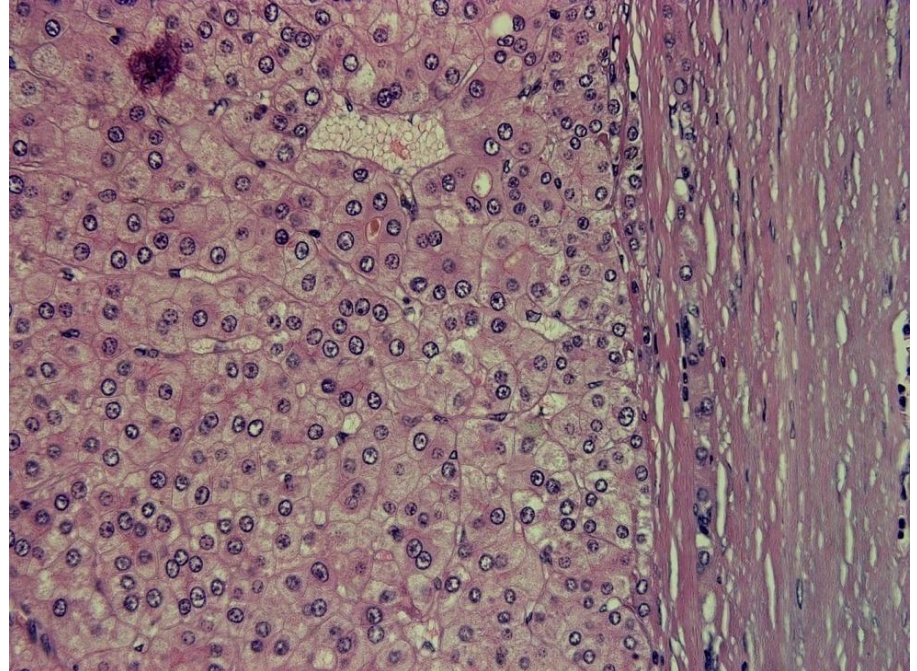
H&E stained image:

MOS: 4.29

colorfulness: 0.4107

sharpness: 10.8614

contrast: 1.5619



RPCA_rgb enhanced image:

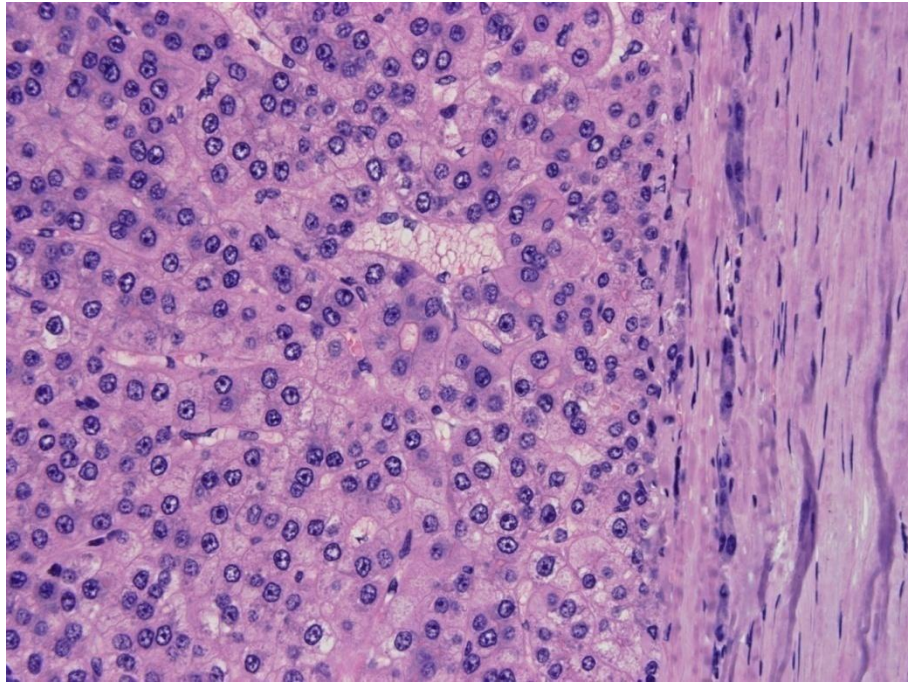
MOS: 4.86

colorfulness: 0.5711

sharpness: 11.0606

contrast: 1.3427

Human liver. Diagnosis: hepatocellular carcinoma.



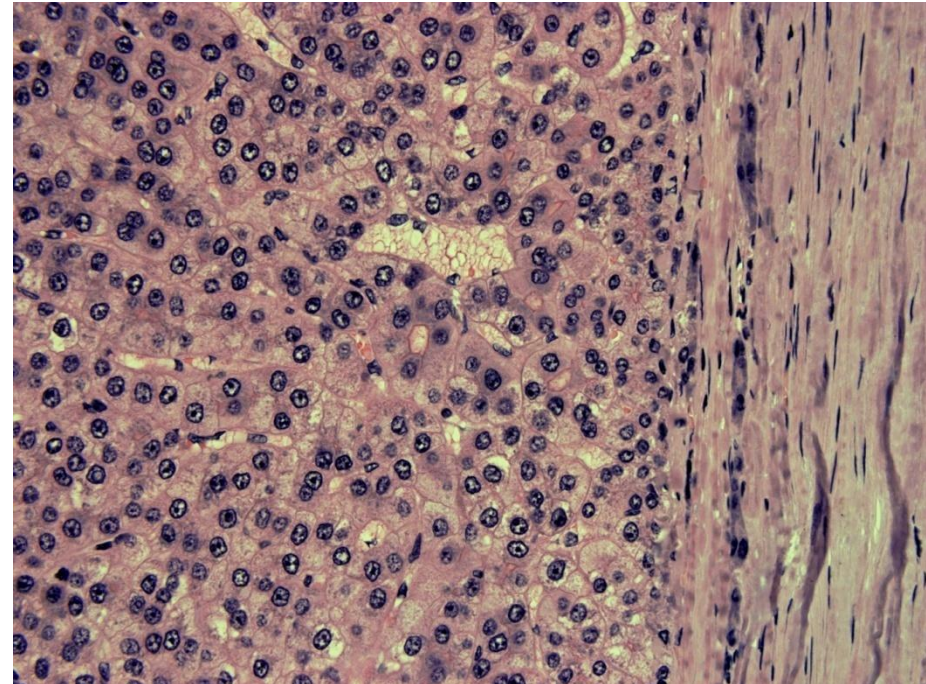
H&E stained image:

MOS: 4.39

colorfulness: 0.4360

sharpness: 9.8572

contrast: 1.6274



RPCA_rgb enhanced image:

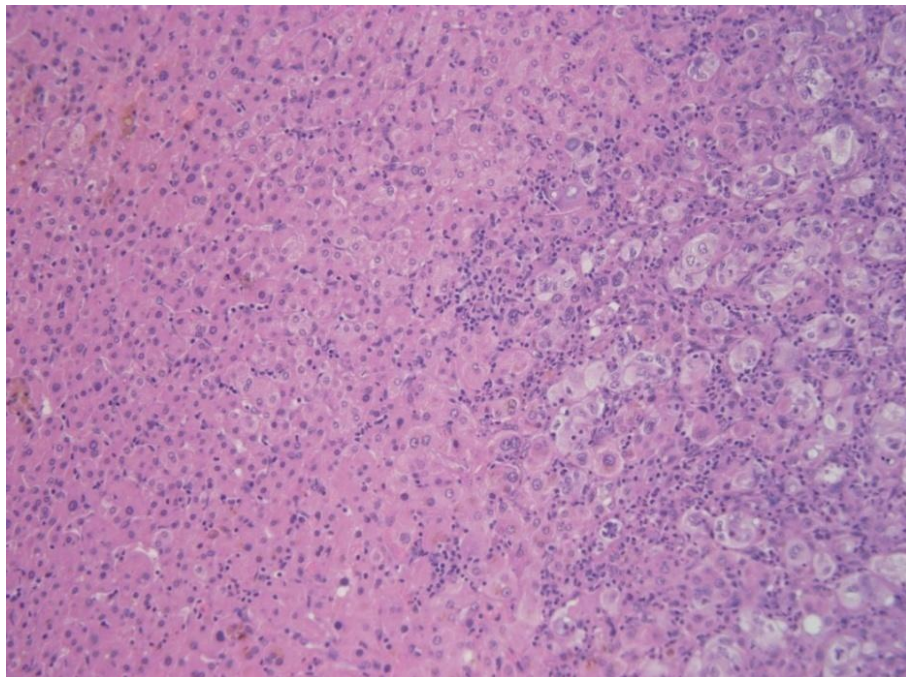
MOS: 4.43

colorfulness: 0.5563

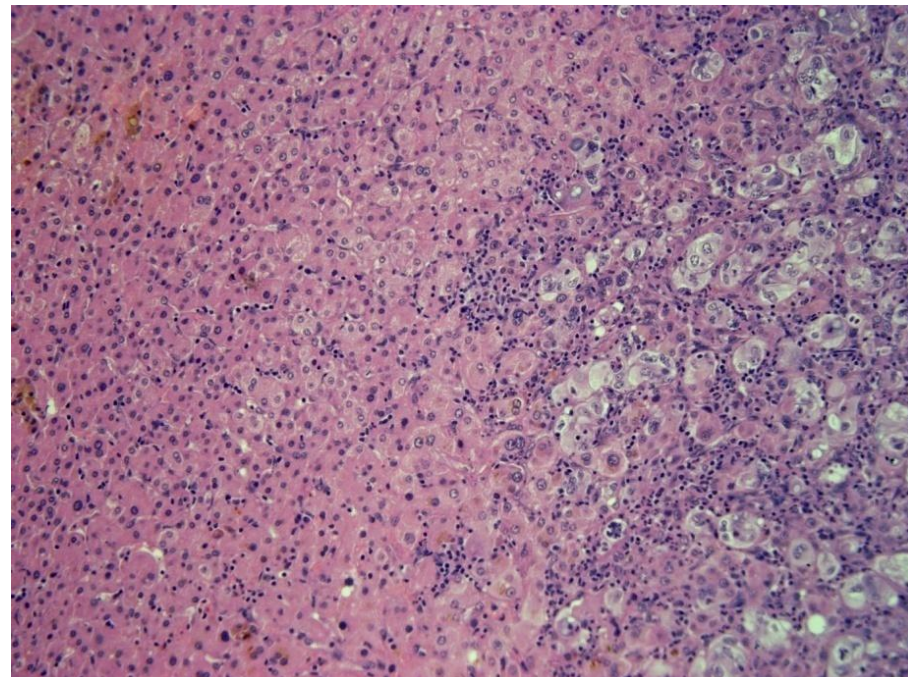
sharpness: 9.9255

contrast: 1.4639

Human liver. Diagnosis: metastasis of primary colon.

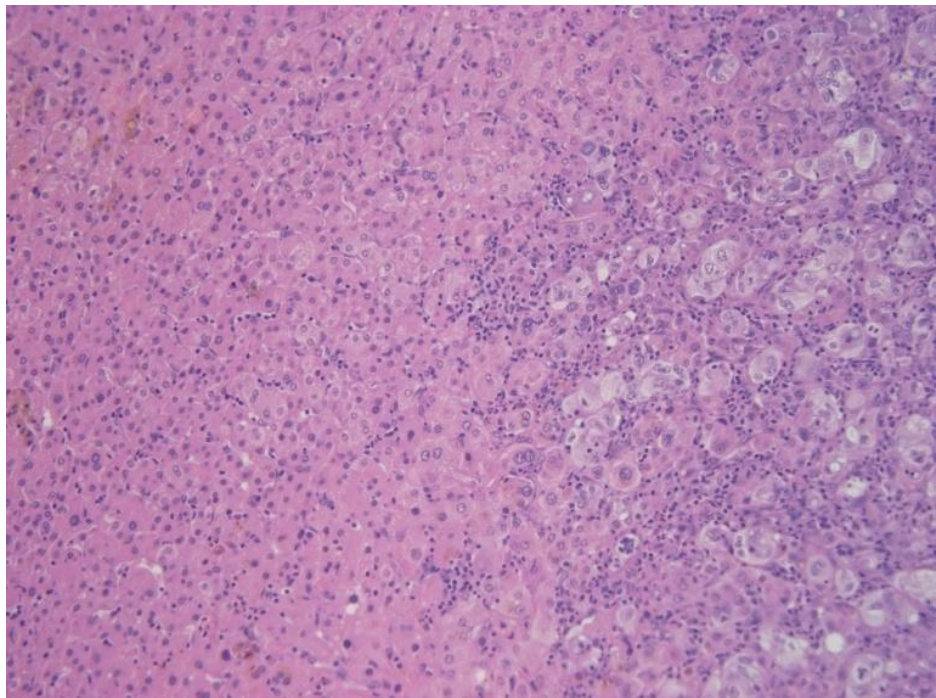


H&E stained image:
MOS: 3.75
colorfulness: 0.3818
sharpness: 10.8398
contrast: 1.7603



RPCA_rgb enhanced image:
MOS: 4.86
colorfulness: 0.5931
sharpness: 10.8653
contrast: 1.5485

Human liver. Diagnosis: metastasis of primary colon.



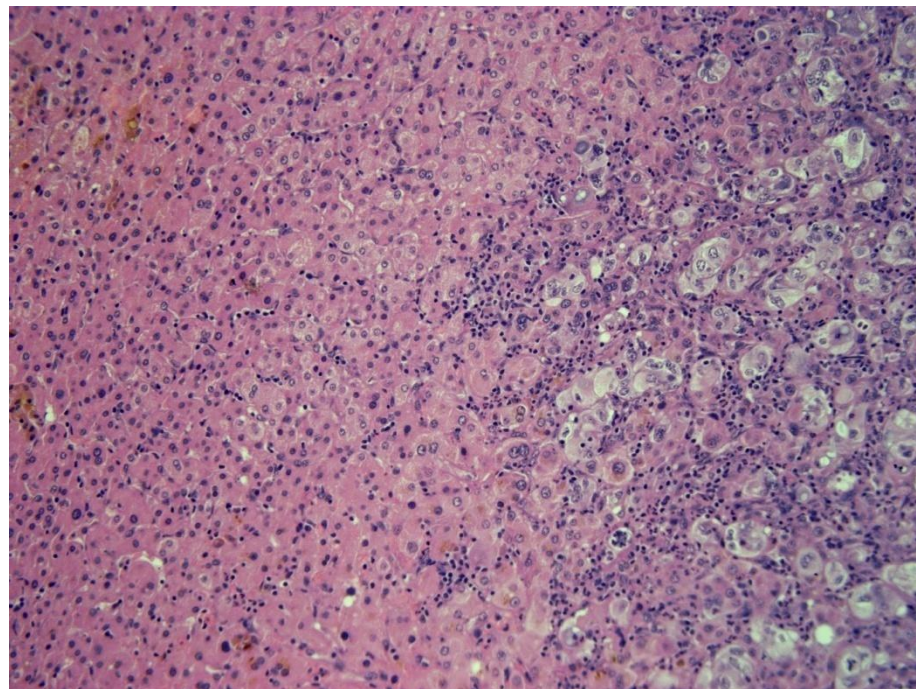
H&E stained image:

MOS: 3.96

colorfulness: 0.3809

sharpness: 10.8139

contrast: 1.7620



RPCA_rgb enhanced image:

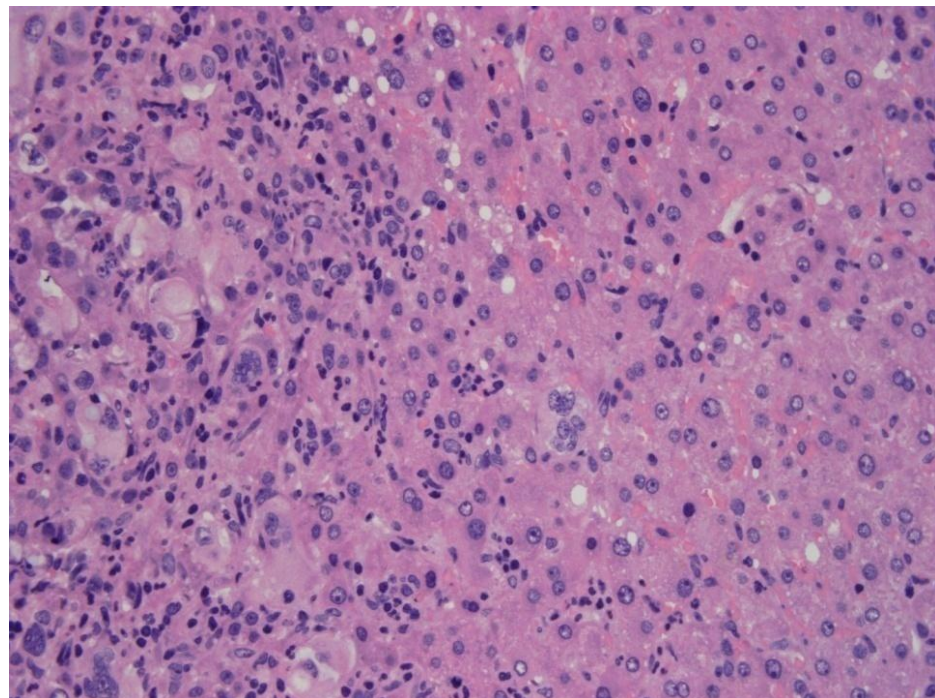
MOS: 4.71

colorfulness: 0.5900

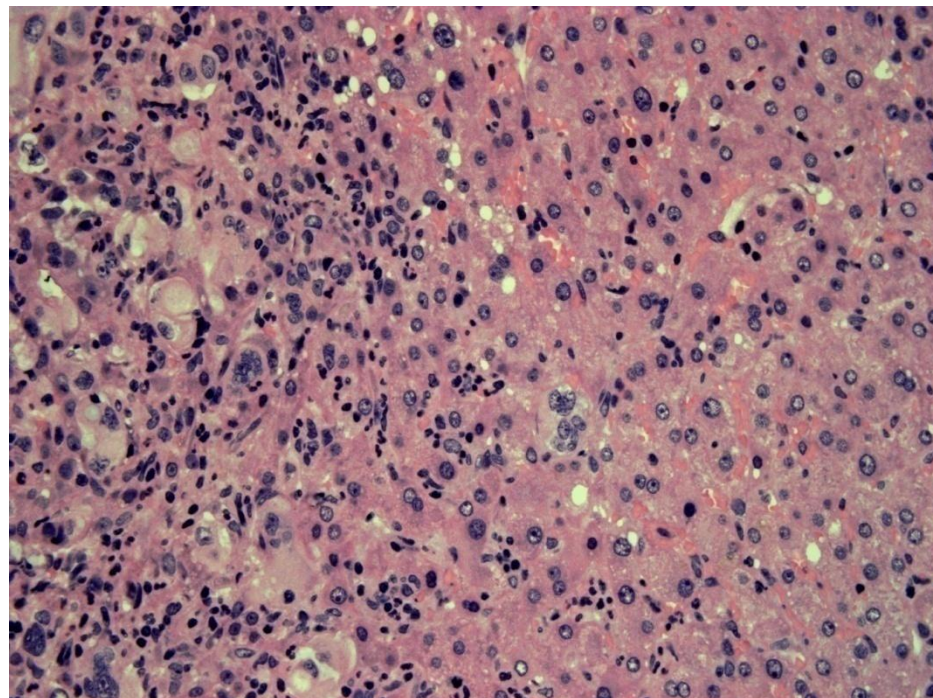
sharpness: 10.8487

contrast: 1.5500

Human liver. Diagnosis: metastasis of primary colon.

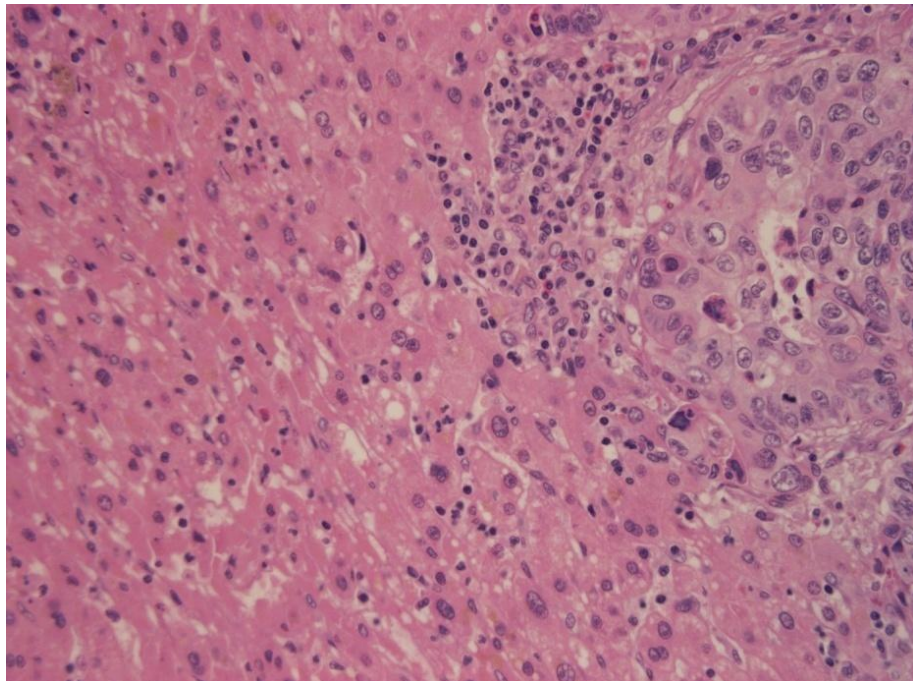


H&E-stained image:
MOS: 4.50
colorfulness: 0.4174
sharpness: 9.7551
contrast: 1.7569



RPCA_rgb enhanced image:
MOS: 4.86
colorfulness: 0.5952
sharpness: 9.8027
contrast: 1.5791

Human liver. Diagnosis: metastasis of primary colon.



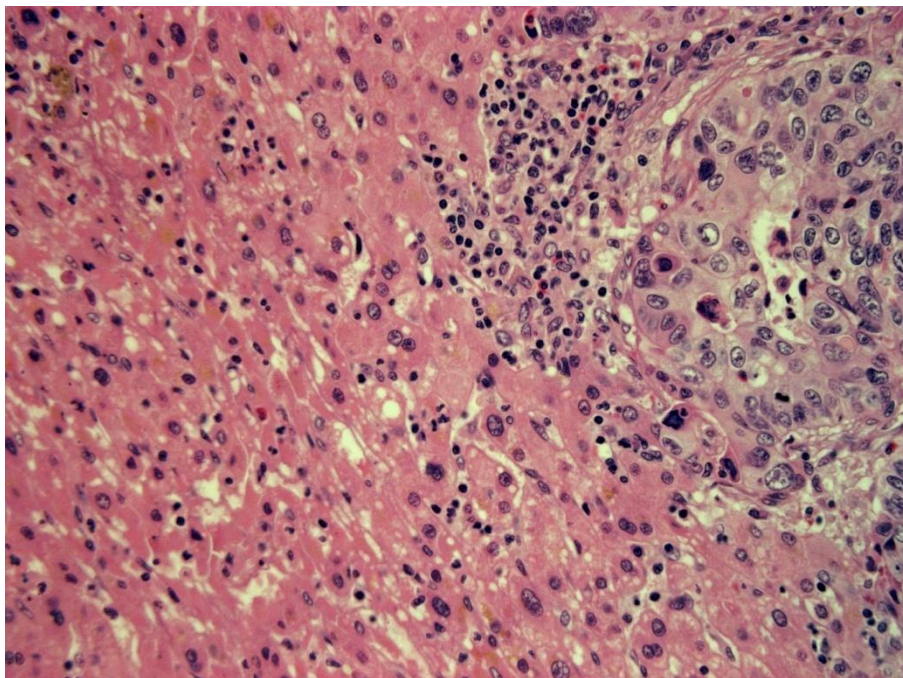
H&E-stained image:

MOS: 4.07

colorfulness: 0.4073

sharpness: 8.8850

contrast: 1.8157



RPCA_rgb enhanced image:

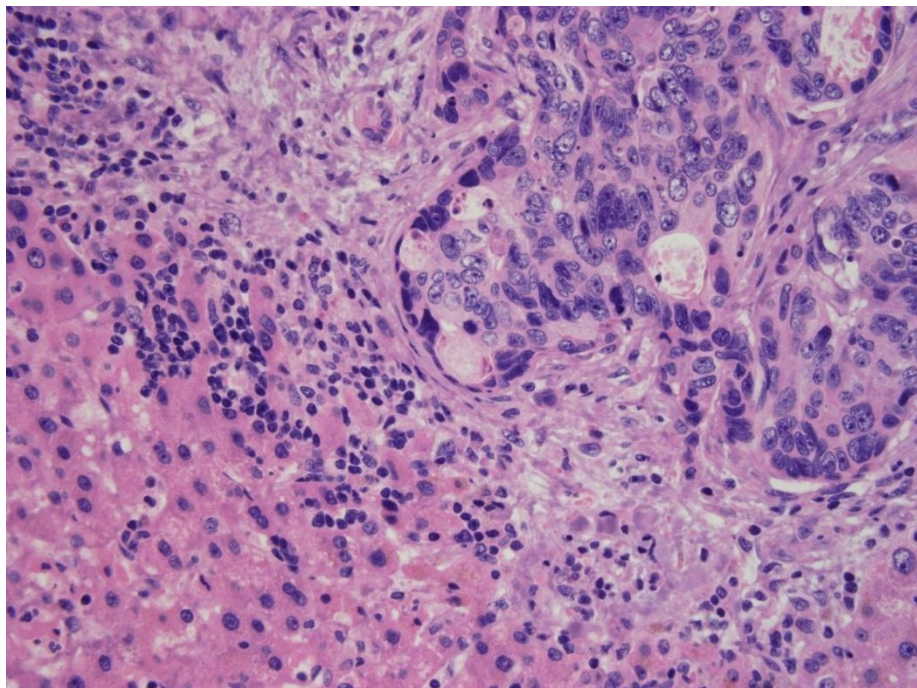
MOS: 5.00

colorfulness: 0.6057

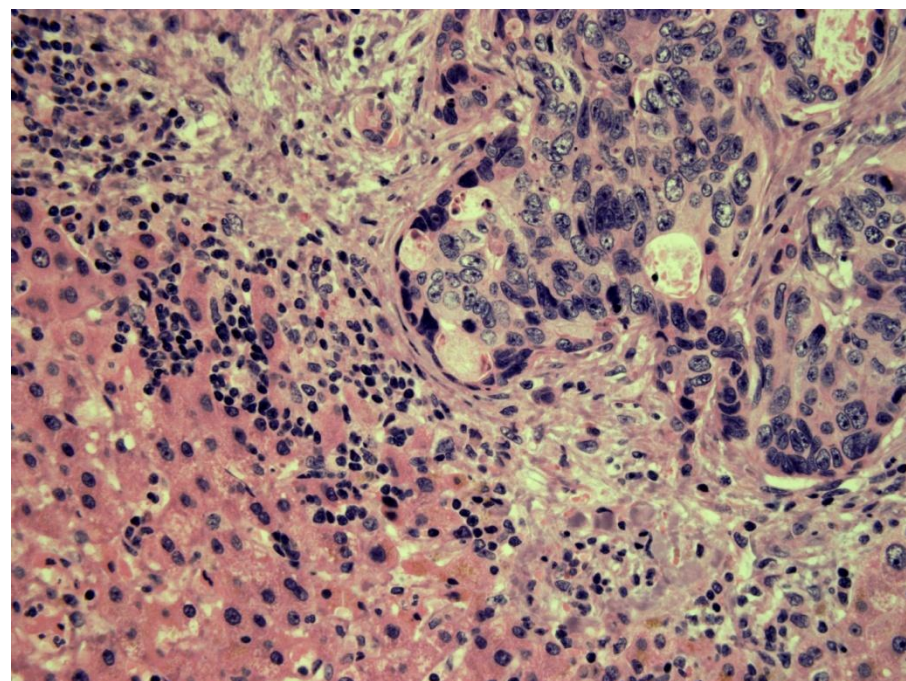
sharpness: 8.9381

contrast: 1.6239

Human liver. Diagnosis: metastasis of primary colon.

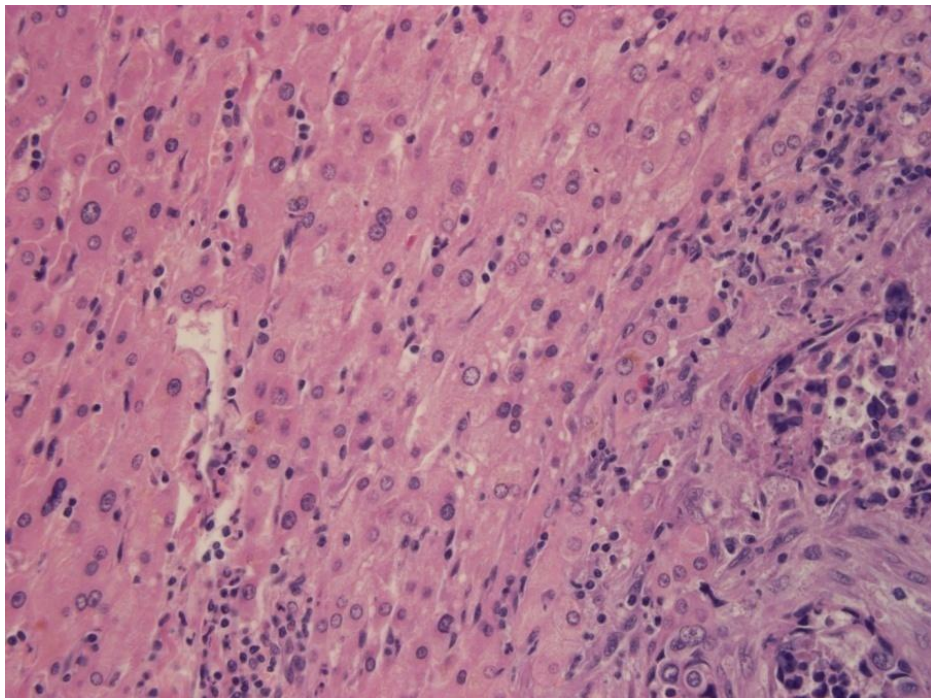


H&E stained image:
MOS: 4.68
colorfulness: 0.5118
sharpness: 9.9531
contrast: 1.6821



RPCA_rgb enhanced image:
MOS: 4.43
colorfulness: 0.6596
sharpness: 9.9744
contrast: 1.5202

Human liver. Diagnosis: metastasis of primary colon.



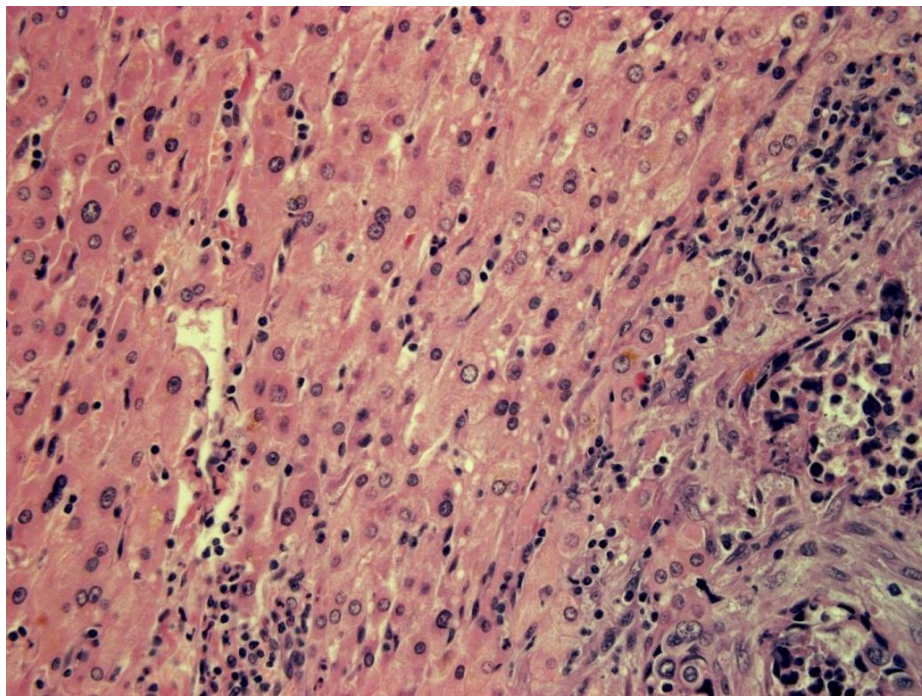
H&E stained image:

MOS: 4.18

colorfulness: 0.4538

sharpness: 8.3945

contrast: 1.7668



RPCA_rgb enhanced image:

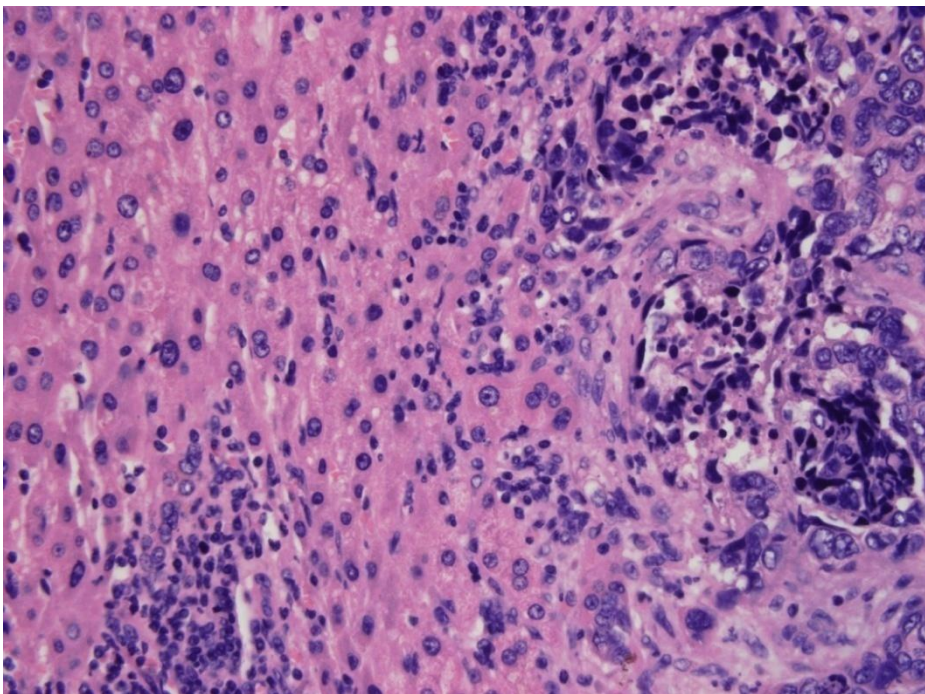
MOS: 4.82

colorfulness: 0.5972

sharpness: 8.4602

contrast: 1.5892

Human liver. Diagnosis: metastasis of primary colon.



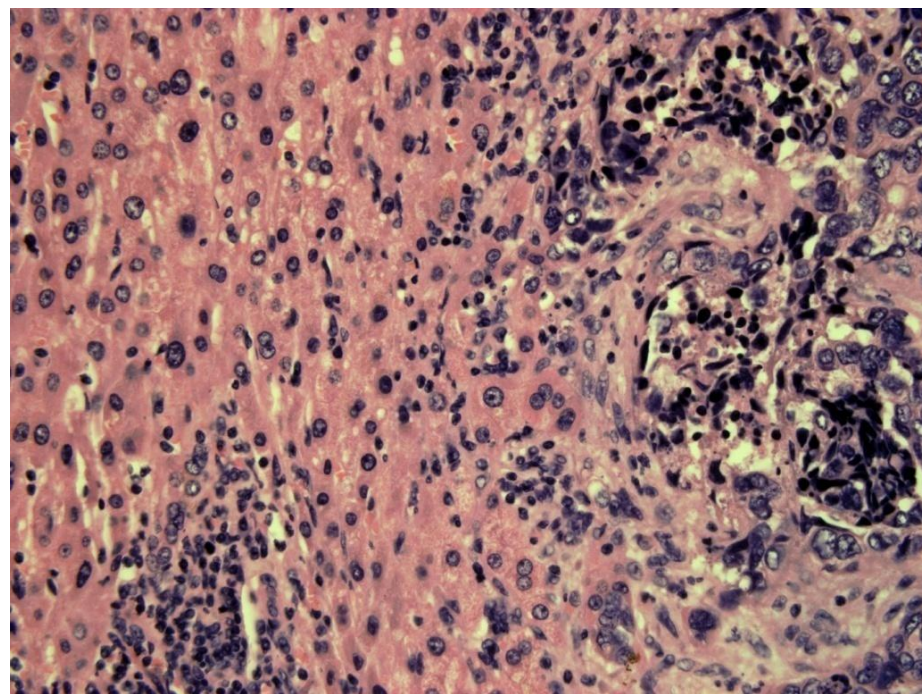
H&E stained image:

MOS: 4.14

colorfulness: 0.5548

sharpness: 9.3740

contrast: 1.6509



RPCA_rgb enhanced image:

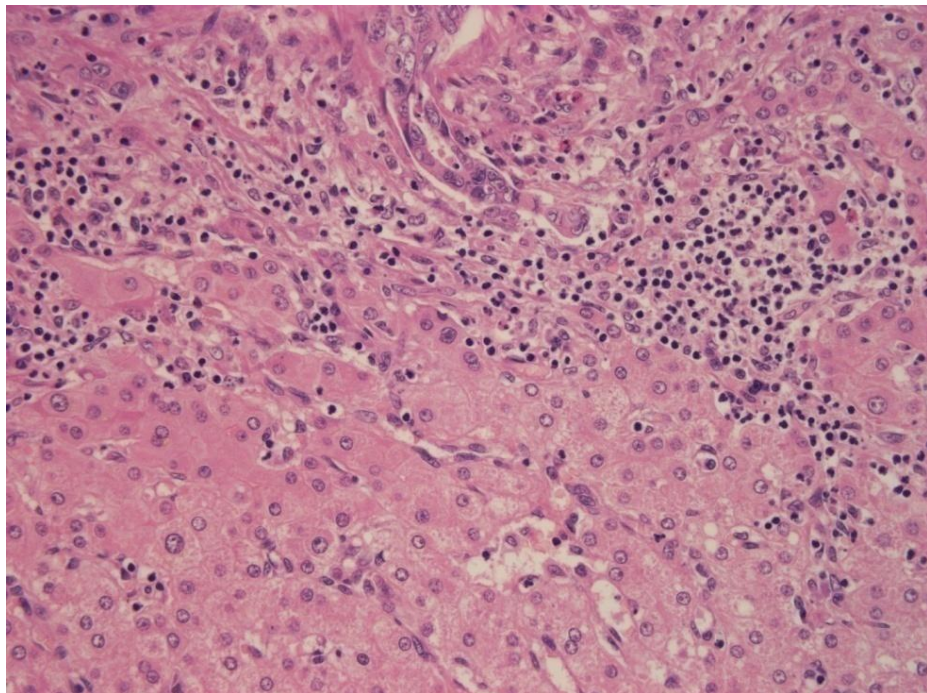
MOS: 4.14

colorfulness: 0.6556

sharpness: 9.3770

contrast: 1.5314

Human liver. Diagnosis: metastasis of primary colon.



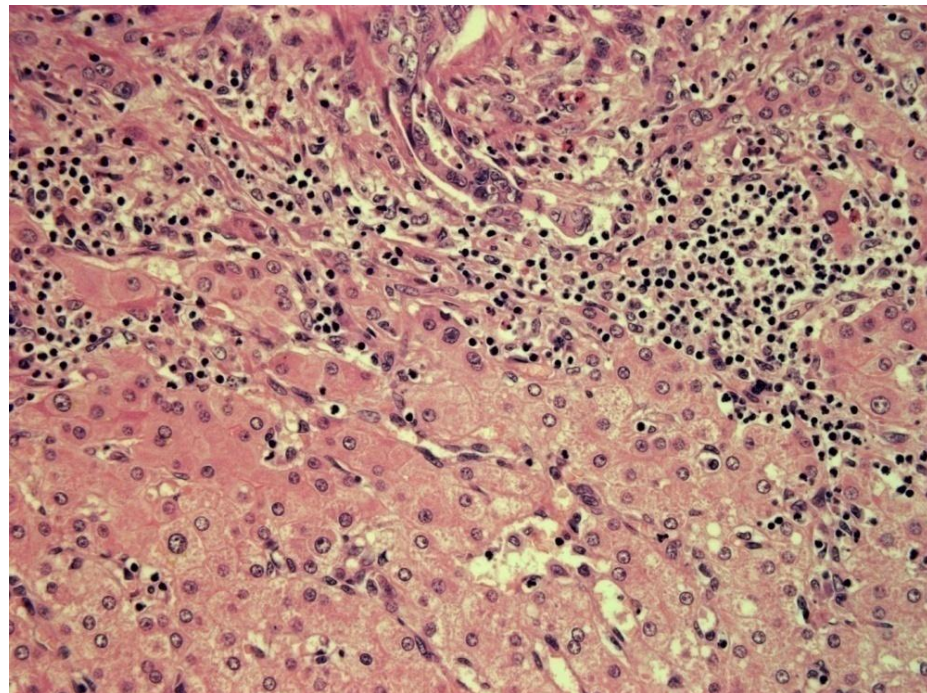
H&E-stained image:

MOS: 4.64

colorfulness: 0.4485

sharpness: 8.7590

contrast: 1.7082



RPCA_rgb enhanced image:

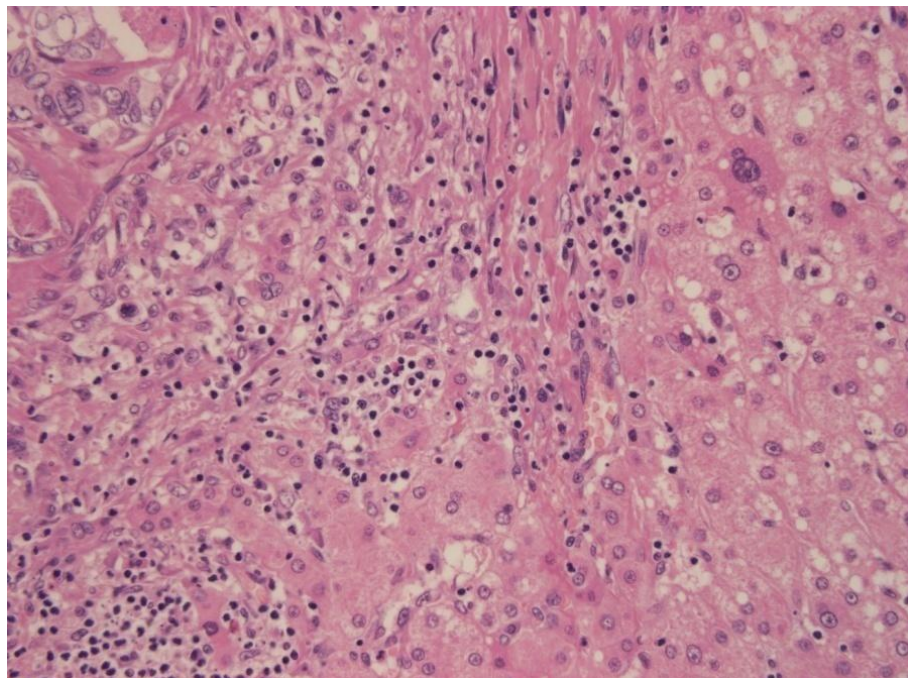
MOS: 4.86

colorfulness: 0.6075

sharpness: 8.8686

contrast: 1.5289

Human liver. Diagnosis: metastasis of primary colon.



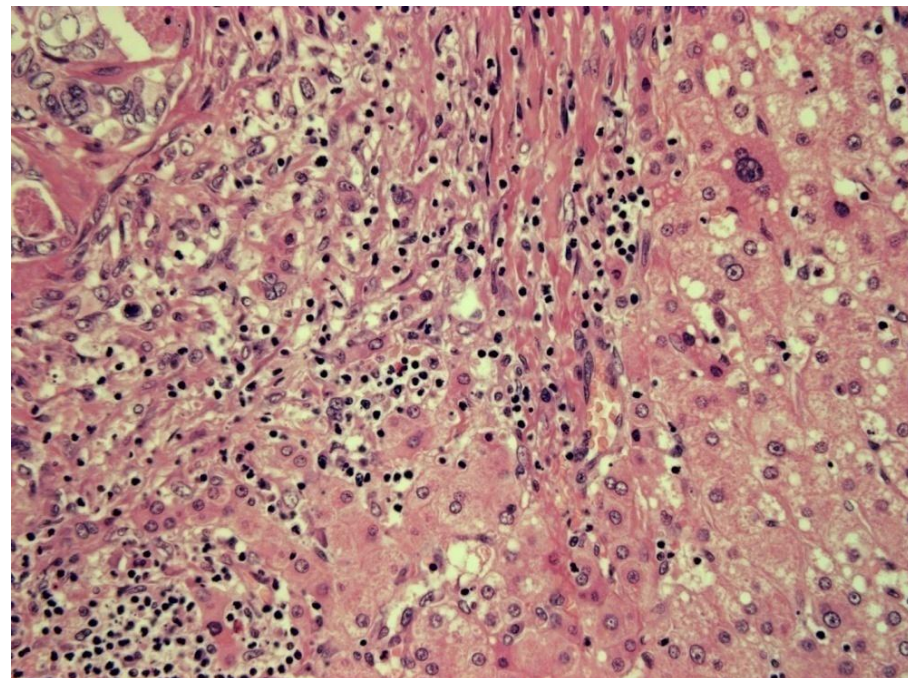
H&E stained image:

MOS: 4.38

colorfulness: 0.4171

sharpness: 7.7336

contrast: 1.7721



RPCA_rgb enhanced image:

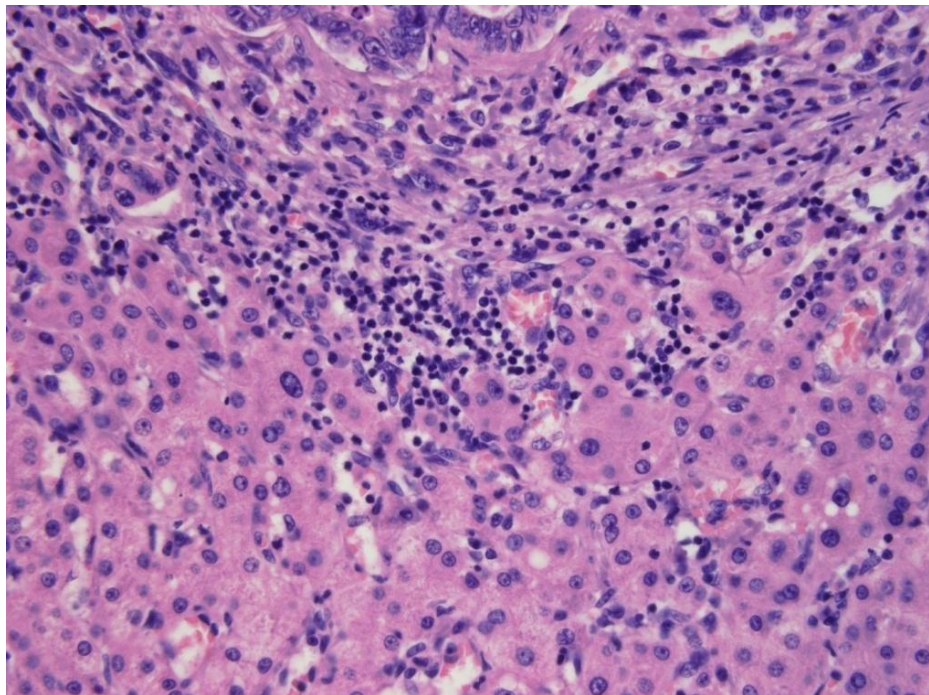
MOS: 4.86

colorfulness: 0.5898

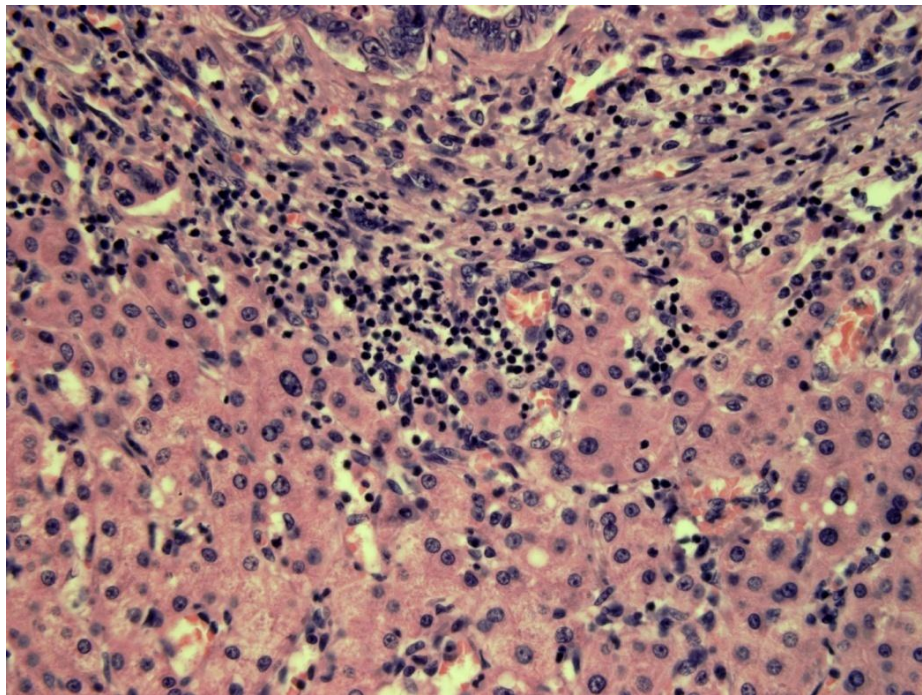
sharpness: 7.8580

contrast: 1.5867

Human liver. Diagnosis: metastasis of primary colon.

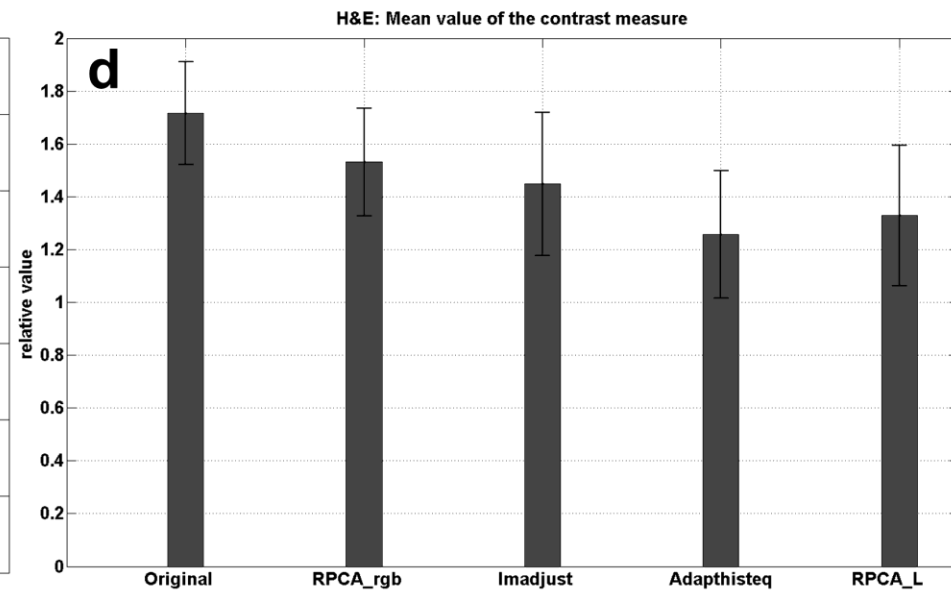
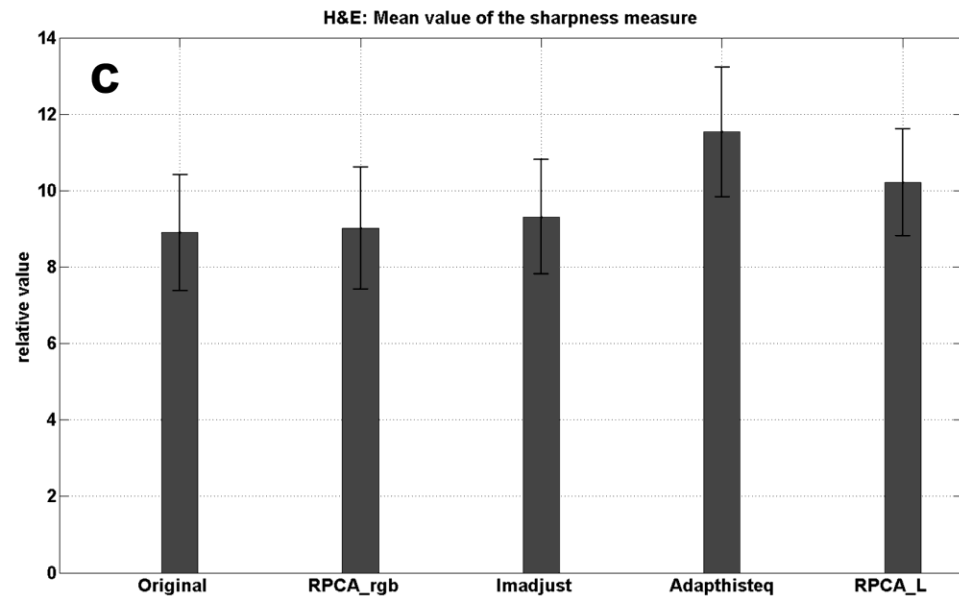
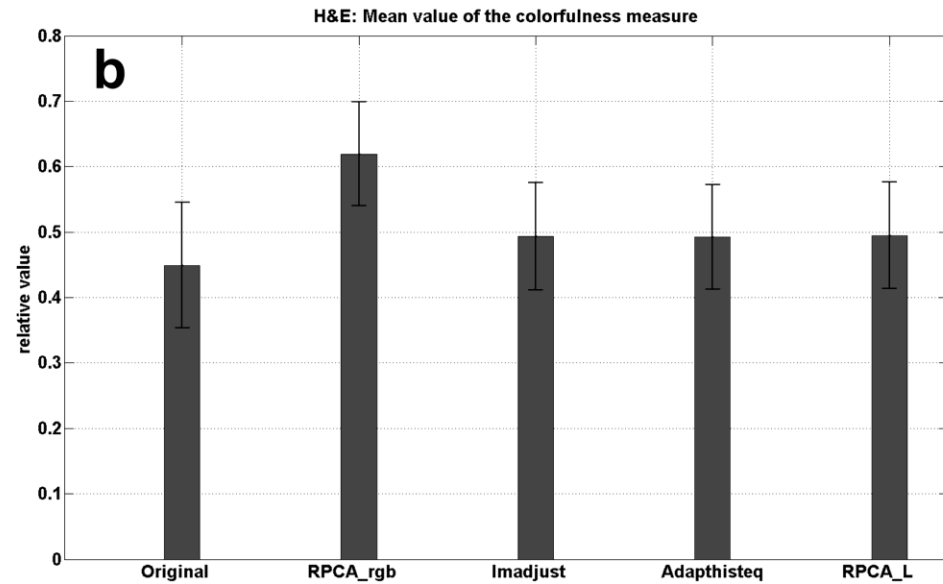
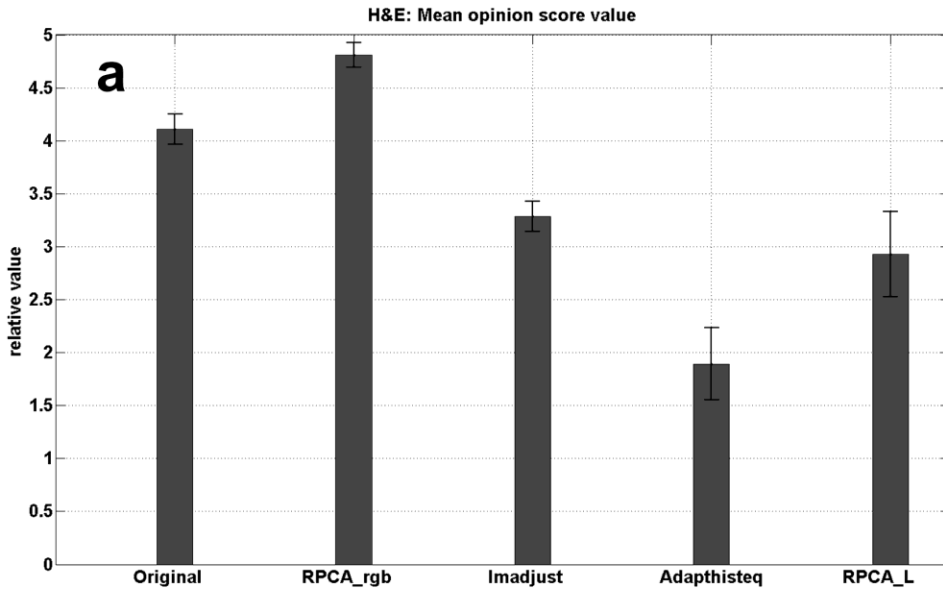


H&E stained image:
MOS: 4.39
colorfulness: 0.5266
sharpness: 8.8343
contrast: 1.6822



RPCA_rgb enhanced image:
MOS: 4.57
colorfulness: 0.6451
sharpness: 8.8407
contrast: 1.5336

H&E stained images: image quality evaluation by the following metrics: Mean opinion score (MOS), colorfulness, sharpness and contrast.



H&E stained images: ranking of algorithms by the following metrics:
Mean opinion score (MOS), colorfulness, sharpness and contrast.

	original	RPCA_rgb	Imadjust	Adapthisteq	RPCA_L
MOS	2	1	3	5	4
colorfulness	5	1	2	2	2
sharpness	5	4	3	1	2
contrast	1	2	3	5	4

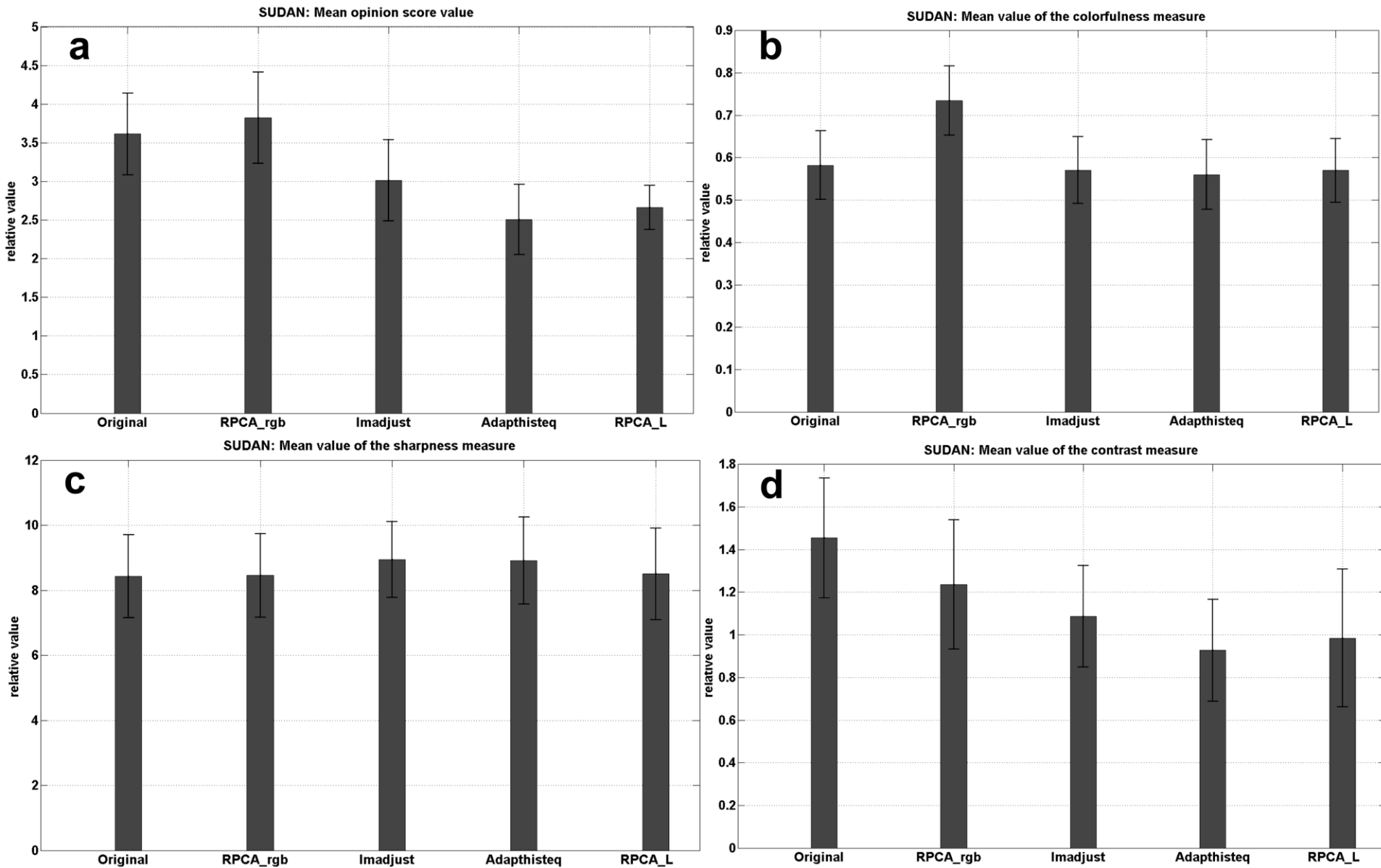
Correlation between inverses of ranking sequences based on mean opinion score (MOS) and image quality metrics. Thus, low rankings are penalized more than high rankings.

$\text{MOS_colorfulness} = 0.92.$

$\text{MOS_sharpness} = 0.54.$

$\text{MOS_contrast} = 0.83.$

SUDAN stained images: image quality evaluation by the following metrics: Mean opinion score (MOS), colorfulness, sharpness and contrast.



SUDAN stained images: ranking of algorithms by the following metrics:
Mean opinion score (MOS), colorfulness, sharpness and contrast.

	original	RPCA_rgb	Imadjust	Adapthisteq	RPCA_L
MOS	2	1	3	5	4
colorfulness	2	1	5	3	4
sharpness	5	3	3	1	2
contrast	1	2	3	5	4

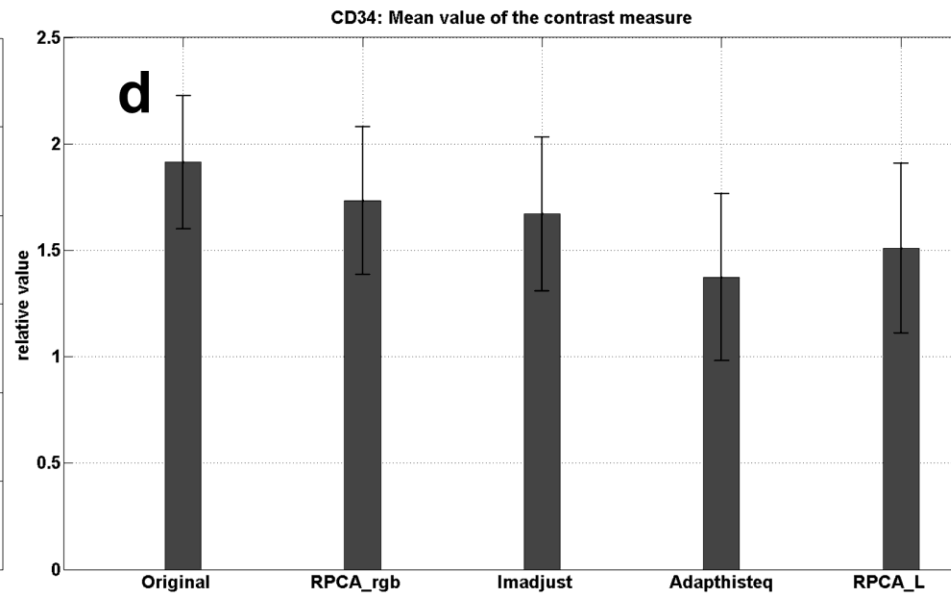
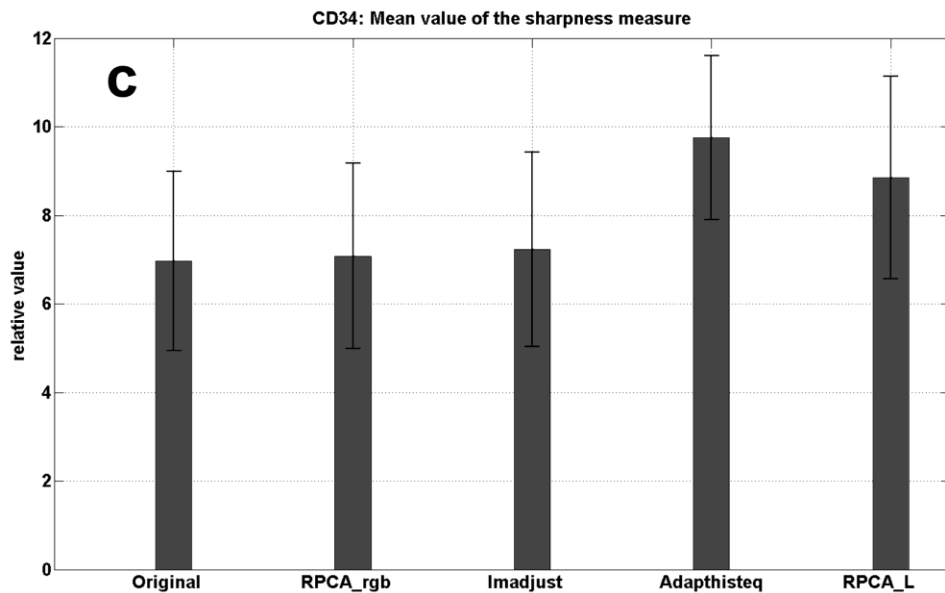
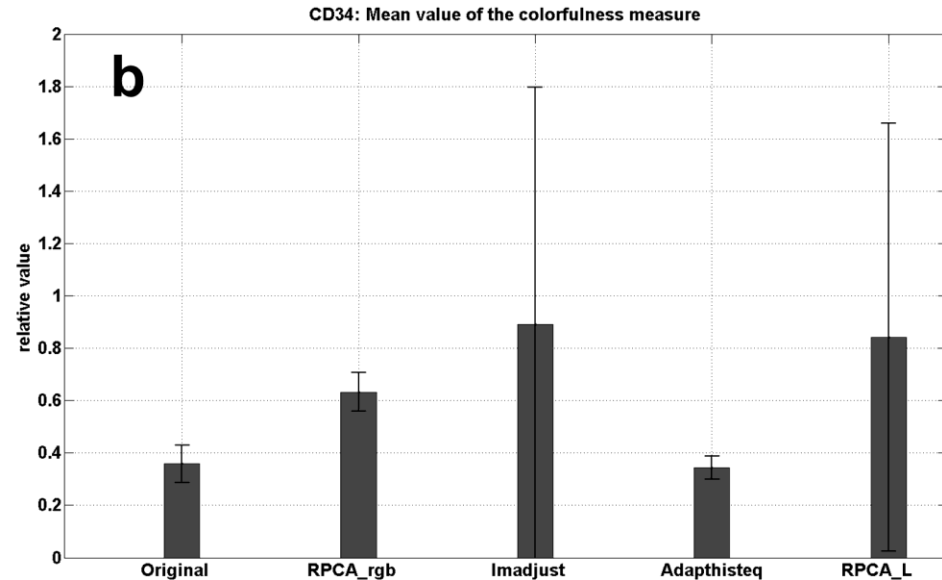
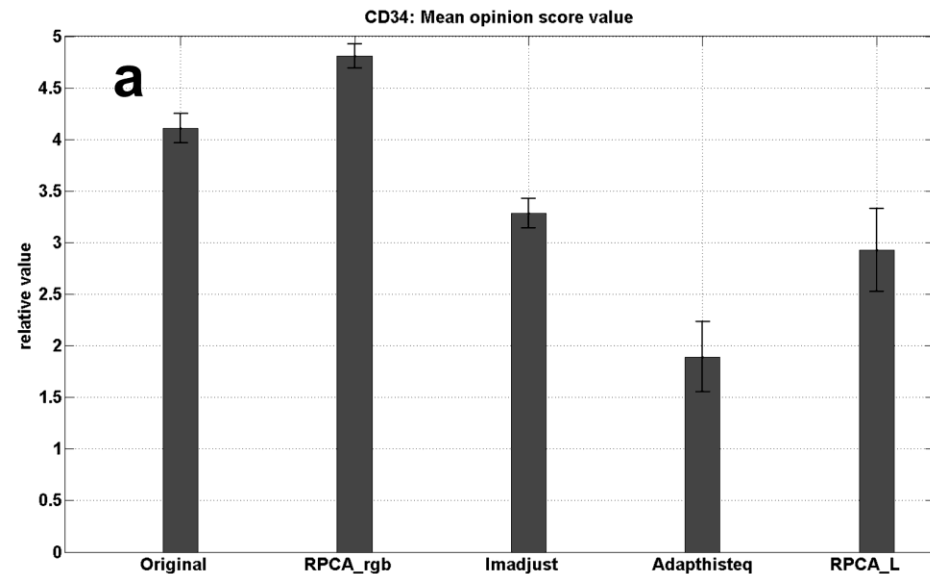
Correlation between inverses of ranking sequences based on mean opinion score (MOS) and image quality metrics. Thus, low rankings are penalized more than high rankings.

MOS_colorfulness=0.99.

MOS_sharpness=0.58.

MOS_contrasts=0.83.

CD34 stained images: image quality evaluation by the following metrics: Mean opinion score (MOS), colorfulness, sharpness and contrast.



CD34 stained images: ranking of algorithms by the following metrics:
Mean opinion score (MOS), colorfulness, sharpness and contrast.

	original	RPCA_rgb	Imadjust	Adaphisteq	RPCA_L
MOS	2	1	3	5	4
colorfulness	2	1	4	3	5
sharpness	3	3	1	1	5
contrast	1	2	3	5	4

Correlation between inverses of ranking sequences based on mean opinion score (MOS) and image quality metrics. Thus, low rankings are penalized more than high rankings. Due to high variance of the estimate of colorfulness attribute *imadjust* and RPCA_L algorithm are ranked low in this category.

MOS_colorfulness=0.99.

MOS_sharpness=0.60.

MOS_contrast=0.83.