Anatomy Segmentation in Laparoscopic Surgery: Comparison of Machine Learning and Human Expertise – An Experimental Study

Supplementary Material

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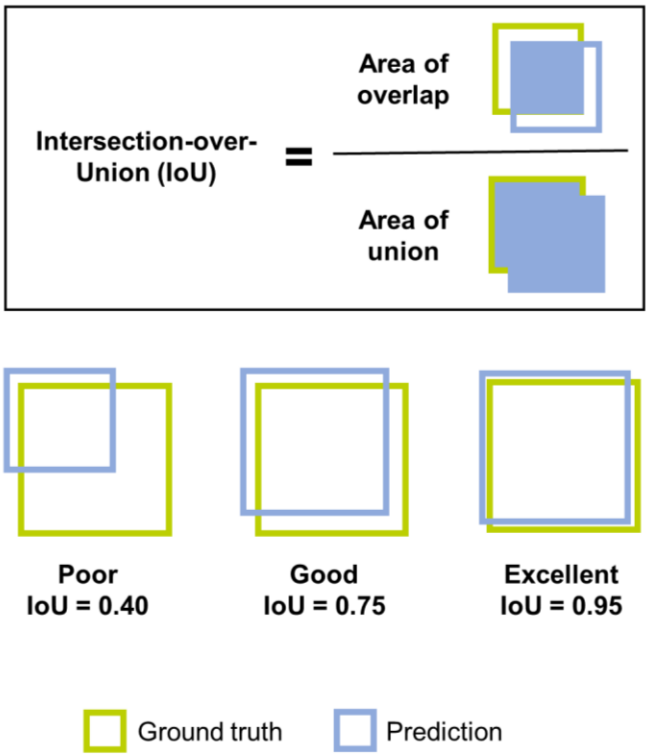
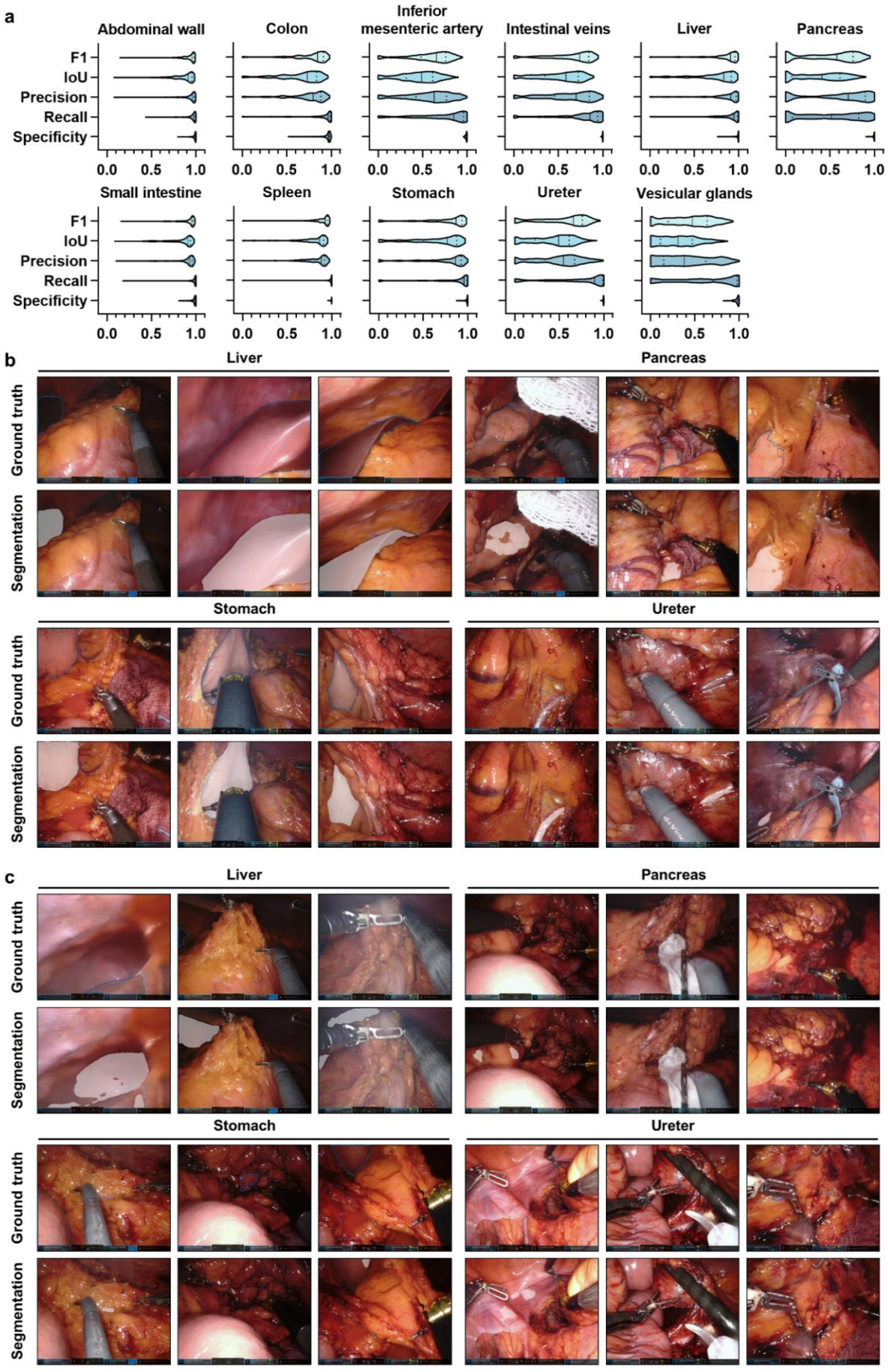
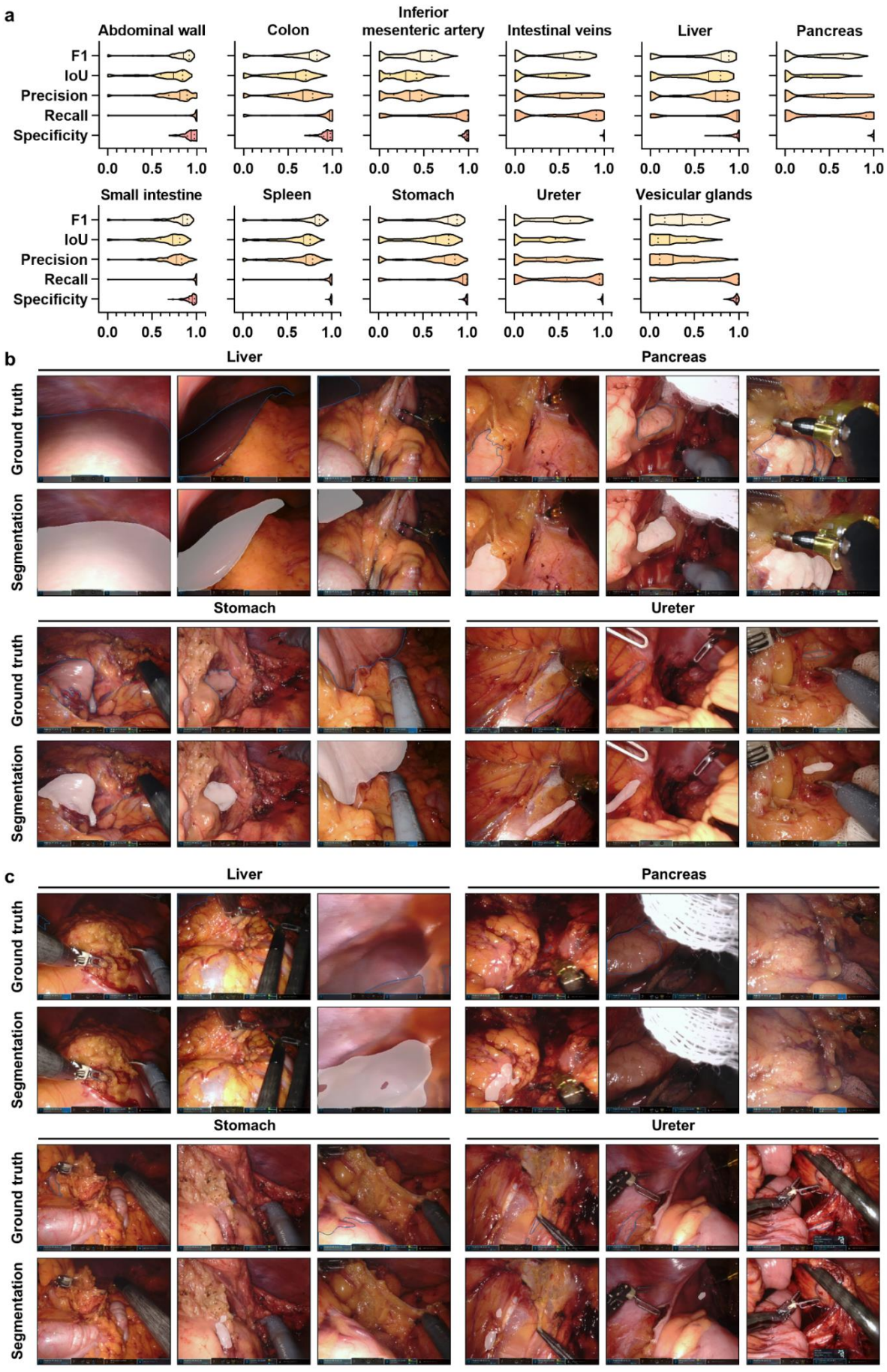


Supplementary Figure 1: Intersection-over-Union (IoU). Schematic illustration of calculation of IoU and examples of poor, good, and excellent IoU in segmentation tasks.


a
Abdominal wall
Colon
Inferior mesenteric artery
Intestinal veins
Liver
Pancreas
Small intestine
Spleen
Stomach
Ureter
Vesicular glands
F1
IoU
Precision
Recall
Specificity
0.0
0.5
1.0
b
c
Liver
Pancreas
Stomach
Ureter
Ground truth
Segmentation

Supplementary Figure 2: Pixel-wise organ segmentation with SegFormer-based structure-specific models trained on the respective organ subsets of the Dresden Surgical Anatomy Dataset. (a) Violin plot illustrations of performance metrics for SegFormer-based structure-specific segmentation models on the test dataset. The median and quartiles are illustrated as solid and dashed lines, respectively. **(b)** Example images from the test dataset with the highest IoUs for liver, pancreas, stomach, and ureter segmentation with SegFormer-based structure-specific segmentation models. Ground truth is displayed as blue line (upper panel), model segmentations are displayed as white overlay (lower panel). **(c)** Example images from the test dataset with the lowest IoUs for liver, pancreas, stomach, and ureter segmentation with SegFormer-based structure-specific segmentation models. Ground truth is displayed as blue line (upper panel), model segmentations are displayed as white overlay (lower panel).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Supplementary Figure 3: Pixel-wise organ segmentation with SegFormer-based combined model trained on the Dresden Surgical Anatomy Dataset across anatomical structure classes with a common encoder and structure-specific decoders. (a) Violin plot illustrations of performance metrics for the SegFormer-based combined segmentation model on the test dataset. The median and quartiles are illustrated as solid and dashed lines, respectively. **(b)** Example images from the test dataset with the highest IoUs for liver, pancreas, stomach, and ureter segmentation with the SegFormer-based combined segmentation model. Ground truth is displayed as blue line (upper panel), model segmentations are displayed as white overlay (lower panel). **(c)** Example images from the test dataset with the lowest IoUs for liver, pancreas, stomach, and ureter segmentation with the SegFormer-based combined segmentation model. Ground truth is displayed as blue line (upper panel), model segmentations are displayed as white overlay (lower panel).

Supplementary Table 1: Summary of performance metrics for anatomical structure segmentation using structure-specific models. Models were based on DeepLabv3 (a: training dataset, b: validation dataset) as well as SegFormer-based architectures (c: training dataset, d: validation dataset). For each metric, mean and standard deviation are displayed.

a DeepLabv3 (Training)

Anatomical structure	F1 score	IoU	Precision	Recall	Specificity
Abdominal wall	0.99 ± 0.01	0.97 ± 0.01	0.98 ± 0.01	0.99 ± 0.01	0.99 ± 0.00
Colon	0.97 ± 0.01	0.95 ± 0.03	0.95 ± 0.03	1.00 ± 0.00	0.99 ± 0.00
Inferior mesenteric artery	0.86 ± 0.06	0.76 ± 0.08	0.76 ± 0.08	1.00 ± 0.00	0.99 ± 0.00
Intestinal veins	0.87 ± 0.05	0.77 ± 0.08	0.77 ± 0.08	1.00 ± 0.00	1.00 ± 0.00
Liver	0.99 ± 0.02	0.97 ± 0.03	0.98 ± 0.02	1.00 ± 0.01	0.99 ± 0.01
Pancreas	0.80 ± 0.08	0.67 ± 0.10	0.67 ± 0.10	1.00 ± 0.00	0.99 ± 0.01
Small intestine	0.98 ± 0.01	0.96 ± 0.02	0.97 ± 0.02	1.00 ± 0.00	0.99 ± 0.00
Spleen	0.89 ± 0.08	0.82 ± 0.11	0.82 ± 0.11	1.00 ± 0.00	1.00 ± 0.00
Stomach	0.85 ± 0.10	0.76 ± 0.13	0.76 ± 0.13	1.00 ± 0.01	0.99 ± 0.01
Ureter	0.87 ± 0.07	0.77 ± 0.09	0.77 ± 0.09	1.00 ± 0.00	1.00 ± 0.00
Vesicular glands	0.68 ± 0.15	0.53 ± 0.16	0.53 ± 0.16	1.00 ± 0.04	0.99 ± 0.02

b DeepLabv3 (Validation)

Anatomical structure	F1 score	IoU	Precision	Recall	Specificity
Abdominal wall	0.91 ± 0.07	0.85 ± 0.11	0.92 ± 0.08	0.92 ± 0.10	0.97 ± 0.04
Colon	0.84 ± 0.14	0.74 ± 0.17	0.83 ± 0.16	0.87 ± 0.16	0.98 ± 0.02
Inferior mesenteric artery	0.62 ± 0.23	0.49 ± 0.22	0.63 ± 0.23	0.73 ± 0.27	0.99 ± 0.01
Intestinal veins	0.66 ± 0.25	0.53 ± 0.24	0.64 ± 0.25	0.75 ± 0.30	1.00 ± 0.00
Liver	0.75 ± 0.27	0.66 ± 0.28	0.83 ± 0.25	0.73 ± 0.29	0.98 ± 0.02
Pancreas	0.72 ± 0.16	0.58 ± 0.16	0.72 ± 0.14	0.77 ± 0.21	0.99 ± 0.01
Small intestine	0.88 ± 0.14	0.81 ± 0.18	0.88 ± 0.15	0.92 ± 0.14	0.97 ± 0.04
Spleen	0.74 ± 0.22	0.63 ± 0.23	0.72 ± 0.23	0.85 ± 0.21	0.99 ± 0.01
Stomach	0.64 ± 0.25	0.51 ± 0.24	0.58 ± 0.23	0.80 ± 0.28	0.97 ± 0.05
Ureter	0.45 ± 0.31	0.34 ± 0.25	0.57 ± 0.29	0.48 ± 0.36	1.00 ± 0.00
Vesicular glands	0.45 ± 0.25	0.32 ± 0.21	0.45 ± 0.28	0.65 ± 0.32	0.96 ± 0.04

c SegFormer (Training)

Anatomical structure	F1 score	IoU	Precision	Recall	Specificity
Abdominal wall	0.99 ± 0.01	0.98 ± 0.01	0.98 ± 0.01	1.00 ± 0.00	0.99 ± 0.00
Colon	0.89 ± 0.07	0.81 ± 0.10	0.82 ± 0.10	0.98 ± 0.02	0.98 ± 0.02
Inferior mesenteric artery	0.91 ± 0.04	0.83 ± 0.06	0.83 ± 0.06	1.00 ± 0.00	0.99 ± 0.00
Intestinal veins	0.84 ± 0.06	0.73 ± 0.09	0.73 ± 0.09	1.00 ± 0.00	1.00 ± 0.00
Liver	0.98 ± 0.02	0.97 ± 0.03	0.97 ± 0.03	1.00 ± 0.01	0.99 ± 0.01
Pancreas	0.83 ± 0.07	0.72 ± 0.09	0.72 ± 0.09	1.00 ± 0.00	0.99 ± 0.01
Small intestine	0.97 ± 0.01	0.94 ± 0.03	0.94 ± 0.03	1.00 ± 0.00	0.99 ± 0.01
Spleen	0.93 ± 0.05	0.87 ± 0.08	0.87 ± 0.08	1.00 ± 0.00	1.00 ± 0.00
Stomach	0.92 ± 0.06	0.86 ± 0.09	0.87 ± 0.09	1.00 ± 0.01	1.00 ± 0.00
Ureter	0.86 ± 0.07	0.77 ± 0.10	0.77 ± 0.10	1.00 ± 0.00	1.00 ± 0.00
Vesicular glands	0.67 ± 0.17	0.52 ± 0.18	0.53 ± 0.18	0.98 ± 0.08	0.98 ± 0.02

d SegFormer (Validation)

Anatomical structure	F1 score	IoU	Precision	Recall	Specificity
Abdominal wall	0.92 ± 0.09	0.85 ± 0.13	0.93 ± 0.08	0.92 ± 0.12	0.97 ± 0.04
Colon	0.81 ± 0.14	0.70 ± 0.17	0.75 ± 0.18	0.92 ± 0.13	0.96 ± 0.03
Inferior mesenteric artery	0.67 ± 0.22	0.54 ± 0.21	0.68 ± 0.24	0.76 ± 0.24	0.99 ± 0.01
Intestinal veins	0.70 ± 0.19	0.56 ± 0.20	0.64 ± 0.21	0.85 ± 0.21	1.00 ± 0.00
Liver	0.84 ± 0.21	0.76 ± 0.23	0.86 ± 0.22	0.85 ± 0.21	0.98 ± 0.03
Pancreas	0.76 ± 0.16	0.64 ± 0.17	0.77 ± 0.14	0.79 ± 0.20	0.99 ± 0.01
Small intestine	0.89 ± 0.13	0.83 ± 0.17	0.86 ± 0.16	0.96 ± 0.09	0.97 ± 0.04
Spleen	0.83 ± 0.17	0.73 ± 0.20	0.80 ± 0.19	0.91 ± 0.15	1.00 ± 0.01
Stomach	0.74 ± 0.25	0.64 ± 0.26	0.71 ± 0.26	0.84 ± 0.24	0.98 ± 0.03
Ureter	0.45 ± 0.33	0.35 ± 0.27	0.48 ± 0.32	0.54 ± 0.39	0.99 ± 0.01
Vesicular glands	0.49 ± 0.26	0.37 ± 0.23	0.49 ± 0.30	0.71 ± 0.32	0.96 ± 0.05

Supplementary Table 2: Summary of performance metrics for anatomical structure segmentation using combined models (common encoder with structure-specific decoders). Models were based on DeepLabv3 (a: training dataset, b: validation dataset) as well as SegFormer-based architectures (c: training dataset, d: validation dataset). For each metric, mean and standard deviation are displayed.

a DeepLabv3 (Training)

Anatomical structure	F1 score	IoU	Precision	Recall	Specificity
Abdominal wall	0.94 ± 0.03	0.89 ± 0.05	0.89 ± 0.05	1.00 ± 0.00	0.96 ± 0.02
Colon	0.89 ± 0.05	0.81 ± 0.08	0.81 ± 0.08	1.00 ± 0.01	0.97 ± 0.02
Inferior mesenteric artery	0.81 ± 0.10	0.69 ± 0.13	0.69 ± 0.13	0.99 ± 0.01	0.99 ± 0.01
Intestinal veins	0.75 ± 0.10	0.61 ± 0.12	0.61 ± 0.13	0.99 ± 0.03	0.99 ± 0.00
Liver	0.93 ± 0.06	0.88 ± 0.10	0.88 ± 0.10	1.00 ± 0.00	0.97 ± 0.03
Pancreas	0.75 ± 0.12	0.62 ± 0.14	0.63 ± 0.14	0.98 ± 0.03	0.99 ± 0.01
Small intestine	0.93 ± 0.04	0.87 ± 0.06	0.87 ± 0.06	1.00 ± 0.00	0.98 ± 0.02
Spleen	0.89 ± 0.09	0.81 ± 0.13	0.82 ± 0.13	0.98 ± 0.02	1.00 ± 0.00
Stomach	0.85 ± 0.10	0.75 ± 0.13	0.76 ± 0.13	1.00 ± 0.04	0.99 ± 0.01
Ureter	0.69 ± 0.14	0.54 ± 0.15	0.55 ± 0.15	0.99 ± 0.04	0.99 ± 0.01
Vesicular glands	0.77 ± 0.15	0.65 ± 0.17	0.67 ± 0.18	0.96 ± 0.11	0.99 ± 0.00

b DeepLabv3 (Validation)

Anatomical structure	F1 score	IoU	Precision	Recall	Specificity
Abdominal wall	0.87 ± 0.10	0.78 ± 0.14	0.85 ± 0.12	0.92 ± 0.13	0.94 ± 0.05
Colon	0.75 ± 0.17	0.62 ± 0.19	0.71 ± 0.18	0.87 ± 0.20	0.96 ± 0.03
Inferior mesenteric artery	0.52 ± 0.29	0.40 ± 0.25	0.57 ± 0.26	0.61 ± 0.35	0.99 ± 0.01
Intestinal veins	0.61 ± 0.25	0.48 ± 0.23	0.61 ± 0.22	0.72 ± 0.31	1.00 ± 0.00
Liver	0.59 ± 0.33	0.49 ± 0.32	0.70 ± 0.30	0.59 ± 0.37	0.97 ± 0.03
Pancreas	0.63 ± 0.21	0.49 ± 0.19	0.65 ± 0.23	0.70 ± 0.23	0.99 ± 0.01
Small intestine	0.84 ± 0.15	0.74 ± 0.18	0.80 ± 0.16	0.91 ± 0.17	0.96 ± 0.04
Spleen	0.68 ± 0.28	0.57 ± 0.28	0.69 ± 0.24	0.78 ± 0.32	0.99 ± 0.01
Stomach	0.46 ± 0.35	0.37 ± 0.31	0.62 ± 0.30	0.48 ± 0.39	0.99 ± 0.02
Ureter	0.30 ± 0.31	0.22 ± 0.24	0.52 ± 0.30	0.36 ± 0.39	1.00 ± 0.01
Vesicular glands	0.45 ± 0.24	0.32 ± 0.20	0.53 ± 0.29	0.51 ± 0.31	0.98 ± 0.02

c SegFormer (Training)

Anatomical structure	F1 score	IoU	Precision	Recall	Specificity
Abdominal wall	0.87 ± 0.10	0.78 ± 0.12	0.80 ± 0.11	0.97 ± 0.11	0.90 ± 0.08
Colon	0.78 ± 0.12	0.65 ± 0.14	0.65 ± 0.14	0.99 ± 0.08	0.94 ± 0.05
Inferior mesenteric artery	0.57 ± 0.15	0.41 ± 0.14	0.42 ± 0.15	0.97 ± 0.08	0.96 ± 0.02
Intestinal veins	0.61 ± 0.16	0.46 ± 0.16	0.48 ± 0.17	0.94 ± 0.14	0.99 ± 0.01
Liver	0.87 ± 0.10	0.78 ± 0.12	0.79 ± 0.11	0.99 ± 0.07	0.91 ± 0.08
Pancreas	0.56 ± 0.15	0.40 ± 0.14	0.42 ± 0.15	0.95 ± 0.13	0.98 ± 0.02
Small intestine	0.83 ± 0.08	0.72 ± 0.11	0.72 ± 0.11	0.99 ± 0.04	0.93 ± 0.06
Spleen	0.81 ± 0.16	0.70 ± 0.19	0.74 ± 0.17	0.93 ± 0.14	0.99 ± 0.01
Stomach	0.80 ± 0.14	0.69 ± 0.17	0.71 ± 0.16	0.97 ± 0.10	0.99 ± 0.01
Ureter	0.58 ± 0.22	0.44 ± 0.20	0.48 ± 0.20	0.90 ± 0.22	0.99 ± 0.01
Vesicular glands	0.54 ± 0.22	0.40 ± 0.21	0.41 ± 0.22	0.96 ± 0.11	0.98 ± 0.02

d SegFormer (Validation)

Anatomical structure	F1 score	IoU	Precision	Recall	Specificity
Abdominal wall	0.80 ± 0.17	0.69 ± 0.19	0.76 ± 0.14	0.90 ± 0.21	0.89 ± 0.07
Colon	0.69 ± 0.21	0.57 ± 0.22	0.65 ± 0.20	0.86 ± 0.25	0.94 ± 0.05
Inferior mesenteric artery	0.44 ± 0.27	0.32 ± 0.22	0.43 ± 0.24	0.68 ± 0.38	0.97 ± 0.02
Intestinal veins	0.57 ± 0.23	0.43 ± 0.21	0.53 ± 0.20	0.77 ± 0.30	0.99 ± 0.01
Liver	0.52 ± 0.36	0.43 ± 0.33	0.71 ± 0.28	0.57 ± 0.43	0.96 ± 0.06
Pancreas	0.62 ± 0.18	0.47 ± 0.17	0.56 ± 0.16	0.79 ± 0.24	0.98 ± 0.02
Small intestine	0.78 ± 0.21	0.67 ± 0.22	0.73 ± 0.17	0.91 ± 0.24	0.93 ± 0.06
Spleen	0.65 ± 0.30	0.55 ± 0.29	0.69 ± 0.26	0.75 ± 0.33	0.99 ± 0.01
Stomach	0.49 ± 0.37	0.40 ± 0.33	0.65 ± 0.29	0.57 ± 0.42	0.98 ± 0.02
Ureter	0.32 ± 0.30	0.24 ± 0.24	0.45 ± 0.29	0.44 ± 0.41	0.99 ± 0.01
Vesicular glands	0.51 ± 0.26	0.38 ± 0.23	0.47 ± 0.28	0.74 ± 0.29	0.96 ± 0.04