Supplementary Material: Learning to Segment Multiple Organs from Multimodal Partially Labeled Datasets

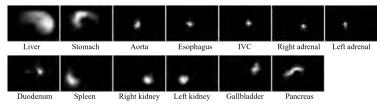


Fig. S1. Example a priori probabilistic atlases for 13 abdominal organs. IVC: inferior vena cava.

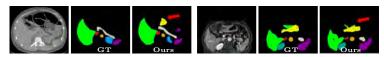


Fig. S2. Example segmentation failures (right: CT; left: MRI) with unsatisfactory regions marked by red arrows, likely due to mistaking for other organs and the complexity of abdominal structures.

Table S1. Sensitivity analysis of the performance concerning the variation of the a priori probabilistic atlas in DSC (mean±std%), where the atlas is constructed with 50% and all available training data for each organ. The performance is stable and no statistical significance is found for the comparison, suggesting that our framework is robust to the variation of the atlas.

Atlas construction	Multimodal				
data	Intramodal Cross-modal				
100%	83.4 ±16.9	74.6 ± 18.2			
50%	83.1 ± 17.2	73.8 ± 18.4			

Table S2. Training-set pseudo-label quality comparison with two pseudo-label-based methods PaNN and U^2PL in DSC (mean \pm std%). *: p < 0.05 for pairwise comparison with our method. The pseudo labels produced by our method are significantly better than those by PaNN and U^2PL , especially in cross-modal circumstances.

	PaNN [40]	$U^{2}PL$ [31]	Ours
Intramodal	$83.2{\pm}14.1^*$	$83.8 \pm 13.4^*$	85.2 ± 15.1
Cross-modal	$62.8 \pm 30.3^*$	$62.6 \pm 29.3^*$	76.5 +23.8

Algorithm S1 Training procedures.

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Input: A set of multimodal partially labeled datasets \{\mathcal{D}^{(i)}\} for training
Output: Trained segmentation network f_{seg}
 1: Construct a priori probabilistic atlas \alpha from training data
 2: Initialize f_{seg}, the pseudo-label refiner network f_{APRN}, the discriminator network
     f_{AMAN}, the prototype anchoring networks \{f_{MICPAM}^{(s)}\} (one for each feature scale), and the modal-invariant class prototypes \{\mathbb{A}^{(s)}\} randomly
 3: for number of epochs do
          for number of mini-batches do
 4:
              p, \{\mathbf{F}^{(s)}\} \leftarrow f_{seg}(x)
                                                             \triangleright forward input image x through the main
 5:
     segmentation network
 6:
               \hat{y} \leftarrow f_{APRN}(p_{\mathbb{C} \setminus \mathcal{C}}, \alpha_{\mathbb{C} \setminus \mathcal{C}})
                                                             ▷ refine pseudo-labels for unlabeled organs
               Update \{\mathbb{A}^{(s)}\} via Eqn. (2) and EMA
 7:
               for s \in all feature scales do Attn<sup>(s)</sup> \leftarrow f_{MICPAM}^{(s)}(\mathbf{F^{(s)}}, \mathbb{A}^{(s)})
 8:
 9:
                                                                                                           ⊳ Eqn. (3)
               end for
10:
               Update f_{APRN} to optimize \mathcal{L}_{APRN}
11:
               Update f_{seg}, \{f_{MICPAM}^{(s)}\} to optimize Eqn. (4)
12:
13:
               Update f_{AMAN} to optimize \mathcal{L}_D in Eqn. (1)
14:
          end for
15: end for
```

Table S3. Multimodal (CT and MRI) partially labeled abdominal multi-organ segmentation performance comparison with SOTA methods in DSC (mean \pm std%). "Intramodal" is the average performance of all organs labeled in the same modality as the test modality and vice versa for "cross-modal". The more challenging cross-modal evaluation results are highlighted with dark shading. Our framework achieves either the best or the second-best performance for 22 of the 26 organ-wise DSCs (and for 13 of 13 cross-modal organ-wise DSCs). *: p < 0.05 for pairwise comparison with our method. IVC: inferior vena cava.

Label	0	Test modality: CT										
modality	Organ	Single	MH-Net [4]	Cond-Dec [6]	DoDNet [38]	DAR-UNet [35]	PaNN [40]	$U^{2}PL$ [31]	VAT [22]	PCL [1]	UniSeg [36]	Ours
	Liver	92.9±8.6*	90.7±7.7*	94.3±7.4*	94.8±7.7	93.2±9.4*	88.0±15.5*	95.0±6.3*	93.8±8.9*	94.2±10.1*	81.6±22.7*	95.4 ± 4.6
	Stomach	$77.5\!\pm\!22.1^*$	$72.6\pm18.9^{*}$	$77.1\pm25.0^{\circ}$	$73.4\pm27.0^{\circ}$	$73.1\pm20.6^{*}$	$69.7 \pm 24.7^{\circ}$	79.1 ± 20.6 *	79.3 ± 20.9 *	79.3 ± 21.4 *	$79.2\pm20.3^{*}$	81.2 ± 22.3
	Aorta	$90.3\pm8.1^{\circ}$	92.5 ± 5.0	92.5 ± 4.6	93.0 ± 4.4	$89.5\pm6.1^{\circ}$	$89.4 \pm 4.5^{\circ}$	$91.1 \pm 4.5.7^{\circ}$	$90.8 \pm 5.5^{\circ}$	$90.6\pm7.3^{\circ}$	$92.7 \pm 5.0^{\circ}$	92.2 ± 5.3
CT	Esophagus	$73.1\!\pm\!14.9^*$	$71.1\pm11.2^{*}$	$74.3\pm18.1^{\circ}$	77.9 ± 15.7	$72.9\pm13.3^{*}$	$72.5\pm14.6^{\circ}$	$75.4\pm14.6^{\circ}$	$74.3\pm12.1^{\circ}$	$75.8\pm17.2^{\circ}$	$77.3\pm16.4^{\circ}$	77.6 ± 14.2
01	IVC	$86.0 \pm 9.4^{\circ}$	87.1 ± 8.7	87.8 ± 6.7	87.9 ± 7.2	82.4±10.6*	$82.5\pm7.8^{\circ}$	$85.6\pm6.5^{\circ}$	$86.0 \pm 8.7^{\circ}$	$86.4\pm7.4^{\circ}$	87.1±7.4*	86.9 ± 7.2
	Right adrenal	$72.4 \pm 11.6^{\circ}$	$70.5\pm12.8^{\circ}$	71.7 ± 13.9	72.0 ± 12.7	$69.9\pm12.2^{*}$	$65.8 \pm 17.5^{\circ}$	$70.1 \pm 15.0^{\circ}$	$71.4\pm11.5^{\circ}$	$71.9\pm12.6^{\circ}$	$74.2 \pm 10.8^{\circ}$	72.6 ± 10.0
	Left adrenal	$66.8 \pm 19.5^{\circ}$	$66.8 \pm 19.7^{\circ}$	68.0 ± 21.2	67.8 ± 21.1	$65.3\pm19.5^{\circ}$	$66.6 \pm 20.7^{\circ}$	$66.1 \pm 20.7^{\circ}$	$66.3\pm21.5^{\circ}$	$66.8 \pm 21.8^{\circ}$	$69.8 \pm 21.4^{\circ}$	67.2 ± 20.3
	Duodenum	70.8 ± 16.2 *	$64.1 \pm 17.6^{\circ}$	65.9 ± 18.8 *	71.9 ± 15.4	66.8±19.2*	$63.2 \pm 16.3^{\circ}$	$66.6 \pm 19.3^{\circ}$	$71.1 \pm 15.6^{\circ}$	$71.4\pm14.5^{\circ}$	$73.1 \pm 13.3^{\circ}$	72.3 ± 14.4
	Spleen	$46.8 \pm 30.5^{*}$	$0.0\pm0.0^{*}$	$35.5\pm30.2^{*}$	$0.0\pm0.0^{*}$	76.6 ± 15.8	$70.7 \pm 4.6^{\circ}$	76.1 ± 15.3	71.9 ± 17.4	$84.2 \pm 10.7^{\circ}$	$85.4 \pm 11.6^{\circ}$	90.2 ± 6.3
	Right kidney	28.6 ± 26.9 *	$0.0\pm0.0^{*}$	24.3±24.1*	$0.0\pm0.0^{*}$	79.9 ± 12.1	$80.7 \pm 13.4^{\circ}$	$67.3 \pm 17.1^{\circ}$	73.3 ± 16.7	$74.4 \pm 11.8^{\circ}$	$72.7 \pm 12.7^{\circ}$	89.8 ± 5.7
MRI	Left kidney	$23.7 \pm 32.5^{\circ}$	$0.0\pm0.0^{*}$	$16.1\pm19.3^{*}$	$0.0\pm0.0^{*}$	69.3 ± 18.9	$23.8{\pm}16.4^{*}$	$65.0{\pm}23.0$	67.6 ± 19.9	$76.1 \!\pm\! 21.0^*$	$75.0\pm23.3^{*}$	$82.9 {\pm} 16.0$
	Gallbladder	$13.6 \pm 19.2^{*}$	$0.0\pm0.0^{*}$	$0.0\pm0.0^{*}$	$0.0\pm0.0^{*}$	67.3 ± 27.6	$60.9 \pm 21.7^{\circ}$	65.9 ± 22.1	57.2 ± 24.9	$63.1 \!\pm\! 25.5^*$	$64.5{\pm}25.5^{*}$	$69.2 {\pm} 17.8$
	Pancreas	$13.2 \pm 21.9^*$	$16.7 \pm 11.2^{\circ}$	$0.0\pm0.0^{*}$	$0.0\pm0.0^{\circ}$	58.2±20.6*	$64.3{\pm}16.4^{*}$	$61.2 \pm 18.9^{\circ}$	$62.7 \pm 19.6^{\circ}$	$67.0 \pm 21.9^{\circ}$	$67.2 \pm 15.0^{\circ}$	74.7 ± 10.7
	Intramodal	78.8±17.5*	76.9±18.1*	79.0±19.2*	79.8 ± 18.5	76.6±18.7*	74.7±19.1*	78.6±18.1*	79.1±17.9*	79.6±17.2*	79.4±17.4*	80.6 ± 16.7
	Cross-modal	$25.2{\pm}13.3^{*}$	$3.3\pm8.4^{*}$	$15.2\pm23.8^{*}$	$0.0\pm0.0^{*}$	70.3±23.0*		$67.1 {\pm} 20.1^*$	$66.5 \pm 21.1^{\circ}$	$72.9\pm19.4^{*}$	$73.0\pm25.3^{*}$	81.4 ± 14.9
						Test modality:						
	Liver		$15.3\pm16.8^{\circ}$	$36.6\pm15.3^{\circ}$	$0.1\pm0.1^{\circ}$	85.1±9.6*	$79.9\pm7.9^{\circ}$			$89.9 \pm 4.8^{\circ}$	$89.5\pm5.6^{\circ}$	92.0 ± 2.4
	Stomach		$20.9\pm19.9^{*}$	$19.4\pm18.4^{\circ}$	$2.0\pm3.4^{\circ}$	55.0 ± 19.9						69.1 ± 17.4
	Aorta		$28.0\pm22.5^{\circ}$	$26.9\pm19.2^{\circ}$	$15.5\pm17.3^{\circ}$	58.1±25.6*						85.9 ± 6.6
CT		$29.4 \pm 26.0^{\circ}$		$0.0\pm0.0^{*}$	$0.7\pm1.8^{\circ}$	30.5 ± 19.5					$46.0\pm25.8^{\circ}$	
	IVC		$12.5\pm11.7^{\circ}$	$4.5\pm6.7^{\circ}$	$0.0\pm0.1^{\circ}$	61.2±19.3*					$63.5\pm11.6^{\circ}$	79.2 ± 10.7
	Right adrenal			$0.2\pm0.7^{*}$	$0.0\pm0.0^{\circ}$	$49.7\pm19.2^{*}$						51.0 ± 13.4
	Left adrenal		$4.3\pm2.7^{\circ}$	$2.2\pm4.1^{\circ}$	$0.1\pm0.2^{\circ}$	42.9 ± 24.3	$35.8 \pm 23.3^{\circ}$	$43.5 \pm 17.7^{\circ}$	45.1 ± 23.8	$46.3 \pm 25.1^{\circ}$	$44.6\pm24.2^{\circ}$	
	Duodenum			$6.5\pm10.3^{\circ}$	0.9±1.9*	41.8±13.5	$29.5\pm12.5^{*}$	$36.0 \pm 16.0^{\circ}$	53.8 ± 15.5	$59.2 \pm 10.4^{\circ}$	$62.7 \pm 9.0^{\circ}$	60.6 ± 12.6
	Spleen	$93.5\pm3.9^{*}$		94.9±4.9	94.0±4.6	88.3±13.7*	$92.2 \pm 4.7^{\circ}$		91.2±3.1*		$94.7 \pm 2.7^{*}$	94.2 ± 2.1
	Right kidney	$91.8 \pm 5.7^{\circ}$	86.9 ± 14.8	93.2 ± 5.2	86.3 ± 18.7	$86.4\pm17.0^{\circ}$	$89.7\pm6.0^{\circ}$	90.0 ± 5.7	$90.6 \pm 5.9^{\circ}$	$90.4\pm6.5^{\circ}$	$91.1\pm6.0^{\circ}$	93.4 ± 3.8
MRI	Left kidney			89.0 ± 9.4	92.8 ± 3.8	$83.5\pm13.8^{\circ}$	$86.3\pm8.0^{\circ}$		$90.9 \pm 5.3^{*}$		$91.5\pm5.7^{\circ}$	92.3 ± 4.1
	Gallbladder			58.5 ± 28.9	55.6 ± 38.7	$59.2\pm30.2^{*}$	$55.2 \pm 30.2^*$				$58.3 \pm 36.5^{\circ}$	69.1 ± 31.0
			$69.8 \pm 10.1^{\circ}$	$70.8\pm10.3^{*}$	79.5 ± 4.2	$62.6\pm17.0^{\circ}$		$64.2 \pm 20.4^{\circ}$			$80.0\pm6.2^{*}$	81.3 ± 3.2
	Intramodal	79.4±23.3*	$76.9\pm25.8^{\circ}$	81.2±20.4*	81.6±24.0*	76.0±24.3*	$78.5\pm20.5^{\circ}$	79.3±21.0*	81.2±19.7*	80.8±21.0*	$83.1 \pm 21.7^{\circ}$	86.1 ± 17.2
	Cross-modal	$36.2 \pm 24.7^{*}$	12.4±18.1*	12.0±17.5*	$2.4\pm8.0^{*}$	53.0±23.4*	$51.7 \pm 26.3^{\circ}$	$57.7 \pm 24.8^{\circ}$	$54.2 \pm 25.7^{\circ}$	$57.1 \pm 24.5^{\circ}$	$57.5 \pm 19.3^{\circ}$	67.8 ± 21.5