Topology-Preserving Hard Pixel Mining for Tubular Structure Segmentation

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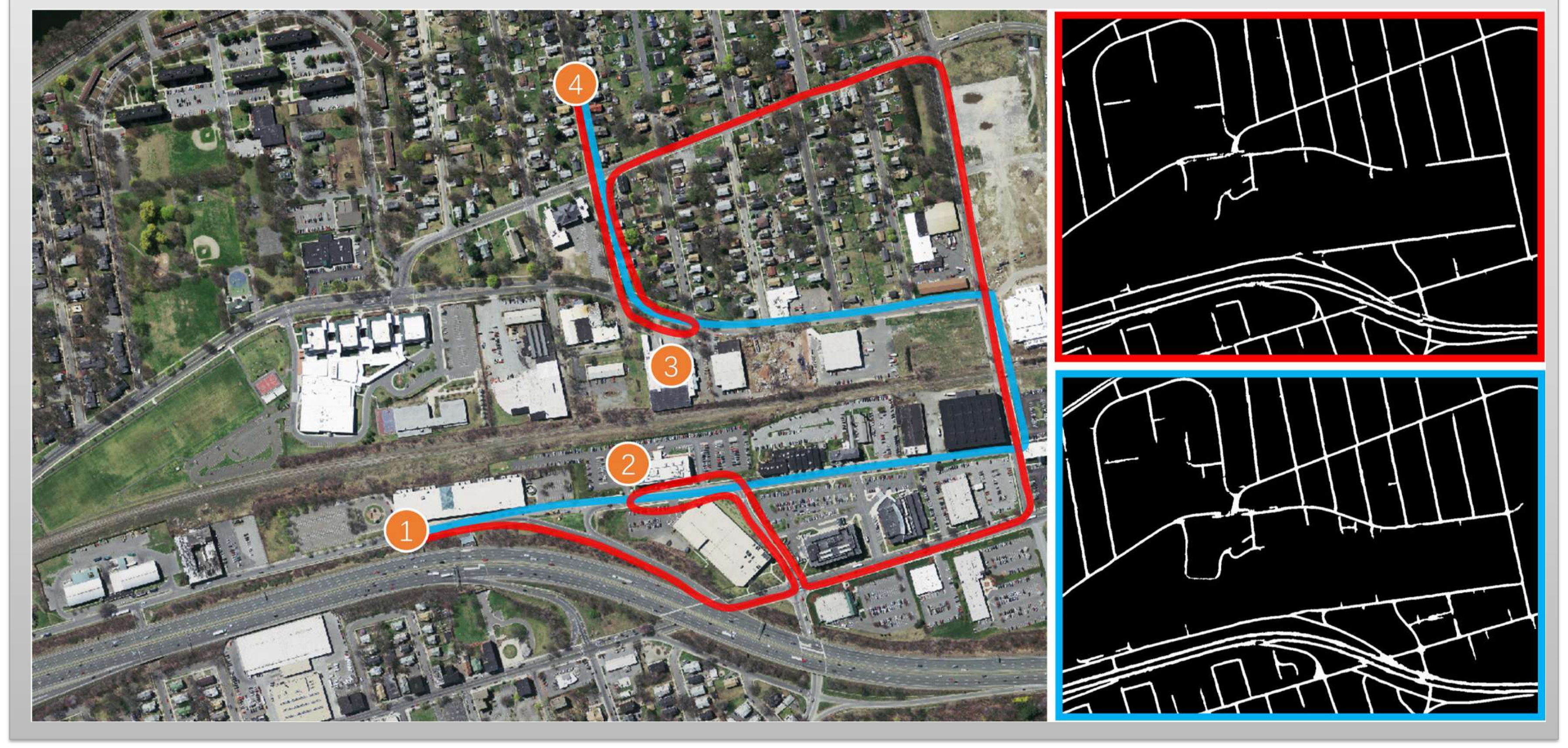
Motivation

Topologically accurate segmentation of tubular structures is crucial in many applications, eg. map reconstruction.

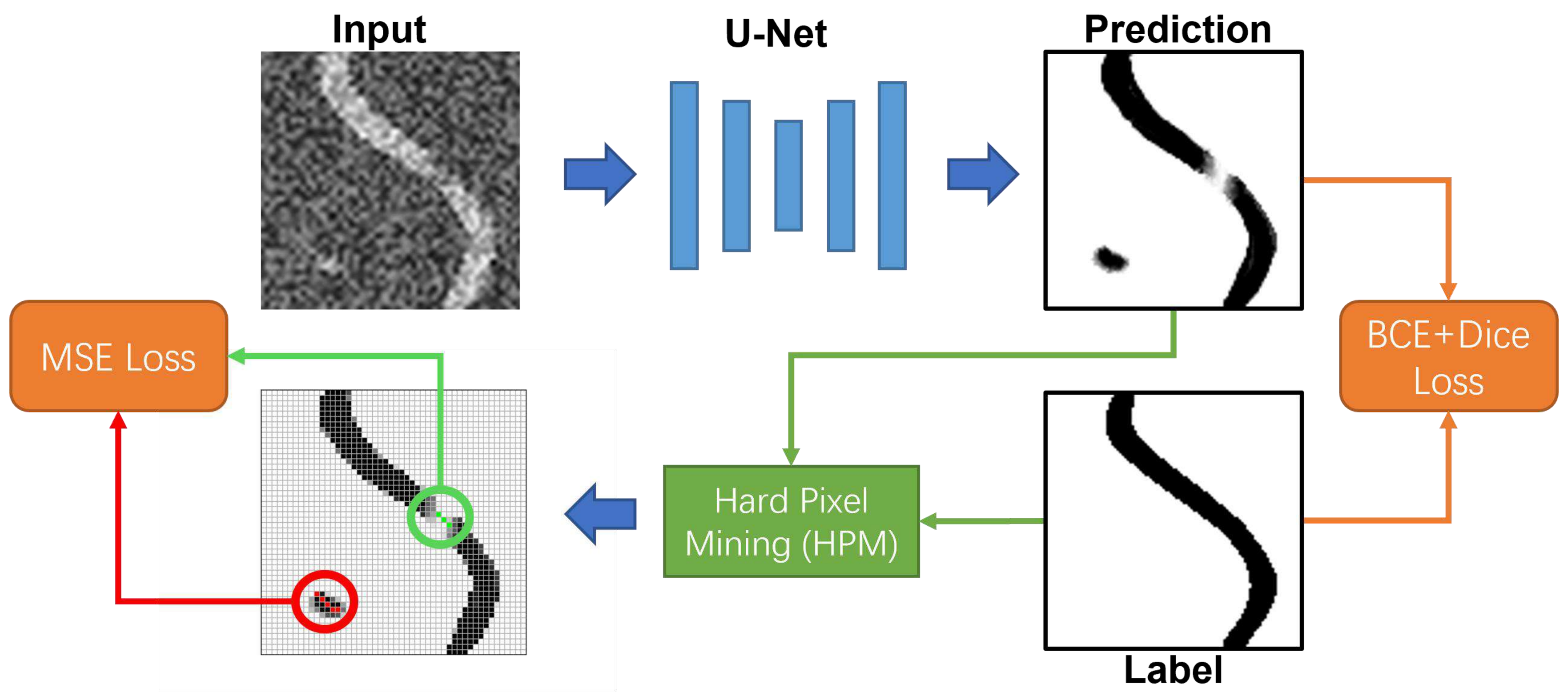


Challenges

- **How to preserve topological information in tubular structure segmentation.**
  - Find the most topology-relevant hard pixels
- **How to efficiently extract topologically critical points.**
  - Skeleton-based hard pixel mining

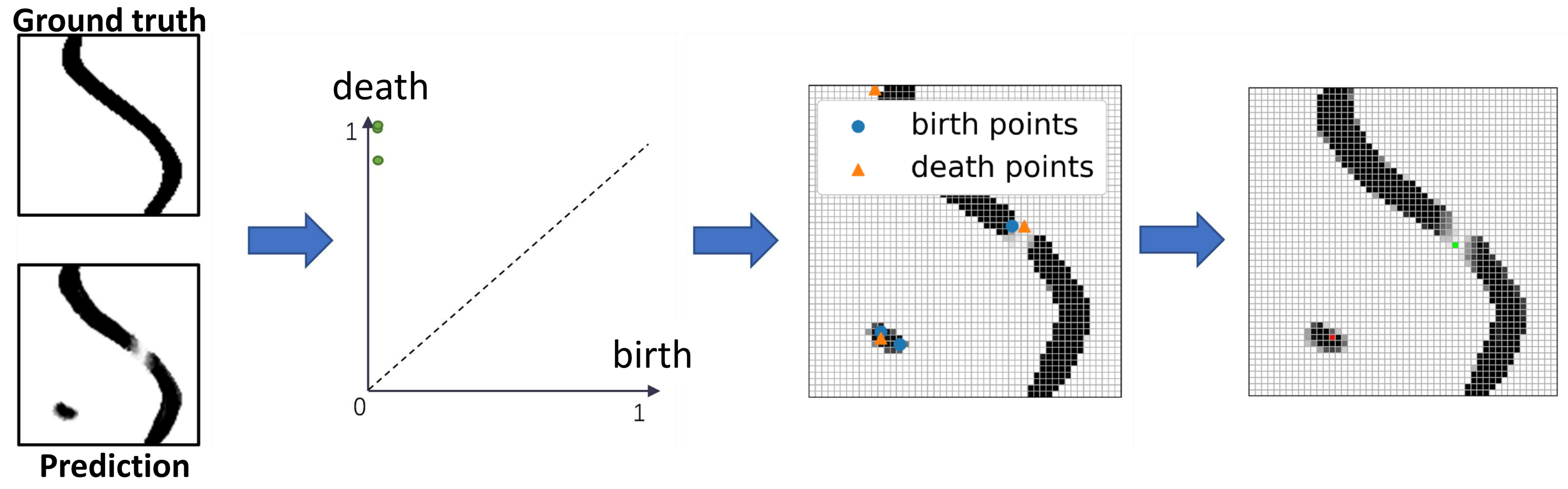
Overview

- We propose to use hard pixel mining (HPM) in image segmentation model for topology preservation.
- We propose persistent homology-based approach and skeleton-based approach for topology-relevant hard pixel mining.

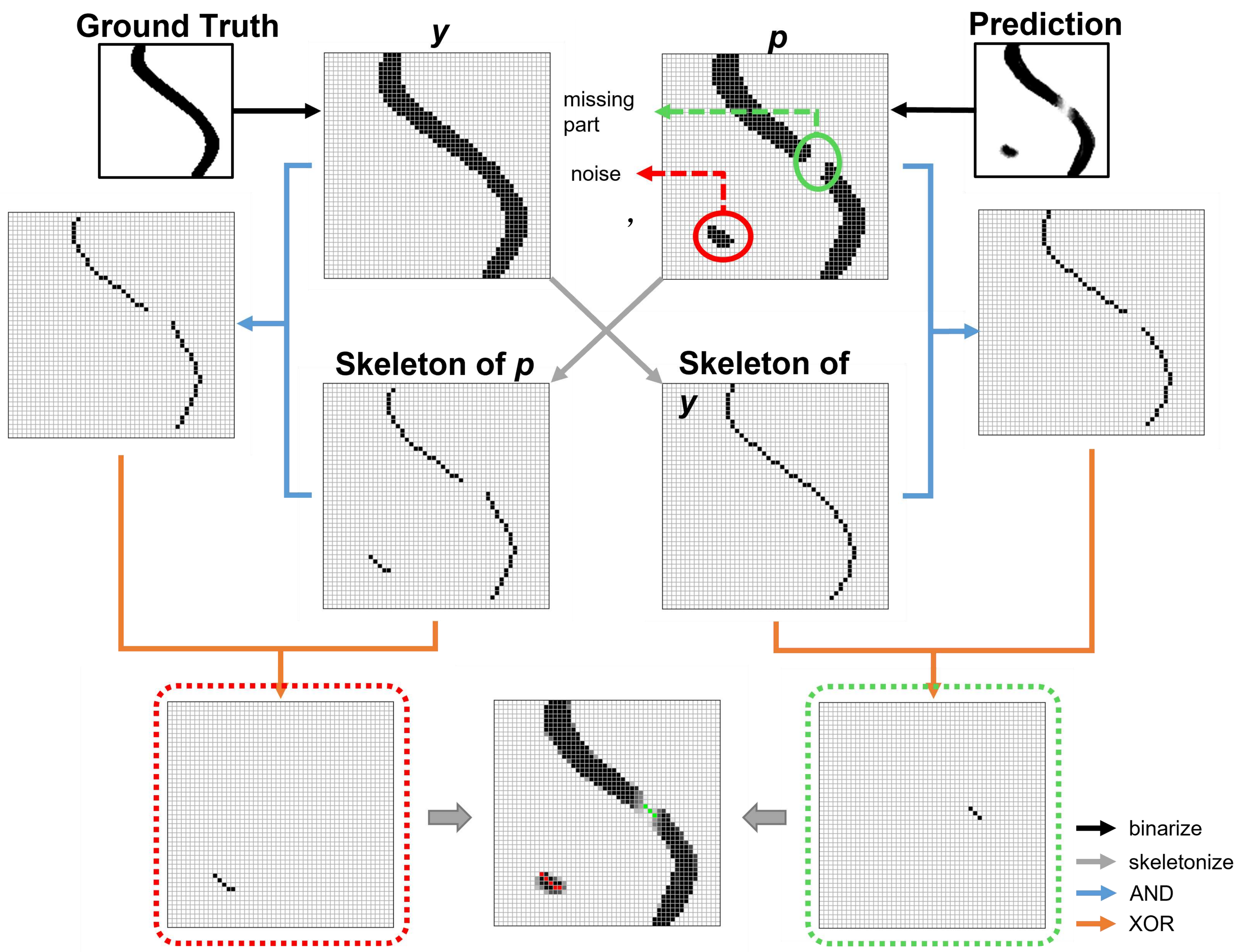


Proposed Methods

Persistent homology-based HPM (PHPM): All critical points are considered as hard pixels.

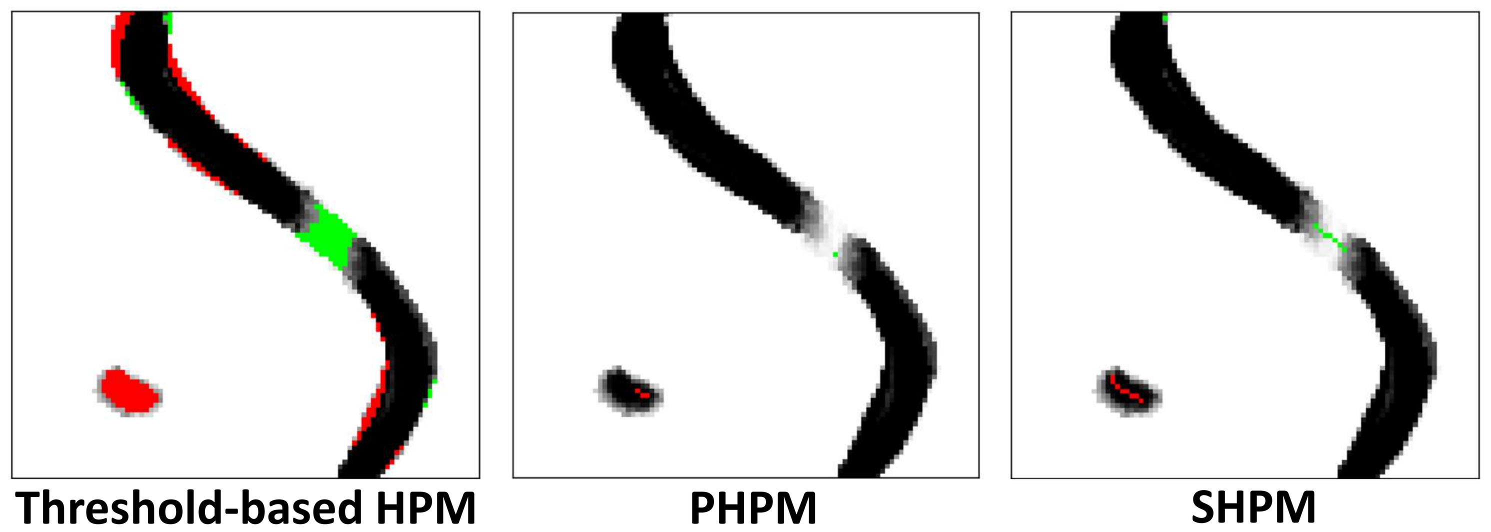


Skeleton-based HPM (SHPM): Thinned structures of the mis-segmented parts are considered as hard pixels.



SHPM is implemented through several simple logical and morphological operations.

Comparison: extracted hard pixels through different HPM strategies.



Experiments

Quantitative results

Dataset	Method	Dice	ARE	β-0 Error	β-1 Error
CREMI-A	U-Net	0.9145	0.2337	2.176	23.960
	U-Net + clDice	**0.9148**	0.2310	2.200	23.552
	U-Net + THPM	0.9007	0.1076	2.016	8.960
	U-Net + PHPM	0.9133	0.2060	2.112	20.352
	U-Net + SHPM	0.9106	**0.1042**	**1.648**	**7.240**
Roads	U-Net	0.7317	0.3191	9.671	28.116
	U-Net + clDice	0.7307	0.3460	9.759	29.676
	U-Net + THPM	0.7242	0.2501	9.062	22.096
	U-Net + PHPM	0.7295	0.3372	8.826	29.232
	U-Net + SHPM	**0.7331**	**0.2381**	**7.510**	**20.332**
ICAS-d (3D)	U-Net	0.6129	0.0011	5.410	0.000
	U-Net + clDice	0.5867	0.0012	6.440	0.000
	U-Net + THPM	0.6115	0.0011	5.290	0.000
	U-Net + PHPM	0.6059	0.0012	**4.590**	0.000
	U-Net + SHPM	**0.6316**	**0.0011**	4.740	0.000

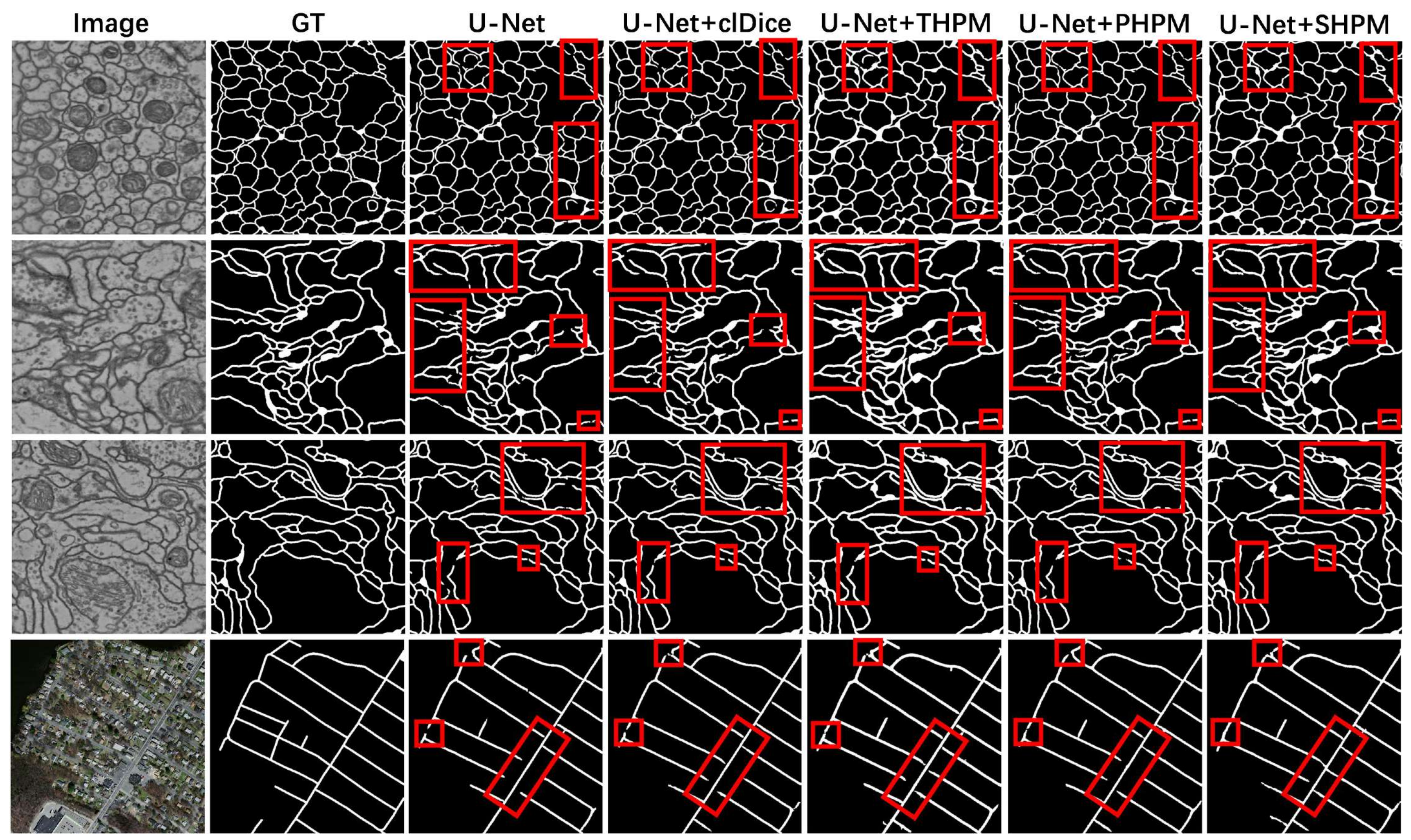
- SPHM demonstrates high superiority on topology-aware metrics while maintaining competitive volumetric accuracy.

Model training time for 100 iterations (s)

	2D Patch (256×256)	3D Patch ($128 \times 128 \times 72$)
U-Net	1.61	24.21
U-Net + clDice	2.22	27.40
U-Net + THPM	1.65	24.33
U-Net + PHPM	11.83	718.59
U-Net + SHPM	1.78	26.73

- SHPM has a training speed comparable to original U-Net and is more efficient than PHPM.

Qualitative results on 2D images



- The predictions by SPHM have more consistent topology.