



GraphMorph: Tubular Structure Extraction by Morphing Predicted Graphs

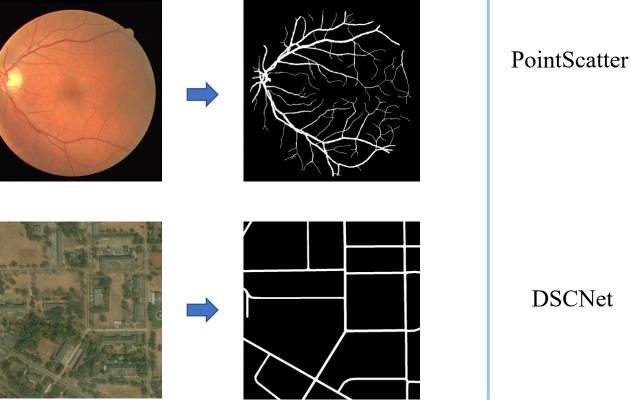
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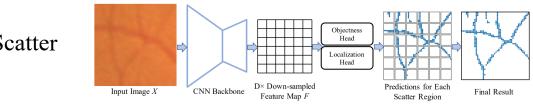
NeurIPS 2024

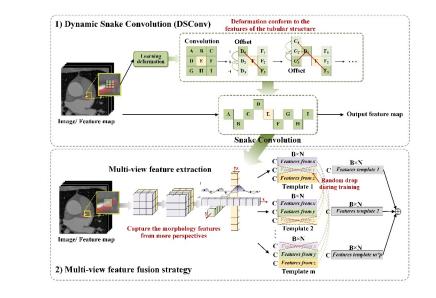




Tubular Structure Extraction





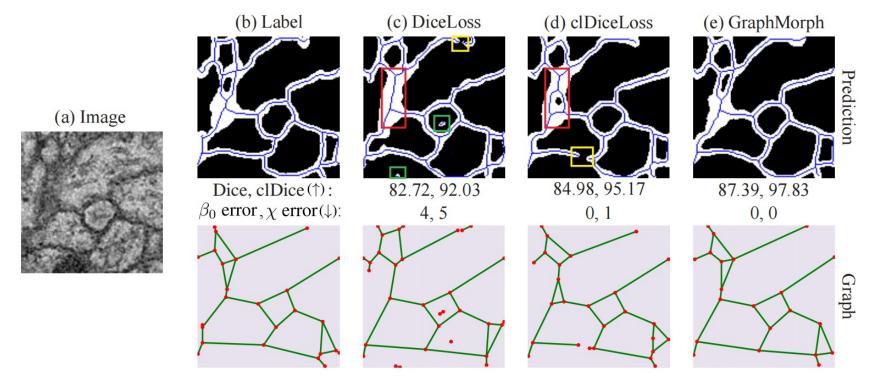






Motivation & Introdution

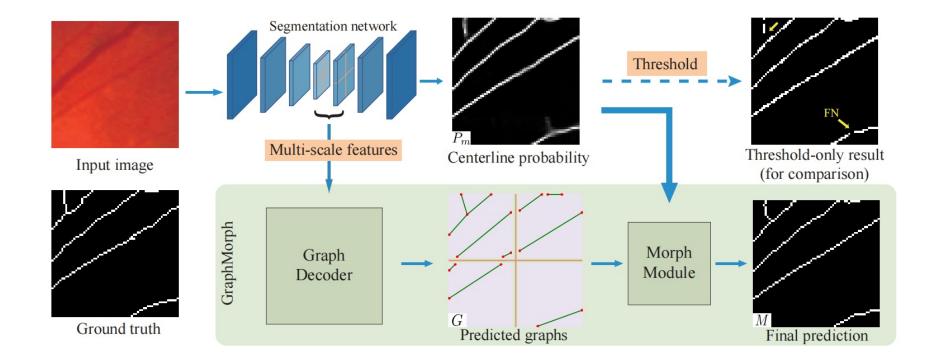
Branch-level features are more essential for accurately capturing the nuances of tubular structures!







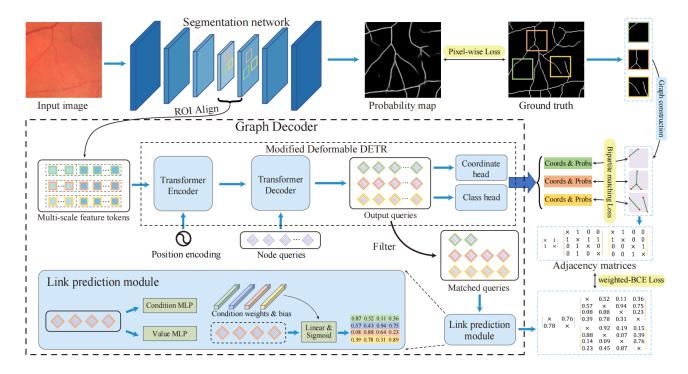
Overview of GraphMorph







Graph Decoder



Loss functions

$$\mathcal{L}_{\text{Hungarian}}(y, \hat{y}) = \sum_{r=1}^{R} \sum_{i=1}^{K} \left[\lambda_{\text{class}} \cdot \mathcal{L}_{\text{focal}}(\hat{s}_{\hat{\sigma}(i)}^{r}, c_{i}^{r}) + \lambda_{\text{coord}} \cdot \mathbb{1}_{\left\{c_{i}^{r} \neq \varnothing\right\}} \mathcal{L}_{\text{coord}}\left(\hat{v}_{\hat{\sigma}(i)}^{r}, v_{i}^{r}\right) \right]$$
$$\mathcal{L}_{\text{Adjacency}}(y, \hat{y}) = \sum_{r=1}^{R} \left\{ \frac{0.5}{N_{\text{pos}}} \sum_{i \neq j}^{P_{r}} \sum_{j=1}^{P_{r}} (A_{ij}^{r} \log \tilde{A}_{ij}^{r}) + \frac{0.5}{N_{\text{neg}}} \sum_{i \neq j}^{P_{r}} \sum_{j=1}^{P_{r}} [(1 - A_{ij}^{r}) \log(1 - \tilde{A}_{ij}^{r})] \right\}$$





Morph Module

Algorithm 1 Morph Module

Input: Node set V, Edge set E, Probability map P_m **Output:** Centerline mask M Initialize M as a zero matrix with the same size as P_m Initialize C_m where $C_m[i][j] = 1 - P_m[i][j]$ for each element for all edges (u, v) in E do $path \leftarrow$ SkeletonDijkstra (u, v, C_m, p_{thresh}) for all points p in path do Set M[p.x][p.y] = 1end for return M

Algorithm 2 SkeletonDijkstra Algorithm

```
Input: Start point s, End point e, Cost map C, Path threshold p_{thresh}
Output: Minimum cost path from s to e under threshold p_{thresh}
  Initialize priority queue Q with (0, [s])
  Initialize visited set Vis
  while not Q empty do
     (cost, path) \leftarrow Q.pop()
     curr \leftarrow last element of path
     Add curr to V is
     if curr = e then
       avg \leftarrow cost / \text{length}(path)
       if avg > p_{thresh} then
           return Ø
        end if
        return path
     end if
     for each n in neighbors of curr do
       if n in Vis then
           continue
        end if
       neis_in_path \leftarrow \text{count of } n's neighbors in path
       if neis_in_path \le 1 then
          path \leftarrow path concatenated with [n]
          cost \leftarrow cost + C[n.x][n.y]
          Q.push((cost, path))
        end if
     end for
  end while
```





Evaluation

Datasets

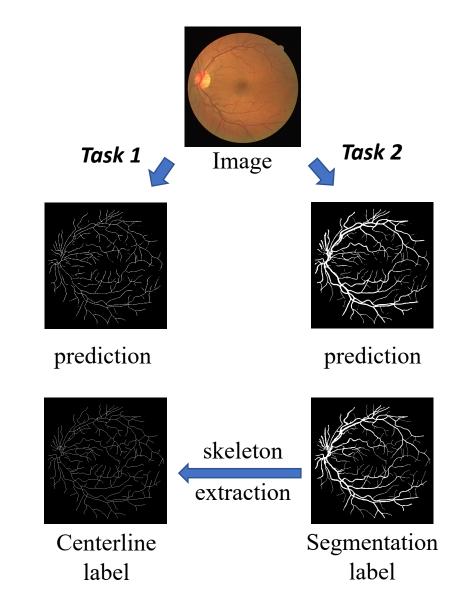
- Medical datasets: DRIVE, STARE and ISBI12
- Satellite dataset: Massachusetts Roads

Tasks

- Centerline extraction (Task 1)
- > Tubular structure segmentation (Task 2)

Metrics

- Volumetric metrics: Dice, Accuracy, AUC, clDice, etc.
- > **Topology-based metrics:** β_{0error} , β_{1error} , χ_{error}







Centerline extraction

- Graph Decoder during training enables the network to learn branch-level features, leading to enhanced performance in both volumetric and topological metrics.
- The combined use of Graph Decoder and Morph Module showcases the ability to preserve the crucial topological characteristics.

Dataset	Method	V	olumetric metrics (↑)	Topological metrics (\downarrow)			
Dutuset		Dice	AUC	ACC	β_0 error	β_1 error	χ error	
DRIVE	softDice 26 PointScatter 40 softDice 26 + Graph Decoder softDice 26 + Graph Decoder + Morph Module	$\begin{array}{c} 0.7353 \pm 0.0127 \\ 0.7381 \pm 0.0133 \\ \textbf{0.7506} \pm \textbf{0.0127} \\ 0.7496 \pm 0.0118 \end{array}$	0.9333 ± 0.0089 0.9401 ± 0.0078 0.9481 ± 0.0082 /	$\begin{array}{c} 0.9768 \pm 0.0013 \\ 0.9775 \pm 0.0013 \\ \textbf{0.9783} \pm \textbf{0.0012} \\ 0.9776 \pm 0.0012 \end{array}$	$\begin{array}{c} 2.169 \pm 0.112 \\ 3.259 \pm 0.153 \\ 1.552 \pm 0.094 \\ \textbf{0.555 \pm 0.038} \end{array}$	$\begin{array}{c} 1.590 \pm 0.107 \\ 2.080 \pm 0.120 \\ 1.382 \pm 0.106 \\ \textbf{1.074 \pm 0.073} \end{array}$	$\begin{array}{c} 2.537 \pm 0.139 \\ 3.500 \pm 0.176 \\ 1.899 \pm 0.125 \\ \textbf{0.893 \pm 0.061} \end{array}$	
ISBI12	softDice 26 Pointscatter 40 softDice 26 + Graph Decoder softDice 26 + Graph Decoder + Morph Module	$\begin{array}{c} 0.6428 \pm 0.0104 \\ 0.6546 \pm 0.0089 \\ 0.6486 \pm 0.0095 \\ \textbf{0.6687 \pm 0.0092} \end{array}$	0.8937 ± 0.0063 0.9104 ± 0.0057 0.9240 ± 0.0061 /	$\begin{array}{c} 0.9737 \pm 0.0013 \\ \textbf{0.9747} \pm \textbf{0.0013} \\ 0.9742 \pm 0.0012 \\ 0.9742 \pm 0.0014 \end{array}$	$\begin{array}{c} 4.045 \pm 0.191 \\ 6.398 \pm 0.277 \\ 4.013 \pm 0.179 \\ \textbf{0.665 \pm 0.049} \end{array}$	$2.696 \pm 0.112 3.156 \pm 0.124 2.732 \pm 0.110 1.207 \pm 0.070$	$\begin{array}{c} 4.294 \pm 0.205 \\ 6.548 \pm 0.290 \\ 4.249 \pm 0.193 \\ \textbf{0.858} \pm \textbf{0.059} \end{array}$	
STARE	softDice 26 Pointscatter 40 softDice 26 + Graph Decoder softDice 26 + Graph Decoder + Morph Module	$\begin{array}{c} 0.7119 \pm 0.0392 \\ 0.7224 \pm 0.0414 \\ \textbf{0.7298} \pm \textbf{0.0428} \\ 0.7291 \pm 0.0387 \end{array}$	0.9290 ± 0.0283 0.9494 ± 0.0179 0.9506 ± 0.0208 /	$\begin{array}{c} 0.9889 \pm 0.0012 \\ 0.9896 \pm 0.0012 \\ \textbf{0.9898} \pm \textbf{0.0011} \\ 0.9898 \pm \textbf{0.0011} \\ 0.9894 \pm 0.0011 \end{array}$	$\begin{array}{c} 1.874 \pm 0.139 \\ 2.080 \pm 0.149 \\ 1.467 \pm 0.113 \\ \textbf{0.482 \pm 0.042} \end{array}$	$\begin{array}{c} 1.209 \pm 0.112 \\ 1.365 \pm 0.116 \\ 1.074 \pm 0.104 \\ \textbf{0.799 \pm 0.077} \end{array}$	$2.063 \pm 0.162 2.213 \pm 0.166 1.654 \pm 0.132 0.653 \pm 0.059$	
MassRoad	softDice 26 Pointscatter 40 softDice 26 + Graph Decoder softDice 26 + Graph Decoder + Morph Module	$\begin{array}{c} 0.6339 \pm 0.0169 \\ \textbf{0.6405} \pm \textbf{0.0149} \\ 0.6289 \pm 0.0175 \\ 0.6388 \pm 0.0168 \end{array}$	0.9718 ± 0.0047 0.9694 ± 0.0042 0.9731 ± 0.0045 /	$\begin{array}{l} \textbf{0.9942} \pm \textbf{0.0009} \\ \textbf{0.9942} \pm \textbf{0.0009} \\ \textbf{0.9941} \pm \textbf{0.0009} \\ \textbf{0.9942} \pm \textbf{0.0009} \end{array}$	$\begin{array}{c} 1.672 \pm 0.056 \\ 3.333 \pm 0.124 \\ 1.933 \pm 0.065 \\ \textbf{0.620} \pm \textbf{0.021} \end{array}$	$\begin{array}{c} 1.627 \pm 0.087 \\ 1.553 \pm 0.086 \\ 1.729 \pm 0.088 \\ \textbf{1.355 \pm 0.083} \end{array}$	$\begin{array}{c} 1.968 \pm 0.097 \\ 3.429 \pm 0.149 \\ 2.229 \pm 0.105 \\ \textbf{1.122 \pm 0.075} \end{array}$	

Table 1: Centerline extraction	performance on four	public datasets based	on UNet.
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Centerline extraction

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Dataset	Method	V	olumetric metrics (↑)	Topological metrics (\downarrow)			
		Dice	AUC	ACC	β_0 error	β_1 error	χ error	
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ISBI12	softDice [26]	$\begin{array}{c} 0.6428 \pm 0.0104 \\ 0.6546 \pm 0.0089 \\ 0.6486 \pm 0.0095 \\ \textbf{0.6687 \pm 0.0092} \end{array}$	0.8937 ± 0.0063 0.9104 ± 0.0057 0.9240 ± 0.0061 /	$\begin{array}{c} 0.9737 \pm 0.0013 \\ \textbf{0.9747} \pm \textbf{0.0013} \\ 0.9742 \pm 0.0012 \\ 0.9742 \pm 0.0014 \end{array}$	$\begin{array}{c} 4.045 \pm 0.191 \\ 6.398 \pm 0.277 \\ 4.013 \pm 0.179 \\ \textbf{0.665 \pm 0.049} \end{array}$	2.696 ± 0.112 3.156 ± 0.124 2.732 ± 0.110 1.207 ± 0.070	$\begin{array}{c} 4.294 \pm 0.205 \\ 6.548 \pm 0.290 \\ 4.249 \pm 0.193 \\ \textbf{0.858 \pm 0.059} \end{array}$	
STARE	softDice [26] Pointscatter [40] softDice [26] + Graph Decoder softDice [26] + Graph Decoder + Morph Module	$\begin{array}{c} 0.7119 \pm 0.0392 \\ 0.7224 \pm 0.0414 \\ \textbf{0.7298} \pm \textbf{0.0428} \\ 0.7291 \pm 0.0387 \end{array}$	0.9290 ± 0.0283 0.9494 ± 0.0179 0.9506 ± 0.0208 /	$\begin{array}{c} 0.9889 \pm 0.0012 \\ 0.9896 \pm 0.0012 \\ \textbf{0.9898} \pm \textbf{0.0011} \\ 0.9894 \pm 0.0011 \end{array}$	$\begin{array}{c} 1.874 \pm 0.139 \\ 2.080 \pm 0.149 \\ 1.467 \pm 0.113 \\ \textbf{0.482 \pm 0.042} \end{array}$	$\begin{array}{c} 1.209 \pm 0.112 \\ 1.365 \pm 0.116 \\ 1.074 \pm 0.104 \\ \textbf{0.799 \pm 0.077} \end{array}$	$2.063 \pm 0.162 2.213 \pm 0.166 1.654 \pm 0.132 0.653 \pm 0.059$	
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Table 1: Centerline extraction performance on four public datasets based on UNet.





Tubular structure segmentation

GraphMorph achieves best results across all methods thanks to the utilization of branch-level features.

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$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	Dataset	Backbone	Method	Volumetric metrics ([†])		Distribution metrics		Topological metrics (\downarrow)			
UNst UNst UNst UNst UNst Dc:User Dc:Use				Dice	clDice	ACC	ARI(↑)	$VOI(\downarrow)$	β_0 error	β_1 error	χ error
Unit Pointscatter fun 0.8155 ± 0.0081 0.8277 ± 0.0175 0.9232 ± 0.0020 0.766 ± 0.009 0.335 ± 0.010 1.360 ± 0.080 1.275 ± 0.083 1.663 ± 0.094 DRIVE within the construction of the											
DRIVE UNit TopoLoss [1] 0.8187±0.0075 0.8194±0.0160 0.9540±0.0020 0.771±0.009 0.352±0.011 0.821±0.050 0.997±0.072 1.110±0.0067 DSCNe [1] sofDice 0.8153±0.0094 0.8139±0.0182 0.9532±0.0021 0.754±0.010 0.354±0.011 1.267±0.075 1.110±0.0067 1.470±0.082 DC-UNet [2] sofDice 0.8153±0.0094 0.8139±0.0166 0.9557±0.0023 0.776±0.011 0.356±0.012 0.692±0.047 1.093±0.068 0.951±0.062 UNet clibice+Ours 0.8163±0.0076 0.8467±0.0146 0.9525±0.0073 0.776±0.019 0.356±0.012 0.692±0.047 0.932±0.068 0.951±0.0023 UNet clibice+Ours 0.8163±0.0070 0.935±0.0078 0.9146±0.0009 0.053±0.018 0.569±0.044 0.569±0.044 0.569±0.044 0.569±0.044 0.569±0.044 0.569±0.044 0.569±0.044 0.569±0.044 0.569±0.044 0.569±0.044 0.575±0.042 0.522±0.037 0.565±0.044 0.565±0.044 0.565±0.044 0.556±0.044 0.556±0.044 0.556±0.044 0.556±0.044 0.556±0.044 0.556±											1.181 ± 0.071
DRIVE DSCNet [3] softDice 0.8118 ± 0.0083 0.8107 ± 0.0172 0.0521 ± 0.0021 0.763 ± 0.010 0.352 ± 0.011 1.267 ± 0.075 1.110 ± 0.076 1.550 ± 0.087 TransUNEt [2] softDice 0.8139 ± 0.013 0.9533 ± 0.0024 0.768 ± 0.010 0.354 ± 0.011 1.267 ± 0.075 1.101 ± 0.076 1.450 ± 0.082 UNet softDice+Ours 0.8238 ± 0.0021 0.8278 ± 0.016 0.9557 ± 0.0023 0.778 ± 0.011 0.356 ± 0.012 0.692 ± 0.047 0.932 ± 0.065 0.957 ± 0.052 UNet softDice+Ours 0.8168 ± 0.0070 0.8467 ± 0.0144 0.9352 ± 0.0078 0.716 ± 0.0020 0.775 ± 0.042 0.452 ± 0.045 0.857 ± 0.045 0.875 ± 0.045 0.563 ± 0.018 0.758 ± 0.040 0.568 ± 0.041 0.568 ± 0.045 0.563 ± 0.045 0.563 ± 0.045 0.563 ± 0.045 0.563 ± 0.045 0.568 ± 0.041 0.568 ± 0.045 0.568 ± 0.041 0.568 ± 0.045 0.563 ± 0.047 0.575 ± 0.042 0.455 ± 0.045 0.563 ± 0.047 0.518 ± 0.041 0.568 ± 0.046 0.575 ± 0.043 0.518 ± 0.041 0.568 ± 0.046 0.575 ± 0.043 0.518 ± 0.041 0.518 ± 0.041				0.8155 ± 0.0081	0.8277 ± 0.0179	0.9525 ± 0.0020	0.766 ± 0.009		1.360 ± 0.080		1.663 ± 0.094
DSC.vet SoftDice 0.810 ± 0.0032 0.810 ± 0.0012 0.932 ± 0.0011 0.252 ± 0.011 1.257 ± 0.075 1.102 ± 0.076 1.250 ± 0.005 DC-UNet softDice 0.810 ± 0.013 0.810 ± 0.0163 0.953 ± 0.0021 0.768 ± 0.0101 0.324 ± 0.0061 1.247 ± 0.074 0.922 ± 0.008 1.252 ± 0.011 1.227 ± 0.074 1.061 ± 0.074 1.499 ± 0.087 UNet softDice 0.8108 ± 0.0076 0.8447 ± 0.0146 0.9552 ± 0.0021 0.776 ± 0.009 0.357 ± 0.012 0.619 ± 0.043 0.924 ± 0.065 0.875 ± 0.0021 0.619 ± 0.043 0.924 ± 0.065 0.875 ± 0.040 0.569 ± 0.046 0.616 ± 0.047 0.785 ± 0.040 0.569 ± 0.046 0.616 ± 0.047 0.785 ± 0.042 0.422 ± 0.025 0.605 ± 0.021 0.767 ± 0.020 0.755 ± 0.042 0.425 ± 0.042 0.425 ± 0.042 0.425 ± 0.042 0.425 ± 0.042 0.425 ± 0.042 0.425 ± 0.042 0.425 ± 0.042 0.425 ± 0.042 0.425 ± 0.042 0.425 ± 0.042 0.425 ± 0.042 0.425 ± 0.042 0.425 ± 0.041 0.564 ± 0.046 0.575 ± 0.043 0.564 ± 0.041 0.564 ± 0.042 0.575 ± 0.043 0.564 ± 0.042 0.755 ± 0.043	DRIVE									0.997 ± 0.072	1.100 ± 0.067
DC-UNE [2] softDice (Dice+Ours) (Dis 323 ± 0.009) 0.808 ± 0.0103 (Dis 20 ± 0.002) 0.760 ± 0.012 (Dis 1 ± 0.011 (Dis 20 ± 0.043 (Dis 2 ± 0.047 (Dis 1 ± 0.043 (Dis 2 ± 0.047 (Dis 2 ± 0.047 (Dis 1 ± 0.043 (Dis 2 ± 0.047	DRIVE	DSCNet 33	softDice		0.8107 ± 0.0172	0.9527 ± 0.0021	0.763 ± 0.010	0.352 ± 0.011	1.267 ± 0.075	1.110 ± 0.076	1.550 ± 0.087
UNAL softDice+Ours 0.8238 ± 0.0091 0.8278 ± 0.0166 0.9577 ± 0.0021 0.778 ± 0.011 0.336 ± 0.012 0.602 ± 0.043 0.924 ± 0.065 0.951 ± 0.062 UNet softDice Corr 0.8168 ± 0.0076 0.8467 ± 0.0146 0.9577 ± 0.008 0.767 ± 0.009 0.357 ± 0.012 0.619 ± 0.043 0.924 ± 0.065 0.659 ± 0.040 0.619 ± 0.043 0.924 ± 0.065 0.657 ± 0.020 0.775 ± 0.012 0.422 ± 0.038 0.563 ± 0.044 0.569 ± 0.046 0.616 ± 0.047 0.738 ± 0.042 0.456 ± 0.041 0.568 ± 0.046 0.576 ± 0.043 0.576 ± 0.043 0.577 ± 0.023 0.563 ± 0.041 0.564 ± 0.044 0.563 ± 0.047 0.576 ± 0.043 0.577 ± 0.033 0.563 ± 0.041 0.564 ± 0.049 0.576 ± 0.043 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.041 0.563 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047		TransUNet 4	softDice	0.8153 ± 0.0094	0.8139 ± 0.0182	0.9538 ± 0.0020	0.768 ± 0.010	0.344 ± 0.009	1.125 ± 0.066	1.184 ± 0.082	1.420 ± 0.082
UNct clDice+Ours 0.8168 ± 0.0076 0.8467 ± 0.0146 0.9520 ± 0.0021 0.767 ± 0.009 0.357 ± 0.012 0.6019 ± 0.043 0.924 ± 0.065 0.857 ± 0.055 UNct softDice C1 0.8043 ± 0.0099 0.9353 ± 0.0084 0.9163 ± 0.0064 0.6669 ± 0.020 0.758 ± 0.040 0.569 ± 0.046 0.564 ± 0.047 0.578 ± 0.047 UNct Pointscatter 10 0.810 ± 0.0099 0.9353 ± 0.0084 0.9163 ± 0.0064 0.6669 ± 0.029 0.775 ± 0.042 0.452 ± 0.018 0.563 ± 0.046 0.568 ± 0.046 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.047 0.578 ± 0.046 0.568 ± 0.046 0.588 ± 0.046 0.588 ± 0.		DC-UNet 22	softDice	0.8086 ± 0.0103	0.8018 ± 0.0163	0.9526 ± 0.0024	0.760 ± 0.012	0.351 ± 0.011	1.227 ± 0.074	1.061 ± 0.074	1.499 ± 0.087
UNet UNet softDice [20] clDice [10] 0.8043 \pm 0.0092 0.9295 \pm 0.0078 0.9146 \pm 0.0060 0.653 \pm 0.018 0.785 \pm 0.040 0.569 \pm 0.046 0.616 \pm 0.047 0.738 \pm 0.052 ISB112 UNet UNet Pointscatter [40] 0.8103 \pm 0.0099 0.9353 \pm 0.0084 0.9163 \pm 0.0063 0.672 \pm 0.020 0.775 \pm 0.042 0.456 \pm 0.044 0.568 \pm 0.046 0.563 \pm 0.045 0.576 \pm 0.043 UNet TopoLoss [12] os101bice 0.8192 ± 0.0101 0.9466 \pm 0.0077 0.9189 ± 0.0063 0.661 \pm 0.017 0.775 \pm 0.043 0.563 \pm 0.046 0.569 \pm 0.046 0.567 \pm 0.043 0.561 \pm 0.041 0.569 \pm 0.046 0.567 \pm 0.043 0.561 \pm 0.041 0.569 \pm 0.046 0.567 \pm 0.043 0.561 \pm 0.041			softDice+Ours	0.8238 ± 0.0091	0.8278 ± 0.0166	0.9557 ± 0.0023	0.778 ± 0.011	0.336 ± 0.012	0.692 ± 0.047	0.932 ± 0.068	
UNet clDice (2)/ topol.oss [14] 0.8103 ± 0.0099 0.9353 ± 0.0046 0.9663 ± 0.0020 0.775 ± 0.042 0.422 ± 0.038 0.563 ± 0.045 0.576 ± 0.043 ISB112 UNet Topol.oss [14] 0.8104 ± 0.0090 0.9324 ± 0.0074 0.9189 ± 0.0063 0.672 ± 0.020 0.775 ± 0.042 0.456 ± 0.041 0.568 ± 0.046 0.587 ± 0.043 DSCNet [33] softDice 0.8104 ± 0.0090 0.9324 ± 0.0074 0.9191 ± 0.0054 0.669 ± 0.016 0.775 ± 0.037 0.450 ± 0.049 0.556 ± 0.044 0.587 ± 0.044 0.587 ± 0.043 DC-UNet [22] softDice 0.8150 ± 0.0080 0.9289 ± 0.0075 0.9191 ± 0.0057 0.678 ± 0.016 0.784 ± 0.037 0.535 ± 0.043 0.556 ± 0.044 0.556 ± 0.044 0.556 ± 0.044 0.556 ± 0.043 0.558 ± 0.046 0.558 ± 0.046 0.558 ± 0.044 0.558 ± 0.046 0.558 ± 0.044 0.558 ± 0.044 0.558 ± 0.044 0.558 ± 0.044 0.558 ± 0.046 0.558 ± 0.044 0.558 ± 0.044 0.558 ± 0.044 0.558 ± 0.044 0.558 ± 0.044 0.558 ± 0.044 0.558 ± 0.046 0.558 ± 0.044 0.558 ± 0.044 0.558 ± 0.045 0.558 ± 0.045 0.558 ± 0.045		UNet	clDice+Ours	0.8168 ± 0.0076	0.8467 ± 0.0146	0.9520 ± 0.0021	0.767 ± 0.009	0.357 ± 0.012	0.619 ± 0.043	0.924 ± 0.065	0.857 ± 0.056
UNet UNet UNet Pointscatter (40) TopLoss (14) 0.819 ± 0.0101 0.9406 ± 0.0077 0.918 ± 0.0063 0.672 ± 0.020 0.778 ± 0.041 0.568 ± 0.044 0.588 ± 0.044 0.588 ± 0.044 0.568 ± 0.044 0.568 ± 0.044 0.568 ± 0.044 0.568 ± 0.044 0.567 ± 0.045 0.561 ± 0.017 0.773 ± 0.039 0.516 ± 0.041 0.567 ± 0.045 0.567 ± 0.047 0.577 ± 0.053 0.561 ± 0.014 0.567 ± 0.047 0.575 ± 0.053 0.516 ± 0.041 0.567 ± 0.047 0.575 ± 0.053 0.516 ± 0.041 0.575 ± 0.053 0.511 ± 0.043 0.575 ± 0.047 0.575 ± 0.053 0.586 ± 0.046 0.652 ± 0.047 0.575 ± 0.053 0.511 ± 0.043 0.521 ± 0.049 0.575 ± 0.053 0.586 ± 0.046 0.652 ± 0.043 0.448 ± 0.041 0.586 ± 0.046 0.652 ± 0.043 0.520 ± 0.043 0.520 ± 0.043 0.520 ± 0.043 0.530 ± 0.044 0.652 ± 0.043 0.530 ± 0.044 0.652 ± 0.043 0.530 ± 0.044 0.652 ± 0.043 0.530 ± 0.044 0.652 ± 0.043 0.530 ± 0.044 0.652 ± 0.043 0.530 ± 0.044 0.652 ± 0.043 0.530 ± 0.044 0.652 ± 0.043 0.530 ± 0.043 0.530 ± 0.043 0.530 ± 0.043 0.530 ± 0.043 0.530 ± 0.043 <td></td> <td></td> <td></td> <td>0.8043 ± 0.0092</td> <td>0.9295 ± 0.0078</td> <td>0.9146 ± 0.0060</td> <td>0.653 ± 0.018</td> <td>0.785 ± 0.040</td> <td>0.569 ± 0.046</td> <td>0.616 ± 0.047</td> <td>0.738 ± 0.052</td>				0.8043 ± 0.0092	0.9295 ± 0.0078	0.9146 ± 0.0060	0.653 ± 0.018	0.785 ± 0.040	0.569 ± 0.046	0.616 ± 0.047	0.738 ± 0.052
ISBI12 UNet DSCNet 13 TransUNet 14 DC-UNet 12 TopoLoss 12 softDice softDice DC-UNet 12 0.8104 ± 0.0097 softDice DC-UNet 12 0.8104 ± 0.0087 softDice DC-UNet 13 0.8104 ± 0.0087 softDice DC-UNet 13 0.8104 ± 0.0080 softDice DC-UNet 13 0.8171 ± 0.0420 softDice DC-UNet 12 0.8171 ± 0.0420 softDice DC-UNet 13 0.8171 ± 0.0420 softDice DC-UNet 13 0.8171 ± 0.0420 softDice DC-UNet 12 0.8171 ± 0.0420 softDice DC-UNet 12 0.8171 ± 0.0474 softDice DC-UNet 12 0.8171 ± 0.0474 softDice DC-UNet 12 0.8171 ± 0.0474 softDice DC-UNet 12 0.8171 ± 0.0474 softDice DC-UNet 12 0.8174 ± 0.0474 softDice DC-UNet 12 0.8174 ± 0.0474 softDice DC-UNet 12 0.8174 ± 0.0474 softDice DC-UNet 12 0.8174 ± 0.0474 softDice DC-UN		UNet	clDice 37	0.8103 ± 0.0099	0.9353 ± 0.0084	0.9163 ± 0.0064	0.660 ± 0.020	0.775 ± 0.042	0.422 ± 0.038	0.563 ± 0.045	0.576 ± 0.043
ISB112 DSCNet 13 (TransUNet 14) softDice softDice (0.8152 \pm 0.0087) 0.9366 \pm 0.0078 (0.9289 \pm 0.0075) 0.9191 \pm 0.0054 (0.9195 \pm 0.0056) 0.659 \pm 0.016 (0.757 \pm 0.037) 0.450 \pm 0.040 (0.757 \pm 0.047) 0.567 \pm 0.045 (0.757 \pm 0.057) 0.575 \pm 0.047 (0.757 \pm 0.057) 0.576 \pm 0.047 (0.757 \pm 0.057) 0.576 \pm 0.047 (0.757 \pm 0.057) 0.576 \pm 0.047 (0.575 \pm 0.047) 0.576 \pm 0.047 (0.757 \pm 0.057) 0.576 \pm 0.047 (0.575 \pm 0.047) 0.576 \pm 0.047 (0.757 \pm 0.057) 0.576 \pm 0.047 (0.552 \pm 0.047) 0.576 \pm 0.047 (0.757 \pm 0.057) 0.576 \pm 0.047 0.576 \pm 0.047 0.576 \pm 0.047 0.520 \pm 0.043 0.488 \pm 0.041 UNet cline+Ours 0.8216 \pm 0.0091 0.9499 \pm 0.0066 0.9719 \pm 0.0056 0.679 \pm 0.017 0.745 \pm 0.039 0.351 \pm 0.043 0.532 \pm 0.043 0.488 \pm 0.041 UNet cline 627 0.817 \pm 0.0386 0.8579 \pm 0.0319 0.9752 \pm 0.0041 0.785 \pm 0.041 0.535 \pm 0.043 0.532 \pm 0.068 0.633 \pm 0.072 0.906 \pm 0.079 UNet cline 433 softDice 0.817 \pm 0.0386 0.8579 \pm 0.0319 0.9752 \pm 0.0041 0.785 \pm 0.047 0.224 \pm 0.030 0.771 \pm 0.072 0.988 \pm 0.076				0.8192 ± 0.0101	0.9406 ± 0.0077	0.9189 ± 0.0063	0.672 ± 0.020	0.758 ± 0.042	0.456 ± 0.041		0.587 ± 0.047
Bit Note 1:1 SoftDice 0.815 ± 0.0080 0.936 ± 0.0078 0.9191 ± 0.0054 0.069 ± 0.016 0.75 ± 0.037 0.430 ± 0.043 0.567 ± 0.043 0.576 ± 0.044 0.576 ± 0.044 0.576 ± 0.044 0.576 ± 0.044 0.576 ± 0.044 0.576 ± 0.044 0.576 ± 0.044 0.576 ± 0.047 0.573 ± 0.043 0.571 ± 0.043 0.586 ± 0.046 0.652 ± 0.047 0.572 ± 0.043 0.521 ± 0.043 0.586 ± 0.046 0.652 ± 0.047 0.572 ± 0.043 0.532 ± 0.043 0.532 ± 0.043 0.532 ± 0.043 0.532 ± 0.043 0.532 ± 0.043 0.532 ± 0.043 0.532 ± 0.043 0.532 ± 0.043 0.532 ± 0.043 0.532 ± 0.043 0.532 ± 0.043 0.532 ± 0.044 0.652 ± 0.047 0.573 ± 0.043 0.532 ± 0.043 0.532 ± 0.044 0.532 ± 0.044 0.652 ± 0.041 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.014 0.532 ± 0.017 0.574 ± 0.017 0.744 ± 0.038 0.571 ± 0.017 0.743 ± 0.0	ISB112		TopoLoss 14		0.9324 ± 0.0074	0.9167 ± 0.0058	0.661 ± 0.017	0.773 ± 0.039	0.516 ± 0.041		0.669 ± 0.049
DC-UNet [22] softDice 0.8150 ± 0.0089 0.9366 ± 0.0084 0.9196 ± 0.0063 0.671 ± 0.019 0.753 ± 0.043 0.511 ± 0.043 0.558 ± 0.046 0.652 ± 0.047 UNet softDice+Ours 0.8216 ± 0.0091 0.9449 ± 0.0069 0.9211 ± 0.0057 0.678 ± 0.018 0.745 ± 0.039 0.361 ± 0.034 0.530 ± 0.043 0.530 ± 0.043 0.482 ± 0.040 UNet softDice+Ours 0.8223 ± 0.0086 0.9459 ± 0.0066 0.9719 ± 0.017 0.774 ± 0.033 0.786 ± 0.064 0.653 ± 0.072 0.960 ± 0.079 UNet clDice [27] 0.817 ± 0.0492 0.8526 ± 0.0306 0.9749 ± 0.0044 0.781 ± 0.042 0.276 ± 0.033 0.786 ± 0.064 0.653 ± 0.072 0.960 ± 0.079 UNet clDice [27] 0.817 ± 0.0395 0.853 ± 0.031 0.9754 ± 0.041 0.781 ± 0.041 0.786 ± 0.033 0.765 ± 0.033 0.765 ± 0.033 0.659 ± 0.050 0.717 ± 0.072 0.960 ± 0.079 UNet polLoss [14] 0.817 ± 0.0439 0.873 ± 0.045 0.781 ± 0.047 0.781 ± 0.047 0.767 ± 0.049 0.724 ± 0.033 0.679 ± 0.017 0.298 ± 0.036 0.777 ± 0.072 0.988	ISBI12			0.8152 ± 0.0087	0.9366 ± 0.0078	0.9191 ± 0.0054					0.581 ± 0.044
UNet UNet softDice+Ours clDice+Ours 0.8216 \pm 0.0091 0.8223 \pm 0.0086 0.9249 \pm 0.0069 0.9211 \pm 0.0057 0.678 \pm 0.018 0.779 \pm 0.017 0.754 \pm 0.039 0.774 \pm 0.018 0.520 \pm 0.043 0.535 \pm 0.034 0.520 \pm 0.043 0.535 \pm 0.043 0.488 \pm 0.041 0.482 \pm 0.040 UNet UNet UNet UNet UNet UNet UNet UNet				0.8056 ± 0.0080	0.9289 ± 0.0075	0.9148 ± 0.0055	0.654 ± 0.016			0.576 ± 0.047	0.757 ± 0.053
UNet clDice+Ours 0.8223 ± 0.0086 0.9459 ± 0.0066 0.9213 ± 0.0056 0.679 ± 0.017 0.744 ± 0.038 0.353 ± 0.034 0.539 ± 0.043 0.482 ± 0.040 UNet softDice [6] 0.8170 ± 0.0420 0.8526 ± 0.0366 0.9749 ± 0.0044 0.781 ± 0.042 0.276 ± 0.033 0.786 ± 0.064 0.653 ± 0.072 0.960 ± 0.079 UNet clDice [37] 0.8171 ± 0.0490 0.8579 ± 0.0319 0.9752 ± 0.0041 0.785 ± 0.040 0.276 ± 0.033 0.786 ± 0.064 0.653 ± 0.072 0.960 ± 0.079 UNet roplo.ss [14] 0.8171 ± 0.0490 0.8579 ± 0.0319 0.9752 ± 0.0041 0.785 ± 0.031 0.276 ± 0.033 0.659 ± 0.069 0.779 ± 0.080 0.979 ± 0.086 UNet TopoLoss [14] 0.8175 ± 0.0439 0.8754 ± 0.0340 0.781 ± 0.047 0.276 ± 0.033 0.659 ± 0.056 0.615 ± 0.058 0.086 ± 0.069 DSCNet [3] softDice 0.804 ± 0.0474 0.8428 ± 0.0370 0.9723 ± 0.0052 0.755 ± 0.043 0.834 ± 0.071 0.721 ± 0.075 0.284 ± 0.034 0.723 ± 0.075 0.088 ± 0.084 UNet softDice 0.8281 ± 0.0464			softDice	0.8150 ± 0.0089	0.9366 ± 0.0084	0.9196 ± 0.0063	0.671 ± 0.019	0.753 ± 0.043	0.511 ± 0.043	0.586 ± 0.046	0.652 ± 0.047
UNet softDice [26] 0.8170 ± 0.0402 0.8526 ± 0.0306 0.9749 ± 0.0044 0.781 ± 0.042 0.276 ± 0.033 0.786 ± 0.064 0.653 ± 0.072 0.960 ± 0.079 STARE UNet clDice [37] 0.8171 ± 0.0395 0.8579 ± 0.0319 0.9752 ± 0.0041 0.785 ± 0.040 0.276 ± 0.032 0.571 ± 0.049 0.659 ± 0.056 0.673 ± 0.075 0.960 ± 0.079 UNet TopoLoss [14] 0.8175 ± 0.0449 0.8506 ± 0.0339 0.9750 ± 0.0044 0.780 ± 0.041 0.780 ± 0.041 0.276 ± 0.033 0.571 ± 0.049 0.659 ± 0.056 0.615 ± 0.007 0.781 ± 0.086 0.606 ± 0.069 UNet TopoLoss [14] softDice 0.798 ± 0.0449 0.8506 ± 0.0390 0.975 ± 0.0045 0.759 ± 0.047 0.276 ± 0.033 0.659 ± 0.056 0.615 ± 0.0072 0.988 ± 0.080 DC-UNET [2] softDice 0.817 ± 0.0449 0.8506 ± 0.0370 0.9775 ± 0.0045 0.759 ± 0.047 0.726 ± 0.033 0.823 ± 0.066 0.707 ± 0.072 0.988 ± 0.080 DC-UNET [2] softDice +Ours 0.8210 ± 0.0454 0.8578 ± 0.0370 0.9775 ± 0.0045 0.755 ± 0.0045 0.756 ± 0.017 <td< td=""><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></td<>											
MassRoad UNct UNct clDice [\$7] Pointscatter 100 UNct 0.8212 ± 0.0386 Pointscatter 100 0.817 ± 0.0499 0.8579 ± 0.0319 0.8573 ± 0.0319 0.9752 ± 0.0041 0.785 ± 0.041 0.276 ± 0.032 0.780 ± 0.041 0.571 ± 0.049 0.629 ± 0.069 0.743 ± 0.065 STARE UNet UNet TopoLoss [14] DSCNet [33] 0.8171 ± 0.0395 0.8579 ± 0.0319 0.9754 ± 0.0041 0.785 ± 0.041 0.285 ± 0.031 0.844 ± 0.070 0.781 ± 0.080 0.997 ± 0.086 DSCNet [33] softDice 0.8175 ± 0.0449 0.8506 ± 0.0399 0.9754 ± 0.0475 0.780 ± 0.047 0.784 ± 0.037 0.823 ± 0.068 0.615 ± 0.056 0.6615 ± 0.056 0.6615 ± 0.056 0.6615 ± 0.058 0.691 ± 0.079 0.988 ± 0.080 0.975 ± 0.0047 0.781 ± 0.047 0.728 ± 0.061 0.772 ± 0.072 0.988 ± 0.080 0.975 ± 0.057 0.288 ± 0.031 0.873 ± 0.076 0.884 ± 0.071 0.721 ± 0.025 0.975 ± 0.057 0.288 ± 0.031 0.844 ± 0.071 0.721 ± 0.025 0.582 ± 0.046 0.884 ± 0.071 0.721 ± 0.026 0.884 ± 0.071 0.721 ± 0.026 0.858 ± 0.084 0.975 ± 0.057 0.288 ± 0.046 0.618 ± 0.067 0.691 ± 0.059 0.976 ± 0.0036 0.776		UNet	clDice+Ours	0.8223 ± 0.0086	0.9459 ± 0.0066	0.9213 ± 0.0056	0.679 ± 0.017	0.744 ± 0.038	0.353 ± 0.034	0.539 ± 0.043	0.482 ± 0.040
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UNet clDice+Ours 0.8283 ± 0.0371 0.8747 ± 0.0284 0.9757 ± 0.0040 0.792 ± 0.039 0.274 ± 0.032 0.450 ± 0.042 0.582 ± 0.065 0.598 ± 0.055 UNet softDice [20] 0.7808 ± 0.0143 0.8768 ± 0.0159 0.9780 ± 0.0036 0.750 ± 0.017 0.239 ± 0.033 0.479 ± 0.020 0.798 ± 0.076 0.777 ± 0.072 UNet clDice [21] 0.7788 ± 0.0143 0.8773 ± 0.0156 0.9775 ± 0.0037 0.747 ± 0.016 0.244 ± 0.033 0.479 ± 0.022 0.998 ± 0.076 0.962 ± 0.086 UNet Pointscatter [40] 0.7788 ± 0.0142 0.8775 ± 0.0156 0.9775 ± 0.0035 0.747 ± 0.016 0.244 ± 0.033 0.512 ± 0.022 0.996 ± 0.090 0.962 ± 0.086 UNet Pointscatter [40] 0.7787 ± 0.0142 0.8775 ± 0.0156 0.9775 ± 0.0035 0.748 ± 0.016 0.244 ± 0.033 0.512 ± 0.022 0.996 ± 0.090 0.962 ± 0.086 UNet TopoLoss [14] 0.7787 ± 0.0169 0.878 ± 0.0164 0.9778 ± 0.0035 0.748 ± 0.016 0.0274 ± 0.013 0.439 ± 0.017 0.734 ± 0.027 0.933 ± 0.076 0.773 ± 0.076 0.771 ± 0.072 0.711 ± 0.072											
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MassRoad UNet Pointscatter 40 0.778 ± 0.0142 0.8750 ± 0.0156 0.9778 ± 0.0035 0.748 ± 0.016 0.242 ± 0.033 0.620 ± 0.027 0.800 ± 0.076 0.908 ± 0.074 MassRoad UNet TopoLoss 14 0.7797 ± 0.0150 0.8758 ± 0.0156 0.9778 ± 0.0035 0.748 ± 0.016 0.242 ± 0.033 0.620 ± 0.027 0.800 ± 0.076 0.908 ± 0.074 TransUNet 1 softDice 0.7707 ± 0.0169 0.8758 ± 0.0182 0.7976 ± 0.0038 0.749 ± 0.017 0.238 ± 0.032 0.439 ± 0.018 0.780 ± 0.076 0.727 ± 0.071 10.075 LinkNet34 SoftDice 0.7752 ± 0.0159 0.874 ± 0.016 0.9775 ± 0.0036 0.744 ± 0.017 0.243 ± 0.033 0.489 ± 0.021 0.773 ± 0.076 0.711 ± 0.072 UNet softDice 0.7752 ± 0.0139 0.874 ± 0.0161 0.9775 ± 0.0036 0.744 ± 0.017 0.243 ± 0.033 0.504 ± 0.022 0.755 ± 0.075 0.771 ± 0.072 UNet softDice+Ours 0.784 ± 0.013 0.886 ± 0.0151 0.9783 ± 0.0035 0.744 ± 0.016 0.237 ± 0.033 0.504 ± 0.022 0.755 ± 0.076 0.772 ± 0.071 U											
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UNet softDice+Ours 0.7849 ± 0.0139 0.8816 ± 0.0151 0.9783 ± 0.0035 0.754 ± 0.016 0.237 ± 0.033 0.386 ± 0.016 0.754 ± 0.076 0.672 ± 0.070											
UNEt cIDice+Ours 0.7851 ± 0.0137 0.8844 \pm 0.0148 0.9779 \pm 0.0036 0.754 ± 0.016 0.241 \pm 0.033 0.393 ± 0.018 0.879 \pm 0.085 0.784 \pm 0.082											
		UNet	clDice+Ours	0.7851 ± 0.0137	0.8844 ± 0.0148	0.9779 ± 0.0036	0.754 ± 0.016	0.241 ± 0.033	0.393 ± 0.018	0.879 ± 0.085	0.784 ± 0.082

Table 3: Comparison with SOTA methods on the segmentation task. Best results are in bold; second-best are underlined. Our approach secures all leading scores and most secondary peaks.





Visulization

GraphMorph reduces false negatives, false positives and topological errors on both tasks.

