CONNECTIVITY-PRESERVING LOSSES FOR 3D CORONARY ARTERY SEGMENTATION

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1. INTRODUCTION

In image segmentation, CNN-based architectures such as nnU-Net can achieve high volumetric accuracy; however, they often fail to preserve topology in thin structures such as coronary arteries, where connectivity is clinically critical. Generic overlap-based losses (e.g., Dice, Cross-Entropy (CE)) do not explicitly penalize errors in connectivity, making segmentation of thin tubular structures prone to discontinuities. We evaluate the effectiveness of the recently proposed Skeleton Recall (SR) loss [1] for coronary segmentation.

2. METHODS

We compare a generic baseline loss $\mathcal{L}_{\text{gen}}$ (Dice + CE) with a connectivity-preserving variant that augments the baseline by the SR loss $\mathcal{L}_{\text{conn}} = \mathcal{L}_{\text{gen}} + \mathcal{L}_{\text{SR}}$.

All experiments are conducted with an nnU-Net-based segmentation pipeline, evaluated using 5-fold cross-validation on 98 Coronary Computed Tomography Angiography (CCTA) volumes from the public ASOCA [2] dataset and an additional in-house dataset [3] used for FFR-CT evaluation.

Segmentation quality is assessed using complementary metrics capturing volumetric overlap and connectivity. Volumetric performance is measured using Dice, centerline Dice (clDice) [4], and ε-relaxed Dice invariant to small ($\varepsilon = 3$ mm) boundary deviations. Connectivity is evaluated using centerline True Positive Rate (clTPR), True Positive β_0 error (TPβ_0E) describing fragmentation of recovered components, and number of residual gaps (GC) distinguishing major structural breaks from small gaps that may be recoverable.

3. RESULTS AND CONCLUSION

Experiments show that volumetric overlap is comparable between $\mathcal{L}_{\text{gen}}$ and $\mathcal{L}_{\text{conn}}$ (see Table 1), while connectivity improves significantly for the latter (Wilcoxon test, $p < 0.001$). Predictions obtained with $\mathcal{L}_{\text{conn}}$ preserve vessel continuity, in contrast to $\mathcal{L}_{\text{gen}}$ (see Figure 1).

In summary, combining generic loss and SR is a simple and effective strategy to boost connectivity in coronary artery segmentation without compromising volumetric accuracy.

Metric	$\mathcal{L}_{\text{gen}}$	$\mathcal{L}_{\text{conn}}$
Dice	79.11 [74.19, 81.46]	77.99 [74.40, 81.38]
clDice	87.58 [84.46, 90.78]	86.71 [82.91, 89.14]
εDice	94.17 [91.77, 95.92]	93.58 [91.43, 95.24]
clTPR	89.89 [84.49, 95.41]	**93.86 [90.54, 97.60]**
TP β_0E	2 [1, 3]	**1 [0, 2]**
GC	1 [0, 2]	**1 [0, 1]**

Table 1. Volumetric overlap and connectivity metrics. Values reported as median [Q1, Q3] across 98 cases; bold indicates statistically significant differences based on paired one-sided Wilcoxon tests ($\alpha = 0.05$).

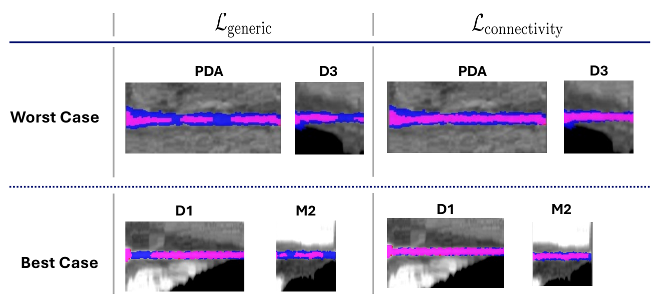

Fig. 1. Qualitative comparison of global worst (top row) and best (bottom row) cases selected according to the Dice score. Results visualized as stretched multiplanar reformats (reference in blue; reference/prediction overlap in magenta).

The authors declare no conflicts of interest. All data were acquired according to the Declaration of Helsinki and institutional review board–approved protocols.

4. REFERENCES

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