SACP: Spatially-Adaptive Conformal Prediction in Uncertainty Quantification of Medical Image Segmentation

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MOTIVATION

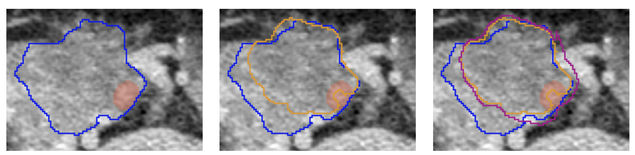
The Challenge:

Standard CP provides uniform uncertainty across all spatial regions, but medical segmentation requires spatially-varying confidence

Our Solution:

Distance-weighted conformal prediction with anatomical context and theoretical coverage guarantees

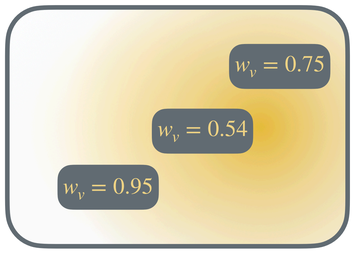
Clinical Context: In pancreatic surgery, millimeter-scale accuracy near critical vessels determines resectability vs. inoperability



tumour-vessel interface | **CP with uniform bounds** | **SACP with adaptive bounds**

METHODOLOGY

Base CP $S_{base}(x \mid \hat{y} = l)$ × **Spatial Weight** $w_v(x, l)$ = **SACP Score** $S_{SACP}(x \mid \hat{y} = l)$



- **Low (near)**
- **Medium**
- **High (distant)**

γ_v = vessel relevance
ϕ_l = distance to tumor
δ_v = distance to vessel

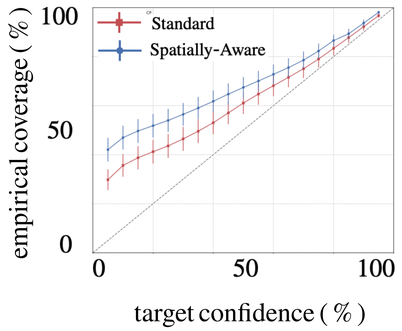
Weight function:

$$w_v(x, l) = \sigma\left(\frac{1}{\gamma_v}(\phi_l - \delta_v \log p(\hat{y} = l \mid x))\right)$$

Theorem: SACP maintains CP coverage guarantees with spatial adaptivity

RESULTS

Key performance
Coverage: 98.1% (target: 95%)
Significant improvement over standard CP (0.05)



Experimental Setup:

- 10 calibration scans
- 20 testing scans
- five European centres
- five relevant vessels
- $\gamma_v = 0.8$ for arteries
- $\gamma_v = 0.6$ for vessels

SACP	CP
98.1% coverage	96.8% coverage
98.1% coverage near vessels ≤ 2 mm	95.4% coverage near vessels ≤ 2 mm
2.76 relative width ratio near vessels ≤ 2 mm	2.89 relative width ratio near vessels ≤ 2 mm

CONCLUSIONS

- Provides anatomically-informed uncertainty
- Maintains theoretical CP coverage guarantees
- Clinically relevant beyond surgical planning
- Generalizable to safety-critical applications

FUTURE WORK

- Larger scale validation across multiple datasets
- Relaxing exchangeability assumptions
- Robust statistics for worst-case guarantees
- Clinical deployment assessment

CONTACT & CODE

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github.com/tailabTMU/SACP