segcsvd$_{PVS}$: A Convolutional Neural Network-Based Tool for Quantification of Enlarged Perivascular Spaces (PVS) on T1-Weighted Images

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INTRODUCTION

Enlarged Perivascular Spaces (PVS) are MRI markers of cerebral small vessel disease (cSVD) associated with aging, disease phenotypes, and overall indicators of brain health.

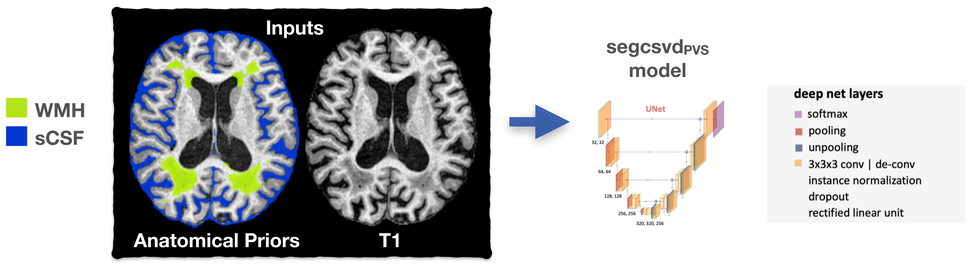
Automated segmentation of PVS on T1-weighted images is desirable given the widespread use of T1-weighted imaging protocols in multisite clinical and research studies.

Accurate PVS quantification on T1-weighted images remains challenging due to protocol variability, small size of PVS, and limited contrast. While deep learning-based methods offer promise, existing tools often perform inconsistently across cohorts or imaging conditions.

We present **segcsvd$_{PVS}$**[3], a convolutional neural network (CNN)-based tool for automated PVS segmentation on T1-weighted images, designed to improve segmentation accuracy and robustness across diverse imaging datasets.

METHODS

The **segcsvd$_{PVS}$** model was developed using a **novel hierarchical framework** that integrates anatomical priors (e.g., WMH[3,4], sulcal CSF[5]) with robust training strategies for improved segmentation performance.



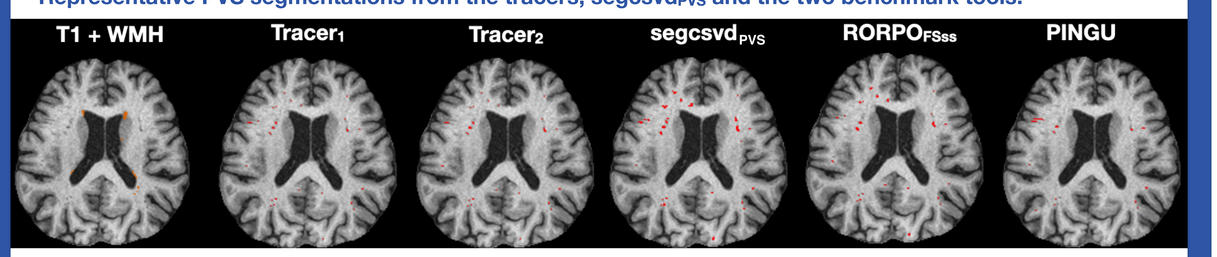
The model was trained using a **large, multi-site dataset** spanning a wide range of imaging protocols and patient populations, including individuals with sleep apnea, carotid stenosis, cerebrovascular disease, Parkinson's disease, and healthy controls (mean age = 63.2 ± 9.4).

Ground truth for model training was derived from **semi-automated RORPO[6]-based segmentations** (n = 206). **Accuracy was validated using manual tracings from two expert raters** on six axial slices per subject (n = 31) and further supported by **age correlation analyses** in two large datasets (ADNI3, n = 350; CAHHM, n = 764).

To address class imbalance and improve model robustness, a patch-based training strategy was employed using Tversky loss and extensive data augmentation (contrast, noise, rotation). Final predictions were obtained from a 12-model ensemble with test-time augmentation to enhance sensitivity.

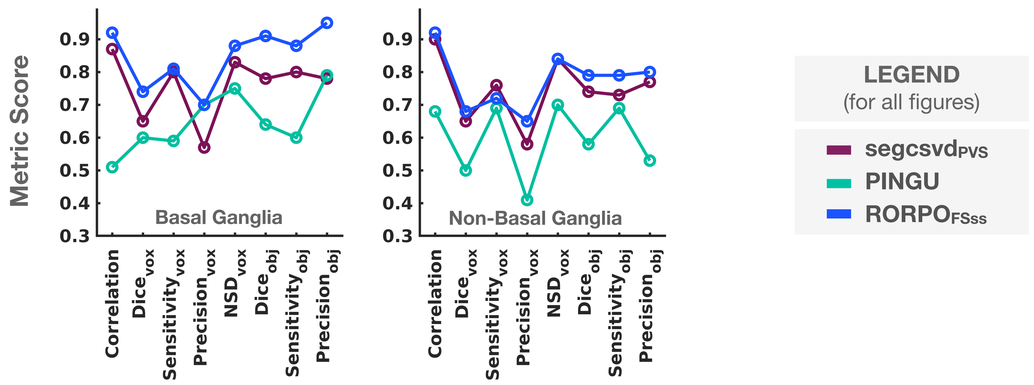
A comprehensive performance evaluation was conducted, including benchmarking against two existing methods: PINGU[7] (CNN-based) and RORPO$_{FSss}$ (filtering with anatomical masking).

Representative PVS segmentations from the tracers, segcsvd$_{PVS}$ and the two benchmark tools:



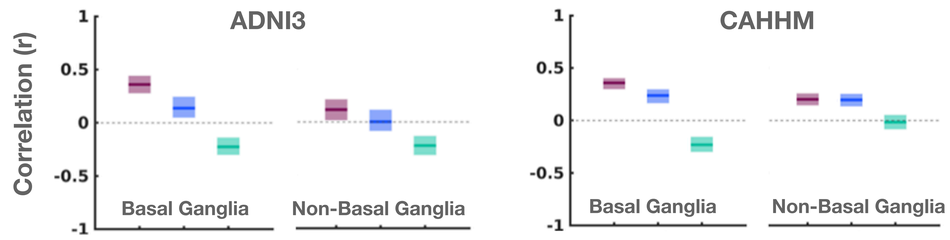
RESULTS

Accuracy Validation: Agreement with consensus manual ground truth tracings



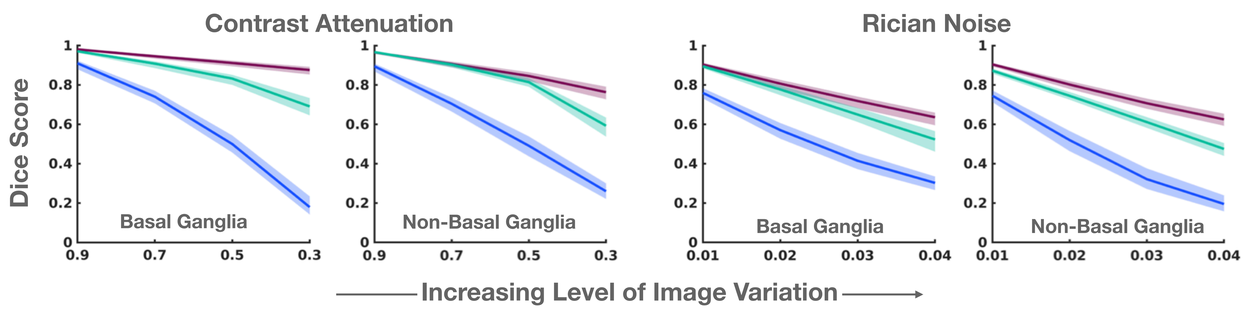
- Both **segcsvd$_{PVS}$** and **RORPO$_{FSss}$** showed high agreement with the consensus manual ground truth, generally outperforming **PINGU** across performance metrics.
- For **segcsvd$_{PVS}$**, object-level precision was high (~0.8 in both regions), while voxel-level precision was approximately 10-20% lower, suggesting a tendency to capture larger PVS objects rather than incorrectly segmenting additional spurious ones.

Biological Validation: Correlation between age and PVS volume in two large cohorts



- **segcsvd$_{PVS}$** was the only method to detect statistically reliable, biologically expected positive correlations between age and PVS volume in both basal ganglia and non-basal ganglia regions across two large cohorts.
- **RORPO$_{FSss}$** showed weaker correlations, while **PINGU** yielded unexpected negative correlations.
- **ADNI3** data were not used during model training and served as an independent validation set for model generalizability in this context.

Robustness Analysis: Voxel-level segmentation consistency under variations in image contrast and noise



- Introducing image variation (contrast attenuation and Rician noise) had minimal impact on segmentation performance for **segcsvd$_{PVS}$**, with Dice scores remaining high relative to baseline (>0.75-0.90) and more stable than both **PINGU** and **RORPO$_{FSss}$** under challenging imaging conditions.

DISCUSSION

- **segcsvd$_{PVS}$** is a reliable tool for PVS segmentation on T1 images, demonstrating strong agreement with manual ground truth, sensitivity to meaningful age-related associations, and robustness to imaging variability.
- These strengths support its use in large-scale research and clinical studies of CSVD and dementia.

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References
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