RESIN: A self-supervised framework for enhancing axial resolution of volumetric imaging data

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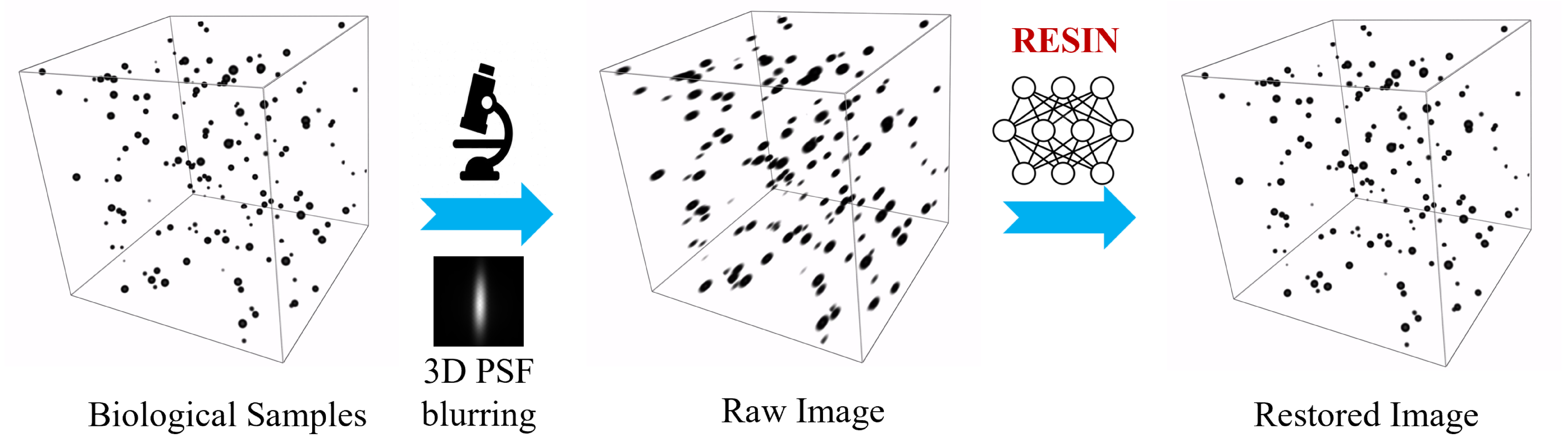
Abstract

Visualization of 3D biological structures heavily relies on volumetric microscopy imaging. However, the intrinsic anisotropy problem caused by the elongation of the point spread function(PSF) along the axial direction, has largely hindered detailed structure analysis. In this study, we introduce a novel framework, termed Resolution Enhancement with Self-Imitation Networks (RESIN), designed to address this challenge. RESIN employs self-supervised learning exclusively on raw anisotropic data, offering a versatile solution applicable across various volumetric imaging microscopy techniques. When applied to neuroscience research, RESIN significantly enhances our ability to observe intricate 3D details of neuronal morphology, thereby facilitating comprehensive investigations into brain organization and network connectivity.



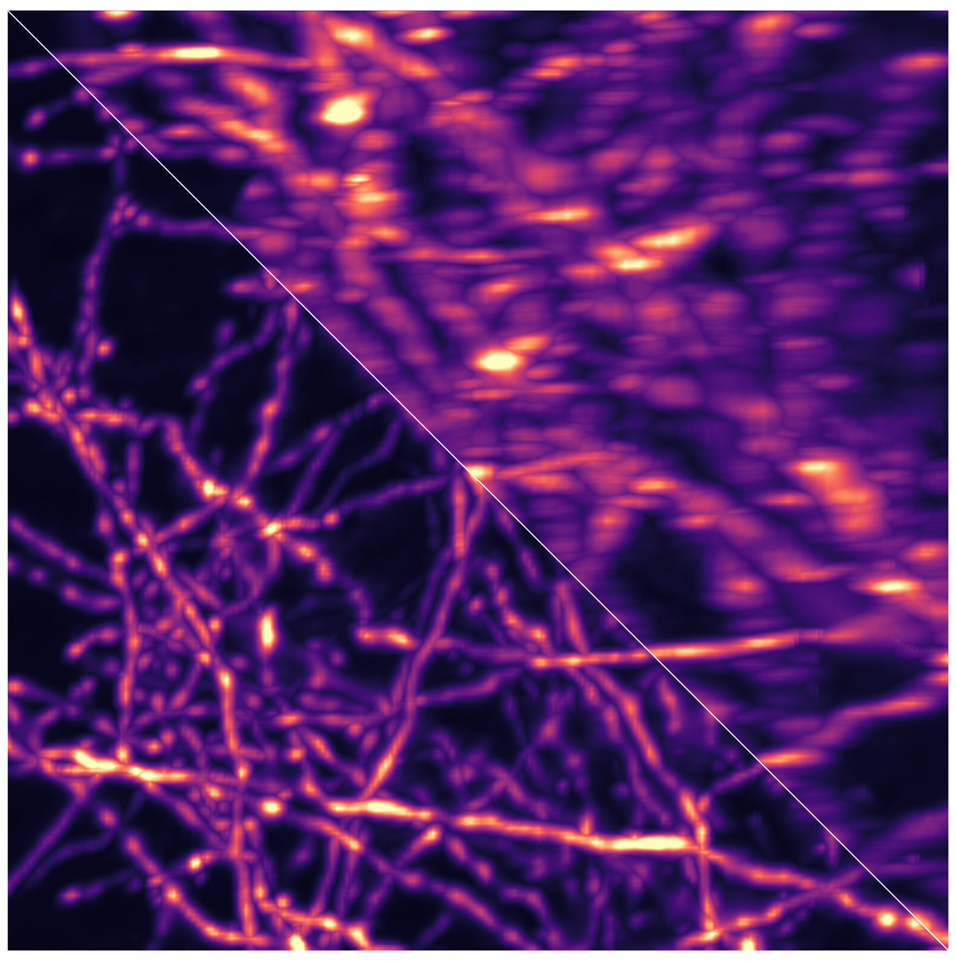
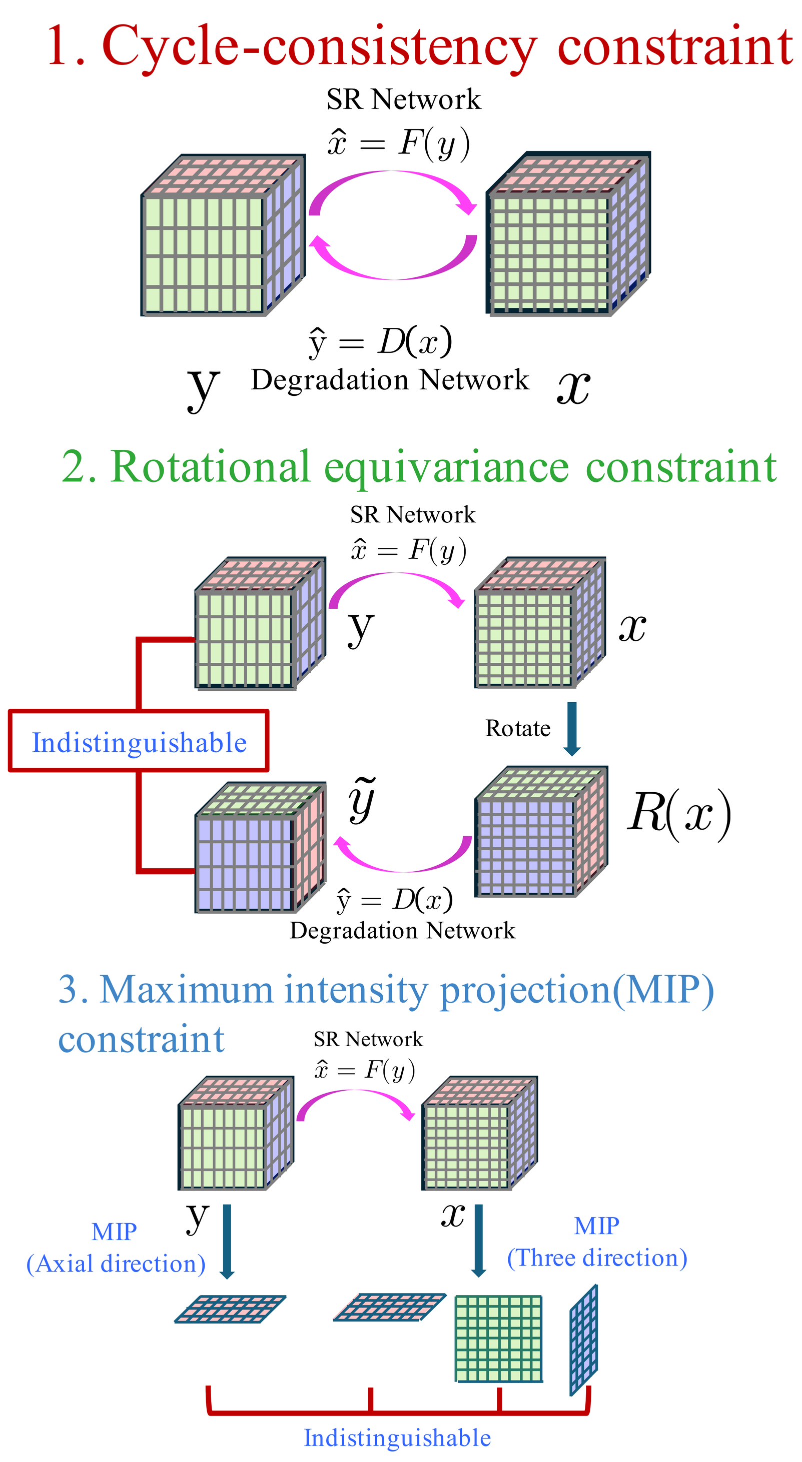


Figure 2. Comparison of raw (top right) and RESIN-enhanced (bottom left) images of macaque neurites obtained through VISoR imaging.

Methods

RESIN comprises a super-resolution (SR) reconstruction network $F(\boldsymbol{y})$, a degradation network $D(\boldsymbol{x})$, and a set of discriminator networks, where $\boldsymbol{y}$ represents the raw image and $\boldsymbol{x}$ denotes the high-resolution image. To facilitate efficient training of these networks without the need for supervision from paired high-resolution data , the following three constraints were enforced.



- The raw volumetric image should stay nearly unchanged after a cycle of SR reconstruction and subsequent degradation.
- Because of the rotation equivariance in the biological samples, The degraded images of $\boldsymbol{x}$ and its rotation $\boldsymbol{R}(x)$ are indistinguishable.
- The MIPs of the HR image in three directions should be indistinguishable from the MIP of the original image in axial direction.

The loss Function are as follows:

$$L_{GAN} = L_G + L_D$$

$$L_G = L_{cycle_1} + L_{cycle_2} + \lambda_{weight}\left(L_{G_{y\_\hat{y}}} + L_{G_{aniso\_proj}} + L_{G_{iso\_proj}}\right)$$

$$L_D = \lambda_{weight}\left(L_{D_{y\_\hat{y}}} + L_{D_{aniso\_proj}} + L_{D_{iso\_proj}}\right)$$

Results

Synthetic images with tubular structures

We simulated the imaging process of synthetic tubular volumes by convolving them with anisotropic Gaussian kernels, with bandwidths of 1 and 5 for the lateral and axial directions, respectively.

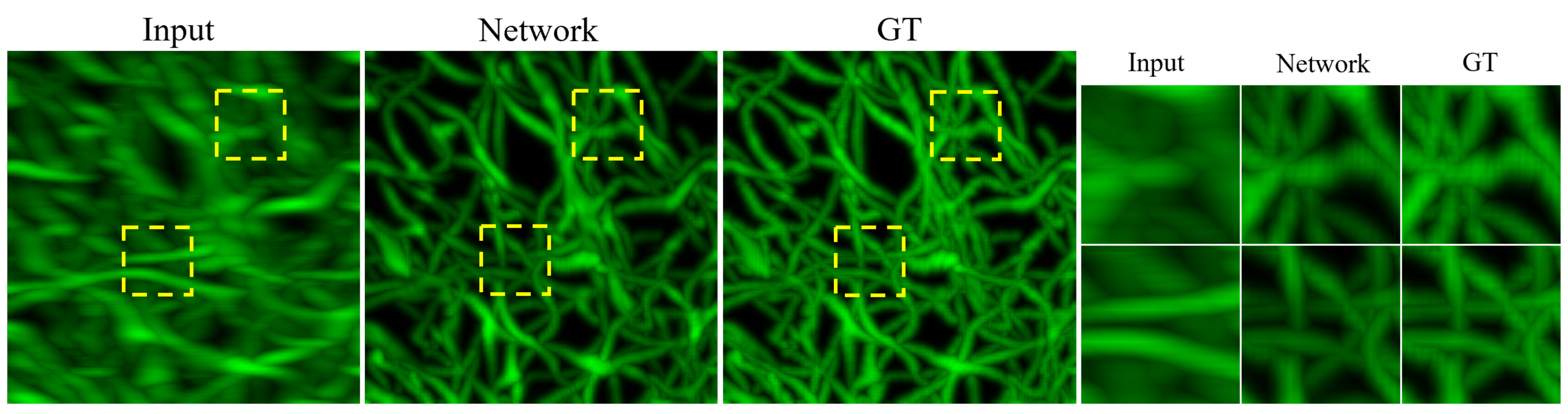


Figure 3. Performance of RESIN on synthetic data

Table 1. Quantitative comparison of RESIN and Self-Net (Ning K. et.al.,LIGHT-SCI APPL, 2023).

Models	Metrics		
	RMSE(↓)	SSIM(↑)	Isotropy Ratio(↓)
Self-Net	8.6	0.87	1.090
RESIN	5.3	0.97	1.063

Real volumetric images of macaque neurons

We validated RESIN using volumetric imaging data of macaque neurons acquired with VISoR (Xu F. et.al., Nature Bio.Tech, 2021). The two datasets were DAPI-stained and GFP-labeled neurons separately.

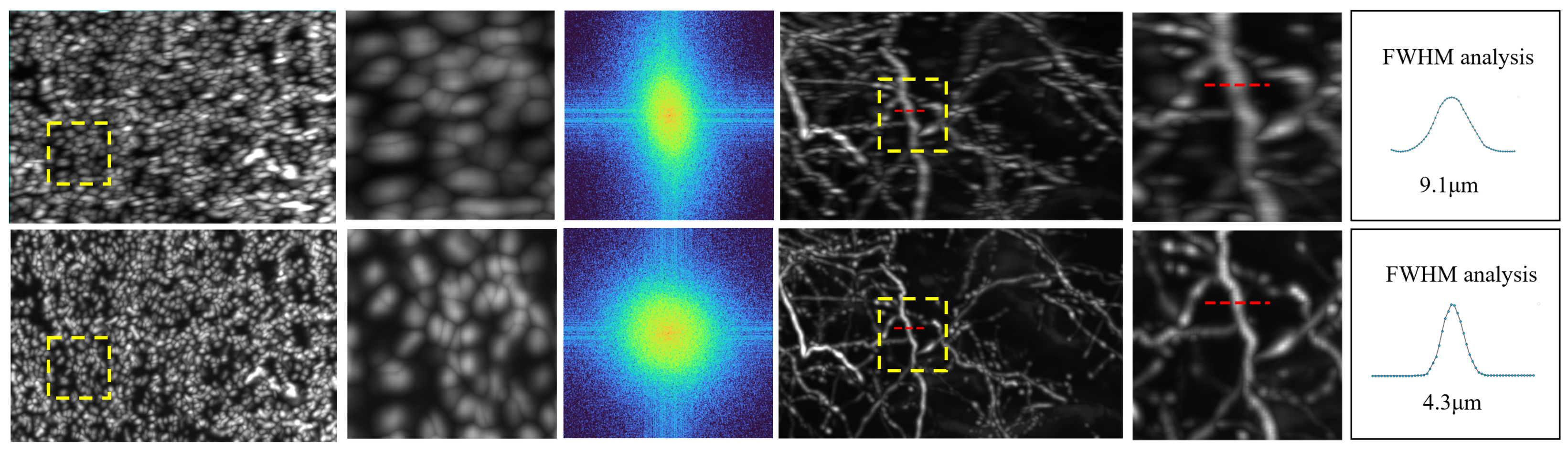


*Figure 4. **Demonstration of RESIN enhancement on the imaging data of macaque neurons.** The Fourier spectrum of the RESIN output (bottom row) and the line intensity profiles demonstrated the enhanced axial resolution.*

Elongated PSF along oblique directions

By default, the axial direction aligns with the z-axis of volumetric imaging data. In some light-sheet imaging setups, the axial resolution is at a 45-degree oblique angle, requiring previous methods to rotate the data for alignment. Our RESIN method eliminates this step for PSFs with arbitrary axial directions.

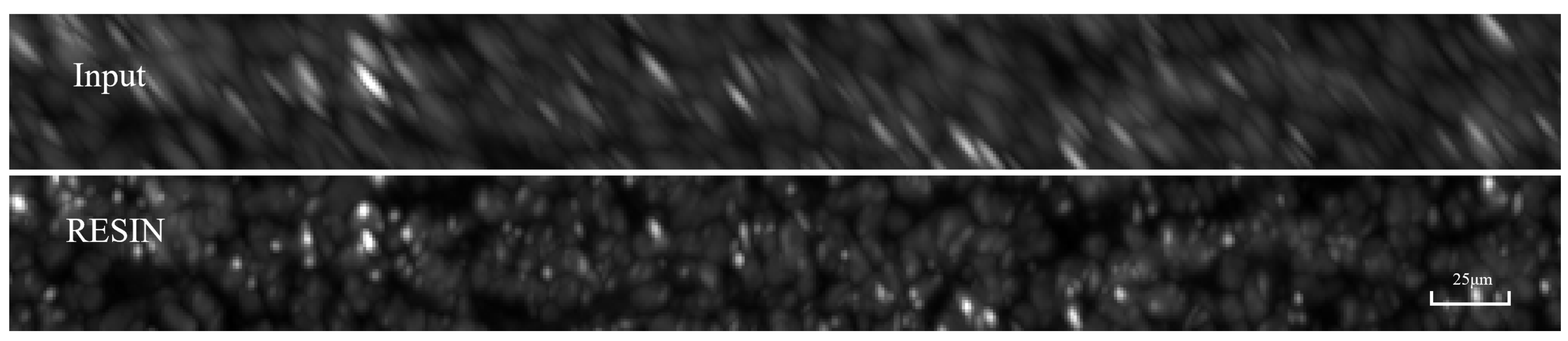


Figure 5. Direct application of RESIN on the raw Nissl-stained VISoR imaging data, where the axial direction is at 45-degree oblique angle.

Resin yields better segmentation of neurites

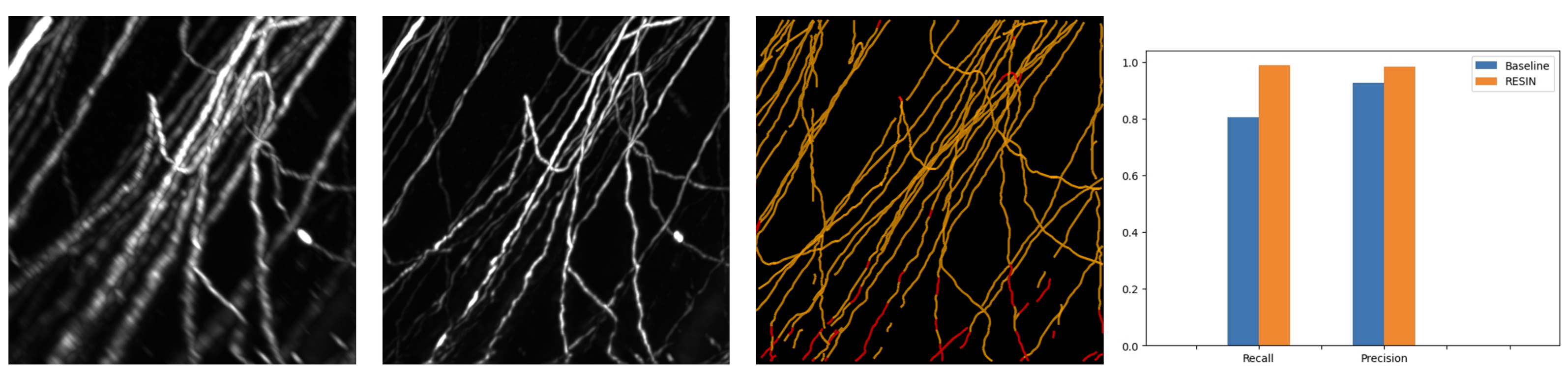


*Figure 6. **Improvement of Segmentation Task.** From left to right: raw data, RESIN-restored data, segmentation skeleton data (orange denotes baseline model's segment results and red denotes RESIN's improvement over baseline model), recall and precision metrics for the segmentation task.*