PINGS-X: Physics-Informed Normalized Gaussian Splatting with Axes Alignment for Fast and Accurate Super-Resolution of Phase-Contrast MRI

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Phase-contrast magnetic resonance imaging (PC-MRI) is a reliable non-invasive method for estimating blood flow velocities, crucial for cardiovascular diagnostics. Unlike standard MRI focused on anatomical structure, PC-MRI requires high spatiotemporal resolution for early detection of critical conditions such as stenosis or aneurysms. Achieving this resolution typically demands lengthy scans, creating a trade-off between acquisition speed and image quality. While recent physics-informed neural networks (PINNs) address super-resolution, their training times remain prohibitively slow, particularly for high-dimensional data such as 4D flow MRI. We introduce PINGS-X, a novel framework modeling high-resolution PC-MRI velocities using axes-aligned spatiotemporal Gaussians. Inspired by the efficiency of 3D Gaussian splatting (3DGS) in novel view synthesis, PINGS-X non-trivially extends 3DGS by introducing: (i) Gaussian weight normalization for the model prediction step, improving robustness to initialization, (ii) a formal convergence theory guaranteeing a highly favorable convergence rate, and (iii) a Gaussian merging procedure that prevents degenerate solutions and enhances computational efficiency. Moreover, PINGS-X incorporates physics-informed losses to robustly handle noisy PC-MRI data. Experiments on synthetic computational fluid dynamics (CFD) and real PC-MRI datasets demonstrate that PINGS-X substantially reduces training time and improves the reconstruction accuracy.

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