MPR-Diff: a Self-Supervised Diffusion Model for Multi-Planar Reformation in Prostate Micro-Ultrasound Imaging

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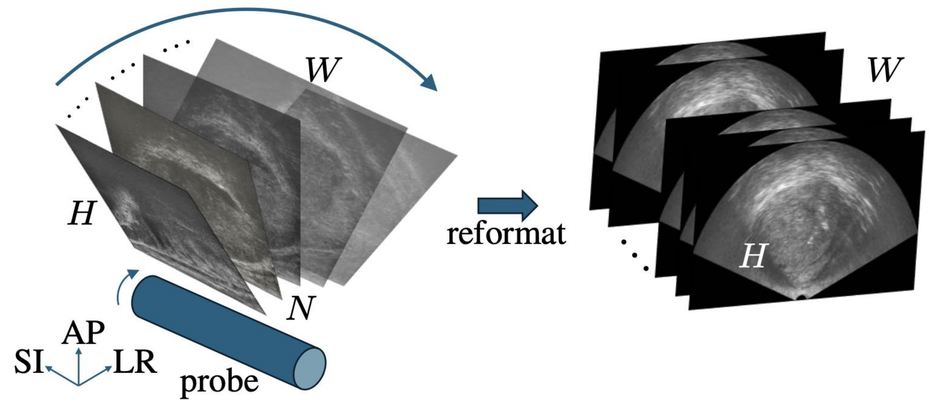
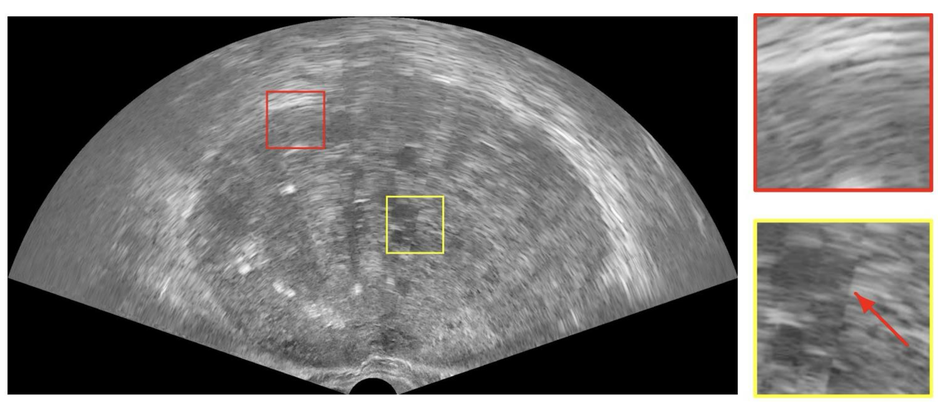
Introduction

- **Micro-ultrasound** is a novel 29-MHz ultrasound imaging with low cost and 3-4× higher resolution than traditional ultrasound.
- **Acquisitions** are fan-shaped with non-uniform angular intervals.
- **Multi-planar reformation (MPR)** is crucial for joint evaluation with MRI, pathology, etc.
- **MPR is challenging** due to low anterior resolution and discontinuity between adjacent slices.

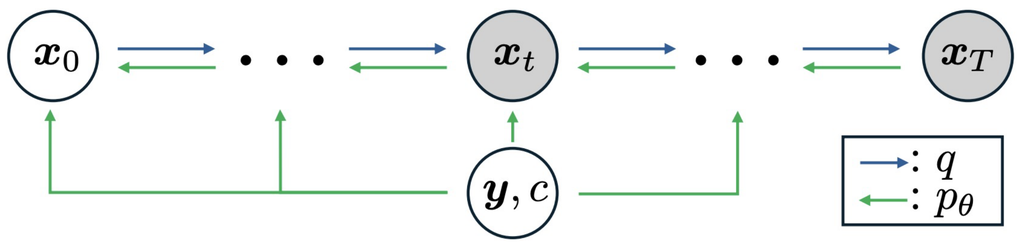




Method

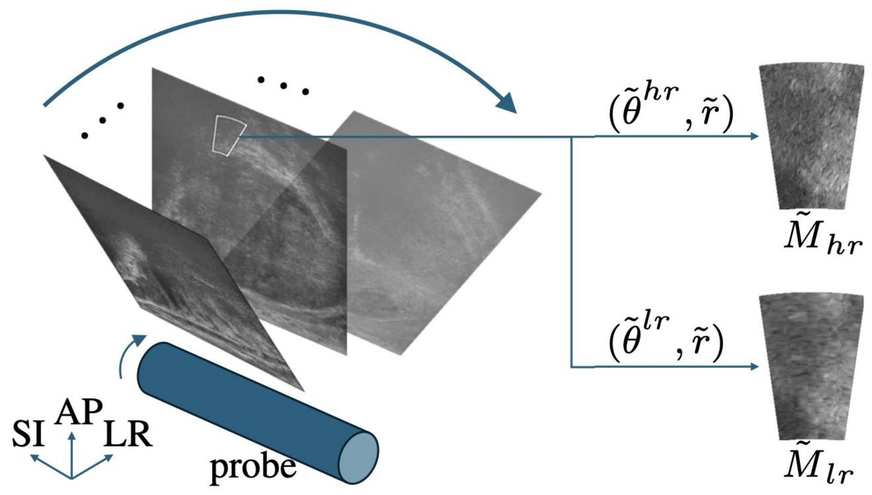
Conditional DDPM

- **Polar coordinate system:** represent each voxel in the MPR plane using polar coordinates (θ, r) to reflect the fan-shaped acquisition.
- **Up-sampling strategy:** super-resolve low-resolution fan-shaped image $y \in \mathbb{R}^{H\times N}$ to $x \in \mathbb{R}^{H\times kN}$ with up-scaling factor k.
- **Conditional generation:** a DDPM is trained to generate the high-quality image conditioned on the degraded image y, and the corresponding polar coordinates c.



Self-supervised Training

- **No high-quality supervision:** true high-resolution target-plane images are unavailable, making direct supervised training infeasible.
- **Patch-sampling training:** simulate training pairs by randomly extracting LR and HR fan-shaped patches from the original plane.
- **Simulated Acquisition Coordinates:** use non-uniform angular coordinates $\{\tilde{\theta}^{lr}\}$ during sampling to mimic the realistic MicroUS acquisition patterns.



Contributions

- **The first deep learning-based approach** for micro-ultrasound MPR.
- **A self-supervised learning strategy** without the need for high-resolution ground truth.
- **Improved image quality**, validated by both quantitative metrics and expert reader studies.

Results

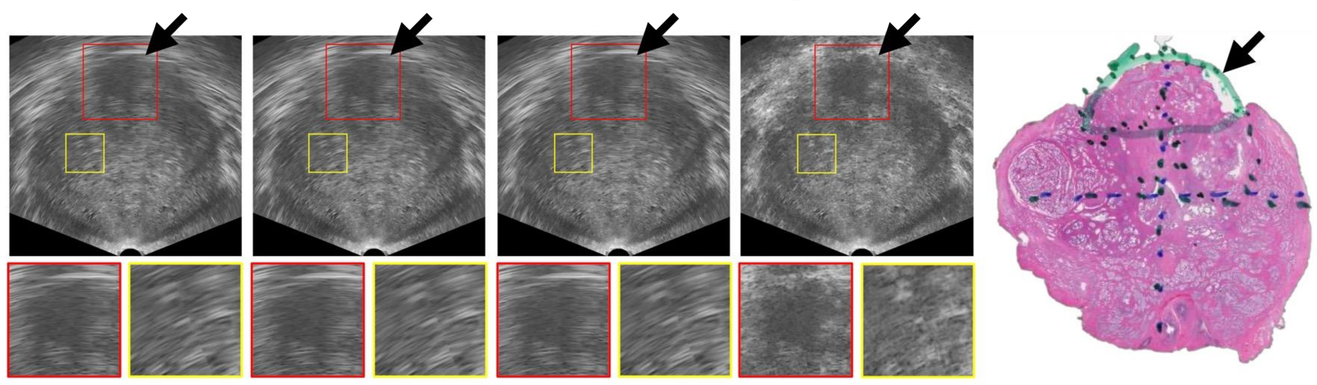
Quantitative Results

- **Best sharpness and perceptual quality!**

Method	Sharpness [14] ($\times 10^2$) ↑	PIQUE [15] ↓
Bilinear [3]	4.35	26.44
SwinIR [6]	4.36	26.24
SRConvNet [12]	4.39	25.18
MPR-Diff	**4.44**	**19.47**

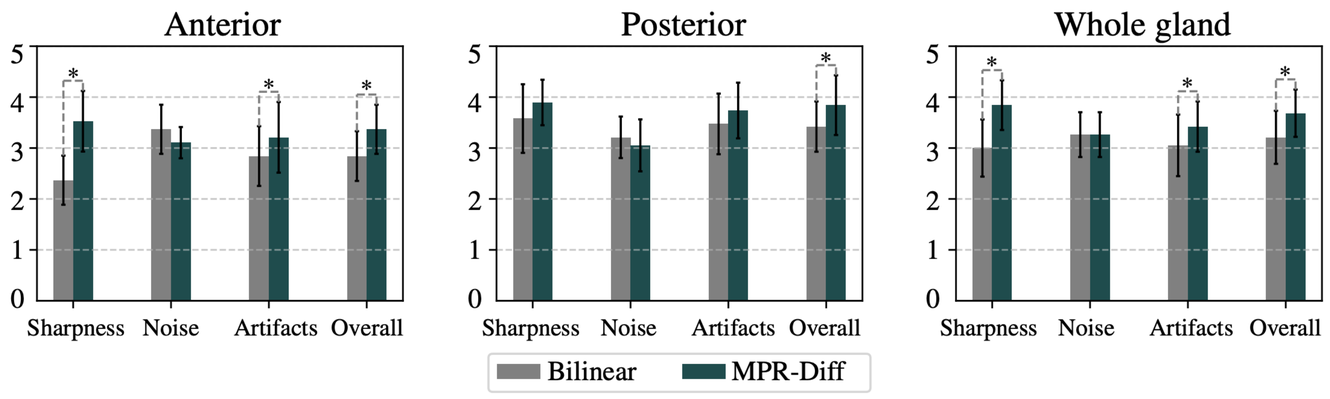
Qualitative Comparison

- **Enhanced details and boundary of lesion!**



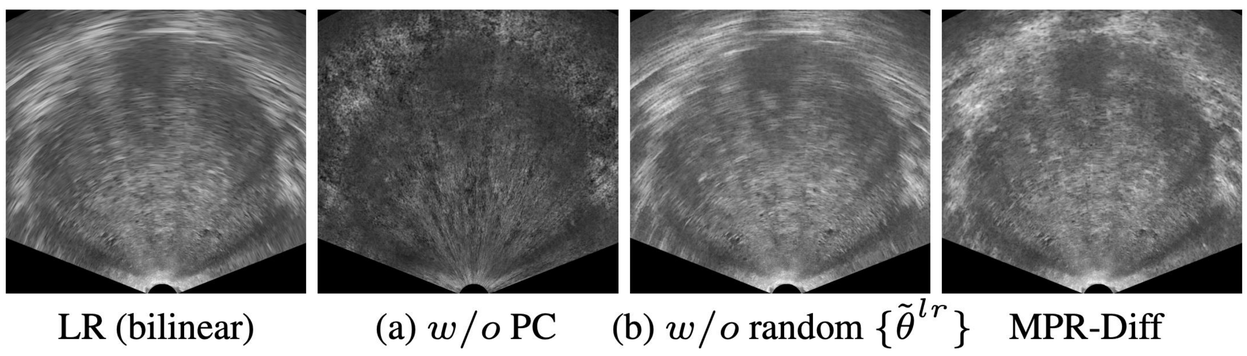
Expert Reader Study

- **Superior reader indicates $p < 0.05$)**



Ablation Study

- (a) remove the positional condition c.
- (b) replace random sampling of $\{\tilde{\theta}^{lr}\}$ with uniform sampling.



Conclusion and Discussion

- **Improved delineation of prostate and lesions**, enhancing the clinical value of MicroUS for prostate cancer diagnosis.
- **Limitation: DDPM suffers from long inference time**, limiting practical use in volumetric reformation.
- **Future work:** we are currently developing **a single-step conditional consistency model-based approach – fast, stable and high-quality!**

Acknowledgment

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