Evaluation of Denoising Methods for ADC Accuracy on Low-Field MR-Linac Diffusion-Weighted Imaging

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ABSTRACT

Diffusion-Weighted Imaging (DWI) on a 0.35T MR-Linac presents challenges of low signal-to-noise ratio (SNR). We compared four denoising methods for preservation of Apparent Diffusion Coefficient (ADC) values and improvement of ADC map quality at this low magnetic field.

ADC accuracy was quantified using a QalibreMD diffusion phantom, and ADC image quality was assessed using a MagPhan MRI quality assurance phantom.

Non-local means (NLM) was identified as optimal ADC denoising method for future clinical implementation to aid lesion detection on thoracic and pelvic DWI at a 0.35T MR-Linac.

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INTRODUCTION

Diffusion-Weighted Imaging (DWI) at a 0.35T MR-Linac DWI is novel and may detect cancerous lesions. However, low field DWI faces challenges of low signal-to-noise ratio (SNR) affecting the resolution of image features.
Introducing an effective denoising method would aid lesion detection. The selected denoising method must uphold the quantitative accuracy of Apparent Diffusion Coefficient (ADC) values to provide confidence in using ADC as a biomarker for cellular density in patients treated on low-field MR-Linacs.

METHODS AND MATERIALS

Test objects:
1) The QalibreMD diffusion phantom which contains 13 tubes with varying concentrations of Polyvinyl-pyrrolidone (PVP) allowed for comparison across a range of reference ADC values.

2) The MagPhan RT phantom mimicked the size and shape of a human torso. Its spherical fiducials and inserts assessed the improvement of spatial resolution and feature detectability after denoising.

Imaging: Both phantoms were imaged on a 0.35T ViewRay MR-Linac. Noisy DW images were acquired with 1 and 8 averages for QalibreMD and MagPhan, respectively. 16 average DWI served as reference for both.

Methods Evaluated: DW images were denoised with Total Variation (TV)[1] and Wavelet[2] from scikit-image, and Non-Local Means (NLM)[3], and Marcenko-Pastur PCA (MPPCA)[4] from DIPY. ADC maps were calculated by mono-exponential fitting of denoised DW images. Figure 1 shows original and denoised ADC examples.

Metrics: Mean ADC and its standard deviation was measured in regions of interest (ROIs) on diffusion phantom vials of denoised images and compared to the scanner ADC maps acquired with 16 averages. MagPhan provided measurements of SNR, Point Spread Function (PSF), 10-90% Edge Spread Function (ESF), as well as number of detected fiducials on denoised and reference ADC maps.

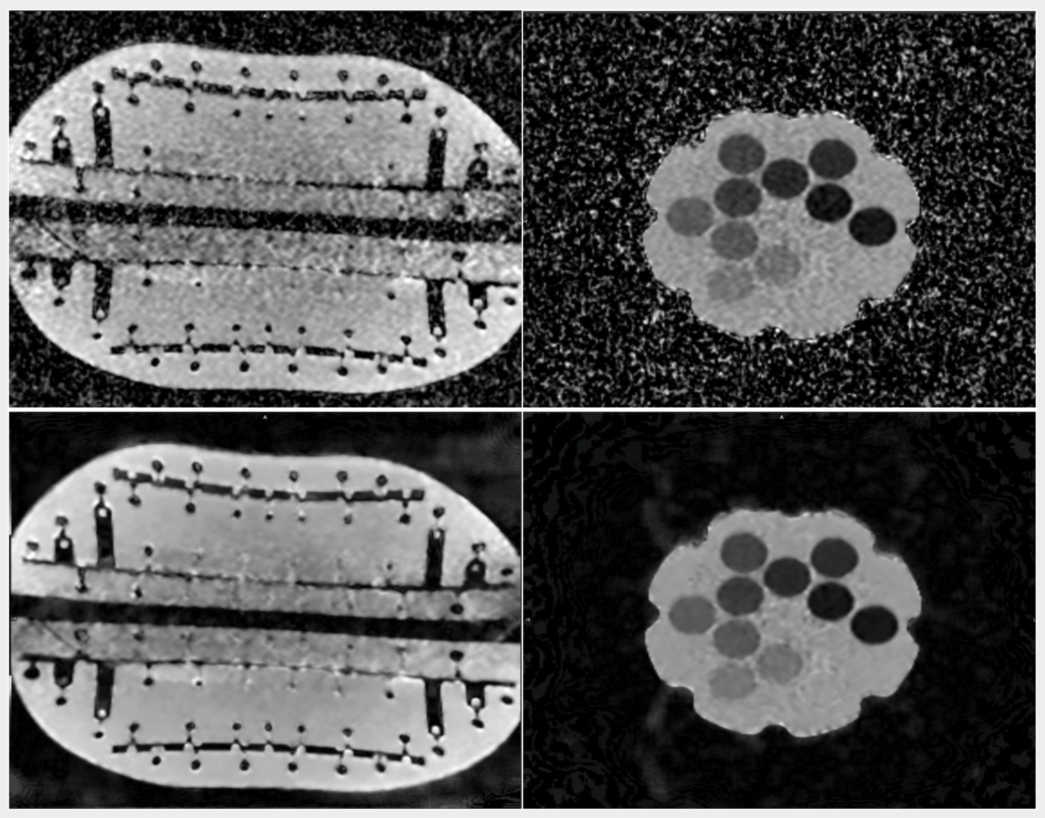
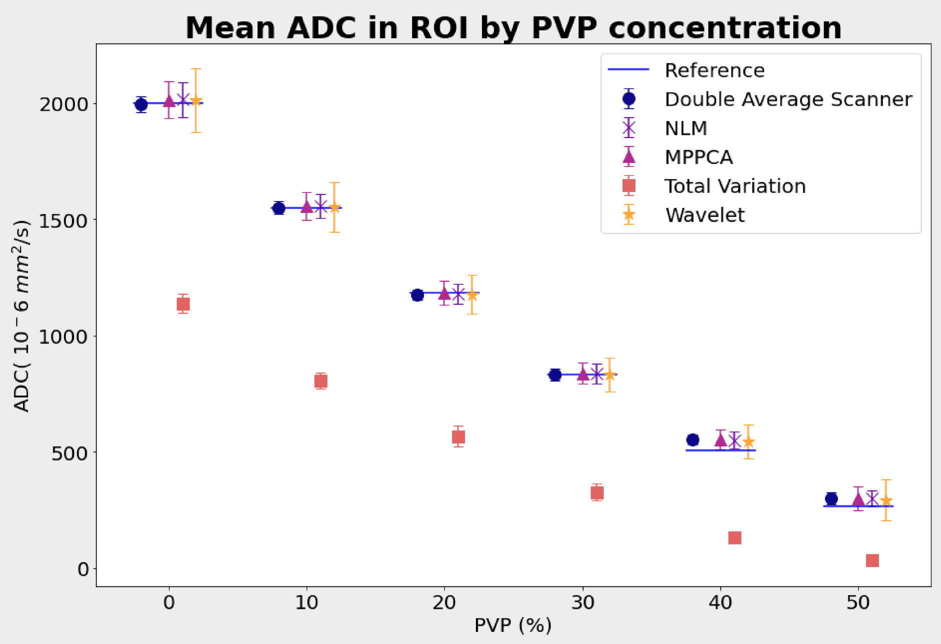


Figure 1. Left column: original 8 average (top) and NLM denoised (bottom) axial image of the MagPhan test object.
Right column: original 1 average (top) and NLM denoised (bottom) axial image of the diffusion phantom.

RESULTS



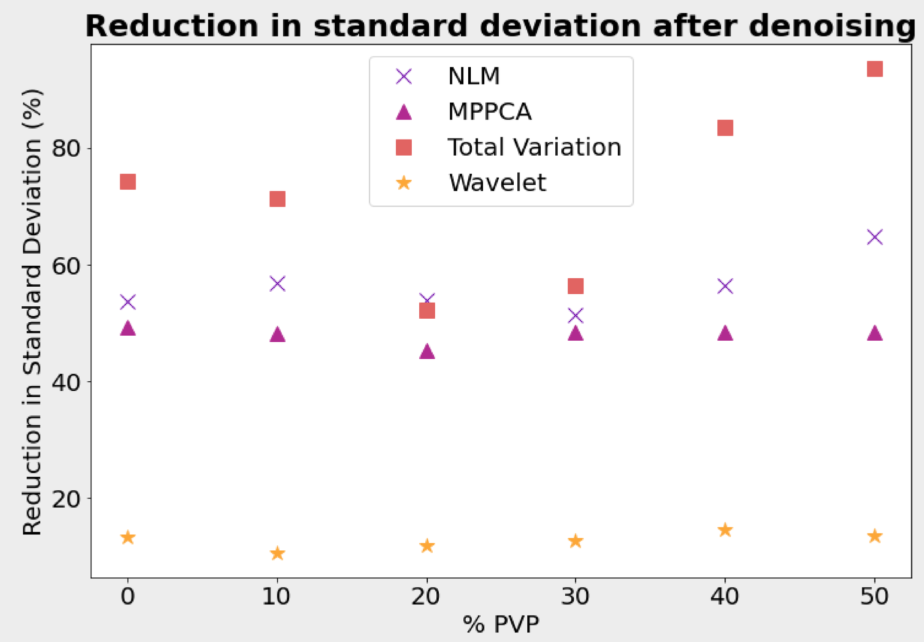


Figure 2.
Left: Mean of ADC values within ROIs placed on Qalibre vials of different PVP concentrations. Error bars represent the standard deviation which served as a measure of noise in ROIs.
Right: Percent reduction in standard deviation after denoising. Standard deviation for each PVP concentration is compared to that of the original 1 average noisy image.

Figure 2 displays diffusion phantom results. Mean ADC was preserved within 2% of the 16 average reference for all methods except TV, which underestimated ADC by 43-88%. NLM demonstrated the best performance by preserving ADC values within 1% of the 16-average reference while improving image quality by reducing the standard deviation by 56% on average. Although TV produced the greatest noise reduction, it substantially underestimated ADC (43-88%), making it unsuitable for quantitative DWI. Wavelet provided the least noise reduction.

MagPhan analysis suggested that sphere detection on ADC maps (Fig. 3A) exhibited best improvement after applying MPPCA and TV denoising methods. TV denoising increased SNR by 811% relative to the 16 average reference (Fig. 3B). NLM ADC also had 268% higher SNR than the scanner reference, which is a notable improvement. PSF and ESF, which quantify image clarity in terms of point blurriness and edge sharpness (Fig 3C-D), showed little change after denoising. NLM and MPPCA were most consistent in the spread function metrics.

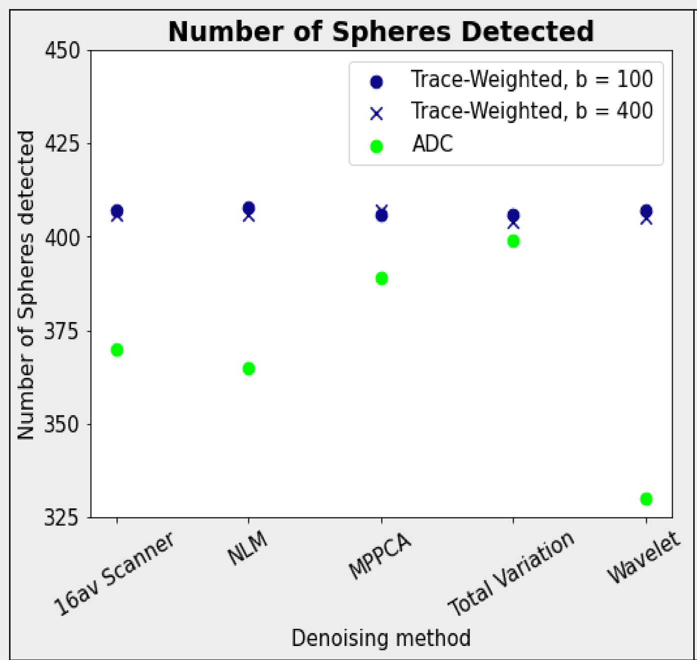


Figure 3A. Number of detected spherical fiducials in MagPhan trace-weighted images and ADC maps denoised using different methods. More detected spheres correspond to better feature detectability in DW images.

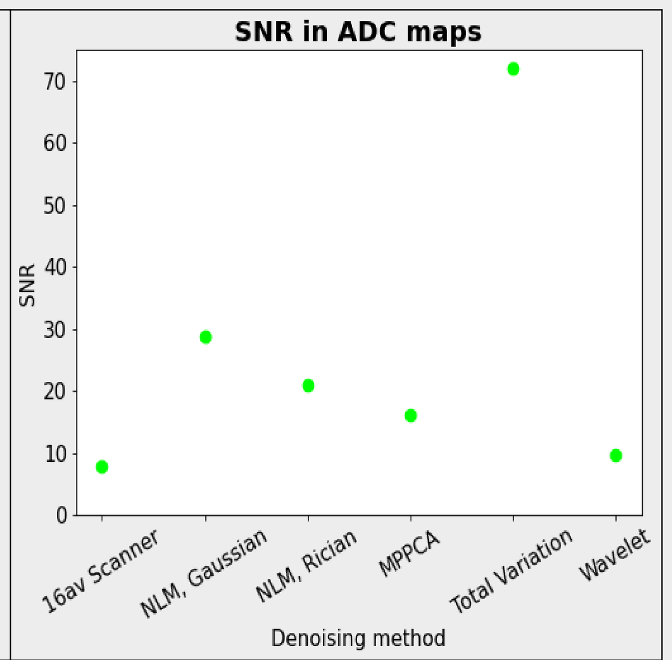


Figure 3B. Signal to Noise ratio for reference and denoised ADC maps of the MagPhan test object. Higher SNR indicates a clearer image with signals that are distinct from background noise.

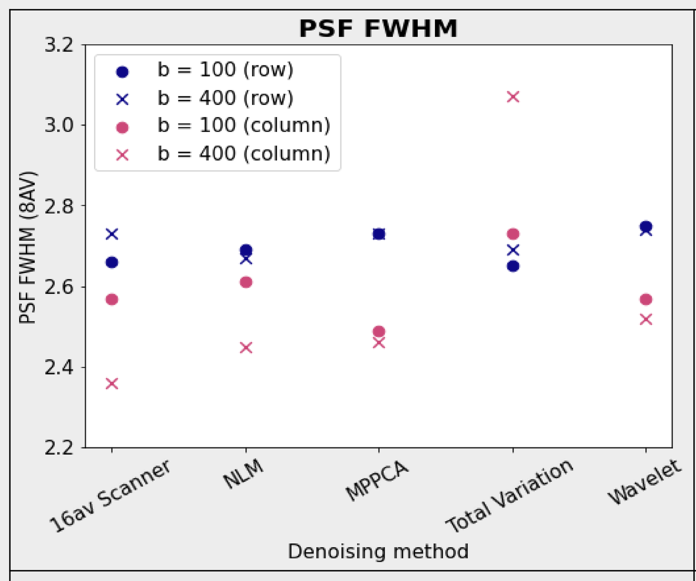


Figure 3C. Full Width at Half Maximum (FWHM) of the Point Spread Function for reference images and each applied denoising method. The FWHM quantifies the spread of signal values that a single voxel takes on in the image set. A smaller FWHM of the PSF signifies higher resolution.

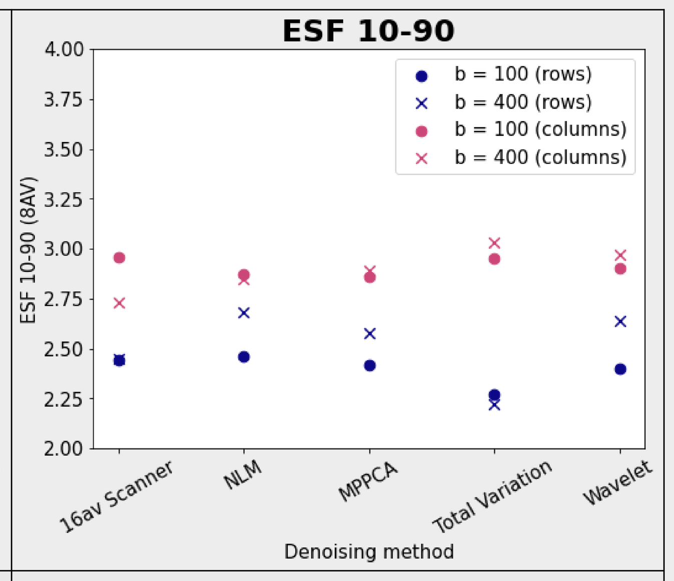


Figure 3D. Width required on the Edge Spread Function for transition between 10 and 90% of a step, representing the sharpness of edges in an image. Lower ESF 10-90 indicates a quicker transition between high and low signal regions, so the edge is better defined.

DISCUSSION

Among the tested algorithms, NLM showed the best ADC preservation compared to the scanner reference for the diffusion phantom. Hence it appears as the most reliable denoising method for accurately reproducing ADC on clinical images. Its noise reduction algorithm determines pixel values by evaluating weighted averages of similar pixels over the whole image. Local filters like MPPCA use patch-based denoising, which may blur images. Therefore, NLM has an advantage over MPPCA in edge preservation metrics. Nevertheless, MPPCA may also be considered in future implementation as its ADC preservation and denoising quality are close to NLM's.

TV failed to accurately reproduce ADC values due to its penalization of the integral of the image gradient magnitude. This smooths images and suppresses image gradients in noisy regions, leading to lower contrast and thus biased ADC calculation. For this reason, it should not be implemented for quantitative evaluation of ADC maps on clinical DWI .

Wavelet provided poor denoising because the method suppresses noise assuming a random Gaussian distribution. However, low SNR DW images have a non-zero noise floor, creating a skewed noise distribution that follows a Rician curve more closely. Consequently, much of the noise is retained in the image after denoising.

CONCLUSIONS

Non-Local Means denoising offered an ideal balance between ADC preservation and image feature detection. These results demonstrate confidence in its implementation to low-field MR-Linac thoracic and pelvic DWI.

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