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MPI Reconstruction Based on System Matrix using a Field Free Line

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Abstract
Magnetic particle imaging (MPI) is a new imaging modality which draws much attention due to its high sensitivity and spatial resolution. The spatial information encoded using a field free line (FFL) exhibit better sensitivity and signal-to-noise ratio compared to field free point (FFP) scanning. In this study, we investigate different reconstruction methods for MPI image based on system matrix and FFL scanning using simulation data. Our results show that existing reconstructed methods are influenced by particle size, noise, iteration coefficient, and trajectory density. We evaluate the weighting iterative method and the results are shown with a phantom. This work bridges the gap between simulation and measurement experimental work by demonstrating the feasibility of reconstructing 2D images using a simulated MPI system matrix and FFL.

I. Introduction

Magnetic particle imaging (MPI) is a emerging and potential imaging modality, which exhibits high sensitivity [1-2], and high spatial resolution in the submillimeter range with high temporal resolution allowing for realtime imaging [3]. Fast and accutate reconstruct MPI image is a potential tool for tracking and diagnosis in clinical applications [4].

Recently, previous studys show that MPI reconstruction based on the system matrix has more accurate reconstruction effect than the X-Space method [5]. To capture spatial information for magnetic nanoparticles (MNPs), certain signals can be obtained using a field free point (FFP), or a field free line (FFL), in which the magnetic field vanishes at a point, or on a line, respectively. Some studies also demonstrate that encoding method of the FFL exhibits better sensitivity and signal-to-noise ratio compared to tthe FFP scanning [5].However, to our best knowledge, whether existing methods could show good performance for MPI reconstruction based on system matrix using a FFL still remains unknown.

Currently, performance analysis of reconstruction algorithms based on MPI canner is still unknown for the magnetic field free line spatial encoding mode. Considering the cost of contructing MPI scanners based on different encoding methods is expensive, and there are limited real MPI data used for researchers.

In this work, we evaluate reconstructed performance of different reconstruction methods for MPI image based on system matrix and FFL scanning. According to mathematical theory of the imaging process, we perform a 2D simulation of MPI based on the system matrix. The MPI reconstruction is carried out and compared using three different methodologies. With the use of a simulated MPI system matrix, our study quantitatively evaluates the performance for different methods.

II. Methods

In order to analyze popular reconstruction methods of Kaczmarz (KZ), Conjugate Gradient Normal Residual (CGNR), and ADMM (Alternating Direction Method of Multipliers), performance analysis for parameters of Gaussian white noise of SNR, paticle size, trajectory density and iterations are conducted. We employ a spatial encoding field that features a FFL to generate simulation data. We also visualize results to show the performance of CGNR method with different parameters.

The reconstruction results are compared from visualization and performance indicators, including the mean squared error (MSE), the structural similarity index measurement (SSIM) and the peak signal-to-noise ratio (PSNR). We also discussed the influence of different parameters on the reconstruction accuracy: the size of the nanoparticle and trajectory density, and iterations. The visualized results of reconstructed images based on the CGNR with different λ is conducted for a simulated phantom.

III. Results

III.I. Performance analysis for noise

In this study, 2D MPI simulation is performed using the mathematical theory of the imaging process, which includes scenarios where the induced voltages are affected by Gaussian white noise of signal-to-noise ratio (SNR). The reconstruction is carried out using three methods: the KZ, CGNR, and ADMM. We compare the reconstruction performance in terms of quantative performance indicators: the MSE, SSIM and PSNR. As shown in Table 1, The KZ method outperforms the others with higher SSIM (0.540) and PSNR (15.050), and lower MSE (0.031). The methods of KZ and ADMM are sensitive to the different noises of SNR. The results also indicates that the change of noise has no effect on the method of CGNR.

III.II. Performance analysis for nanopaticle size

As shown in Table 2, We compare the reconstruction performance for each method with different nanoparticle size. The KZ method shows the best performance with the highest SSIM (0.649) and PSNR (16.283), and the lower MSE (0.024) when the nanoparticle size of diameter is 20nm. The methods of KZ and CGNR are sensitive to the nanoparticle size of diameter. The influence of particle diameter on ADMM method is not obvious. The results also indicates that good quality of reconstructed image requires the selection of appropriate particle size.

Table 1: Performance comparisons for different methods with different Gaussian white noise of signal-to-noise ratio (SNR).

Method	Noise	SSIM	PSNR	MSE
KZ		0.217	10.781	0.084
CGNR	30db	0.036	7.953	0.160
ADMM		0.096	7.821	0.165
KZ		0.405	14.673	0.034
CGNR	40db	0.036	7.936	7.946
ADMM		0.096	11.024	0.079
KZ		**0.540**	**15.050**	**0.031**
CGNR	50db	0.036	7.946	0.160
ADMM		0.118	12.541	0.056

Performance indicator abbreviation, SSIM: structural similarity; MSE: mean squared error; PSNR: peak signal-to-noise ratio; Reconstruction method, KZ: Kaczmarz; CGNR: Conjugate gradient normal residual; ADMM: Alternating direction method of multipliers.

Table 2: Performance comparison for different methods with different nanopaticle size (diameter).

Method	diameter	SSIM	PSNR	MSE
KZ		0.502	11.853	0.056
CGNR	10nm	0.090	2.287	0.591
ADMM		0.644	6.651	0.216
KZ		**0.649**	**16.283**	**0.024**
CGNR	20nm	0.088	4.956	0.319
ADMM		0.627	6.644	0.217
KZ		0.579	15.168	0.030
CGNR	30nm	0.036	7.943	0.161
ADMM		0.617	6.640	0.217

III.III. Performance analysis for trajectory density

We evaluate the three reconstruction methods with different trajectory density (TD). As shown in Table 3, the results show that The KZ method outperforms the others and shows the best performance with the highest SSIM (0.649) when the trajectory density is 20. The KZ method shows the highest PSNR (16.283) and the lowest MSE (0.024) when the trajectory density is 15. The results indicate that the KZ and ADMM shows robust performance for MPI reconstruction and show little disturbance caused by the change of TD.

III.IV. Performance analysis for iterations

To investigate the influence of different iterations values of λ, we compare the three reconstruction methods with different iterations. As shown in Table 4, the results show that the KZ method outperforms the others

10.18416/ijmpi.2023.2303007

Table 3: Performance comparison for different methods with trajectory density (TD) of 20.

Method	TD	SSIM	PSNR	MSE
KZ		0.579	15.168	0.030
CGNR	10	0.036	7.943	0.161
ADMM		0.617	6.640	0.217
KZ		0.629	**16.067**	**0.024**
CGNR	15	0.090	2.303	0.588
ADMM		0.637	6.643	0.217
KZ		**0.697**	16.050	0.025
CGNR	20	0.090	2.328	0.585
ADMM		0.636	6.635	0.217

Note: TD denotes trajectory density.

Table 4: Performance comparison for different methods with different iterations.

Method	iteration	SSIM	PSNR	MSE
KZ		0.579	15.168	0.030
CGNR	$\lambda=10^{-6}$	0.036	7.943	0.161
ADMM		0.617	6.640	0.217
KZ		0.583	**15.171**	**0.030**
CGNR	$\lambda=10^{-1}$	0.036	7.943	0.161
ADMM		0.147	12.645	0.054
KZ		**0.589**	15.138	0.031
CGNR	$\lambda=1$	0.036	7.943	0.161
ADMM		0.147	12.645	0.054

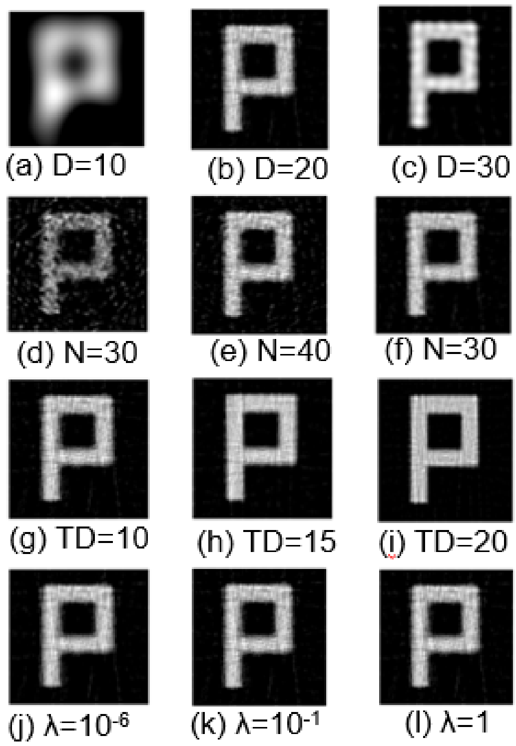

Figure 1: The reconstruction results based on CGNR method of different parameters with P-shaped phantom. Abbreviation: D represents particle size of diameter; N denotes Gaussian white noise with different signal to noise; λ denotes weight parameter in each reconstruction method; TD denotes trajectory density.

and shows the best performance with the highest SSIM (0.589) when the λ is 1. The KZ method shows the highest PSNR (15.171) and the lowest MSE (0.03) when the λ is 0.1. The results indicate that the KZ shows robust performance for MPI reconstruction.

III.V. Performance evaluation for different parameters

Based on the previous findings, the results shows that the CGNR method has poorer performance than the others. As shown in Fig. 1, we take the CGNR method as example and visualize the reconstructed images based on different parameters. The results show that the reconstruction method of CGNR is sensitive to the particle size and noise. Furthermore, it's almost unaffected by the iteration.

IV. Discussion and conclusion

In our study, we compare three reconstruction methods based on different parameters to implement a 2D simulation of MPI based on the system matrix and the FFL scanning. Three methods are used to conduct and compare the MPI reconstruction using three indicators for the performance evaluation. The KZ method outperform other methods for MPI reconstruction, which may be related to the simulation data set, the further work for MPI reconstruction we should do in real MPI data.

Considing the cost of contructing MPI scanners based on encoding method of system matrix, this work bridges the gap between simulation and measurement experimental work by demonstrating the viability of reconstructing 2D images using a simulated MPI system matrix.

We draw following conclusions based on the experimenal results: (1) The KZ method shows good and robust performance for MPI reconstruction based on system matrix using a FFL. (2) With different Gaussian white noise, The KZ method in MPI reconstruction is with higher anti-noise performance. (3) The KZ method in MPI reconstruction is with higher anti-noise performance. Compared with the PCG method, Tikhonov regularization and LSQR method are with stronger robustness regarding higher noise levels. (4) Different particle size and iteration coefficient should be considered for MPI reconstruction performance.

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