International Journal on Magnetic Particle Imaging
Vol 10, No 1, Suppl 1, Article ID 2403030, 4 Pages

Proceedings Article

Improving the Resolution of Single-harmonic MPI Using Perpendicular Signal Transformation

Yidong Liao[a,b,c] · Lei Li[a,b,c] · Dawei Ge[a,b,c] · Ning He[a,b,c] · Pengyue Guo[a,b,c] · Jiawei Hu[a,b,c] · Chenxiao Xu[a,b,c] · Yunpeng Gao[a,b,c] · Zhonghao Zhang[a,b,c] · Qibin Wang[a,b,c] · Lingwen Hou[a,b,c] · Kai Liu[a,b,c] · Yu Zeng[a,b,c] · Chenglong Shi[a,b,c] · Man Luo[a,b,c] · Yihan Wang[a,b,c] · Shouping Zhu[a,b,c,*]

[a]School of Life Science and Technology, Xidian University & Engineering Research Center of Molecular and Neuro Imaging, Ministry of Education, Xi'an, Shaanxi 710126, China
[b]Xi'an Key Laboratory of Intelligent Sensing and Regulation of trans-Scale Life Information & International Joint Research Center for Advanced Medical Imaging and Intelligent Diagnosis and Treatment, School of Life Science and Technology, Xidian University, Xi'an, Shaanxi 710126, China
[c]Innovation Center for Advanced Medical Imaging and Intelligent Medicine, Guangzhou Institute of Technology, Xidian University, Guangzhou, Guangdong 51055, China
[*]Corresponding author, email: spzhu@xidian.edu.cn

Abstract

In single-harmonic magnetic particle imaging (MPI), image reconstruction is typically achieved through deconvolution using the point spread function (PSF) corresponding to the 3^{rd} harmonic signal received parallel to the excitation field. In this study, we present an improved single-harmonic MPI reconstruction method. The method is based on transforming the 3^{rd} harmonic signal received perpendicular to the excitation field. Specifically, we perform a quadratic derivation operation on the original perpendicular signal in the image domain along the non-excitation direction for deconvolution reconstruction. Experimental results demonstrated that our method, compared to the reconstruction using the raw original parallel 3^{rd} harmonic signals and raw perpendicular 3^{rd} harmonic signals, not only effectively improves resolution but also better recovers the shape contour of the phantom. Specifically, the proposed method achieves at least a 2-fold increase in resolution compared to the deconvolution reconstruction by the raw parallel 3^{rd} harmonic signals.

I. Introduction

Magnetic particle imaging (MPI) is an emerging imaging technique that enables the detection of superparamagnetic iron oxide nanoparticles (SPIONs)[1]. MPI holds great potential in various applications, including stroke detection, cancer tracking, and vascular imaging[1]–[4].

In magnetic particle detection and imaging, one of the common methods is to detect a specific single harmonic signal that represents the magnetic response of the particles. Single-harmonic MPI is an advanced narrowband MPI technique, where the reconstructed images are obtained through deconvolution with the point spread function (PSF) corresponding to the 3^{rd} harmonic. This approach reduces the bandwidth requirements and improves the signal-to-noise ratio at a fixed

10.18416/ijmpi.2024.2403030

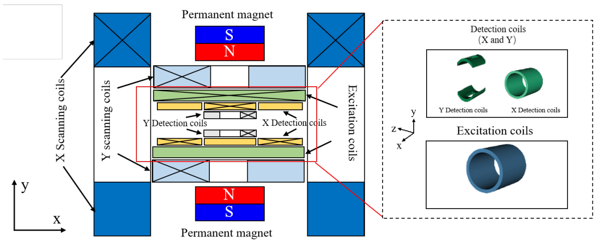

Figure 1: Schematic of the single harmonic MPI scanner.

specific absorption rate.

In some single-excitation MPI setups, the receive coil and excitation coil are placed in the same direction[1], [5], [6]. However, in the literature, it has been mentioned that the receive coil can be placed in a non-excited direction to capture the magnetization signal perpendicular to the excitation field, known as the perpendicular magnetization signal[7],[8]. Perpendicular magnetization is a method used to enhance the signal sensitivity by receiving the SPIONs signal in a direction perpendicular to the excitation field[7]–[9].

In this study, we proposed utilizing a transformation of the perpendicular magnetization signal for deconvolution reconstruction. Experimental results demonstrated that this approach effectively improves the resolution of the reconstructed images compared to the raw perpendicular third harmonic deconvolution results.

II. Material and methods

II.I. In-house Single-harmonic MPI scanner

Figure 1 illustrates the coil configuration schematic of our single-harmonic MPI scanner. A pair of NdFeB permanent magnets generate a field-free point (FFP) with gradients of approximately 3.2 T/m in the y direction and 1.6 T/m in the x and z directions. The solenoidal coil generates an excitation field of approximately 10 mT in the x direction at 25 kHz.

The scanning coils produce scanning fields in the x and y directions under 50 Hz and 1 Hz, respectively. The amplitude of the scanning fields is approximately 18 mT (x-direction) and 36 mT (y-direction), resulting in a 2D field of view (FOV) of approximately 23 mm× 23 mm.

Compared to[6], our scanner uses an additional saddle detection coil to receive the perpendicular magnetization signal. The SPIONs 3^{rd} harmonic signals in the parallel (x-direction) and perpendicular direction(y-direction) are received synchronously utilizing a lock-in amplifier (Zurich Instruments, Zurich, Swiss Confederation). In addition, our device has achieved complete electrical scanning by adding a pair of scanning coils, which reduces the measurement time to 1 s.

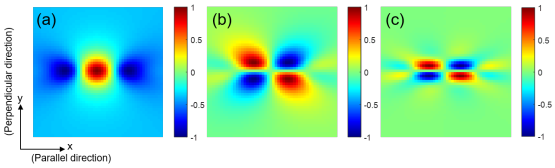

Figure 2: The simulated PSF. (a) The simulated PSF in the x-direction (parallel PSF); (b) The simulated PSF in the y-direction (perpendicular PSF); (c)The PSF obtained from the second-order derivative transformation along the y-direction of Figure2 (b) (perpendicular PSF transformation).

II.II. 2D Perpendicular signal transformation

Based on the orientation of the receive coil, each harmonic PSF typically exhibits two distinct shapes[10]. In this study, we used the 3^{rd} harmonic as an example. These PSFs can be directly measured by placing a point source at the center of the FOV. The PSF parallel to the excitation coil is known as the parallel PSF(shown in Figure 2(a)), while the PSF corresponding to the perpendicular signal received perpendicular to the excitation is referred to as the perpendicular PSF(shown in Figure 2(b)). In single-harmonic MPI, these PSFs can be directly used as the deconvolution kernels for reconstruction.

Figure 2(b) shows that the raw perpendicular PSF exhibits significant variations in signal, which can introduce signal indistinguishability and distortions during the deconvolution process.

This study proposed a method by performing a second derivative transformation along the non-excitation field direction (perpendicular direction) in the image domain for the raw perpendicular PSF. Figure 2(b) and (c) illustrate the simulation of this approach. Figure 2(c) shows that the perpendicular PSF transformation leads to a reduction in PSF area. This results in a more localized PSF, effectively mitigating signal spreading during deconvolution and enhancing resolution. Specifically, the second-order derivation of the perpendicular PSF is equivalent to extracting the boundary contour of the PSF to obtain a more local PSF (the area of the PSF decreases). Since the original MPI image can be represented as the convolution result of the spatial distribution of particle concentration and the PSF. So the smaller the PSF, the deconvolution will yield a higher resolution spatial distribution of particle concentrations[10], [11].

II.III. Image reconstruction

In single-harmonic MPI, to obtain the concentration distribution of SPIONs, the raw image (harmonic distribution map) should be deconvoluted with the PSF obtained from a point-like phantom. In practice, deconvolution is accomplished by solving Eq.1 and Eq.2:

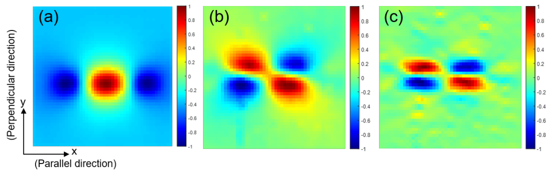

Figure 3: The measured PSF in our in-house MPI scanner. (a) The measured PSF in the x-direction (parallel PSF); (b)The measured PSF in the y-direction (perpendicular PSF); (c)The PSF obtained from the second-order derivative transformation along the y-direction of Figure 3(b) (perpendicular PSF transformation).

$$A_{//} \times c = M_{//} \tag{1}$$

$$A_{\perp} \times c = M_{\perp} \tag{2}$$

where $A_{//}$ and $A_{\perp}$ are the system matrices converted from the parallel PSF and the perpendicular PSF, respectively. c represents the concentration distribution of SPIONs. $M_{//}$ and $M_{\perp}$ are the measured parallel and perpendicular raw images, respectively. For more details, please refer to[6].

In our proposed method, we perform a second derivative transformation along the non-excitation field direction (y-direction) on $A_{\perp}$ and $M_{\perp}$, resulting in high-resolution perpendicular PSF and perpendicular raw image. We then utilize these for deconvolution reconstruction, as shown in Eq.2.

Eq.1, Eq.2, and Eq.3 are all solved using the weighted Kaczmarz method[12].

$$A_{\text{trans}} \times c = M_{\text{trans}} \tag{3}$$

where $A_{\text{trans}} = (A_{\perp})''_{xx}$,$M_{\text{trans}} = (M_{\perp})''_{xx}$.

III. Results

III.I. Measured 2D PSF

To obtain $A_{//}$ and $A_{\perp}$, measurements were performed using a 5µL undiluted synomag-D SPIONs sample purchased from Micromod GmbH (Rostock, Germany). Figure 3 shows the PSFs obtained through measurements on our in-house developed device.

III.II. Resolution enhancement based on perpendicular signal transformation

To confirm the effectiveness of resolution enhancement through the transformation of the raw perpendicular signal, we conducted a comparison of the resolution performance between the parallel signal, perpendicular signal, and the transformed perpendicular signal using line pair phantoms with intervals of 2mm, 1.8mm, 1.6mm, 1.4mm, and 1mm on our in-house MPI system. The line pair phantoms were filled with undiluted synomag-D particles.

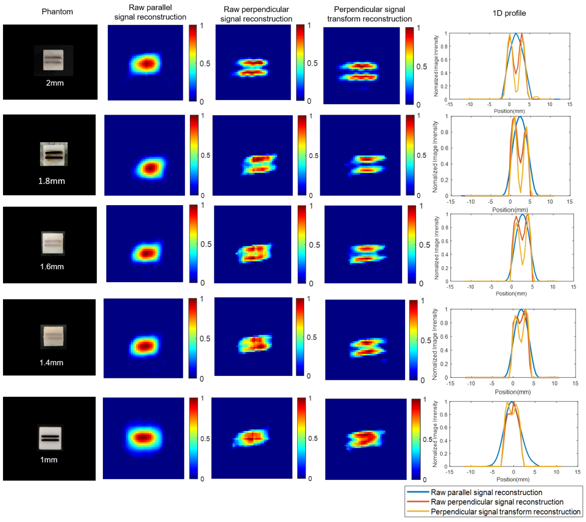

Figure 4: Experimental imaging results of line pair phantoms using the in-house single-harmonic MPI scanner.

In Figure 4, the first column displays the images of the phantom. The second column shows the reconstruction results of the raw parallel receive signal, which is parallel to the excitation field (solved by Eq.1). The third column displays the reconstruction results of the raw perpendicular receive signal, which is perpendicular to the excitation field (solved by Eq.2). The fourth column presents the reconstruction results of the transformation on the raw perpendicular signal. The fifth column of Figure 4 shows the 1D profile comparison of these imaging results.

When using the parallel signal for reconstruction, it is apparent that no distinction can be made between any pairs of lines in the phantom. With the raw perpendicular signal used for reconstruction, the best achievable resolution is 1.4mm. However, when using the transformed perpendicular signal for reconstruction, it can be observed that the resolution is the best among the three methods, reaching approximately 1mm. Furthermore, the reconstructed results using the transformed perpendicular signal exhibit an advantage in shape contour compared to the line pair imaging results obtained from the reconstruction using the raw perpendicular signal.

IV. Discussion

In this study, we proposed a single-harmonic MPI reconstruction method based on perpendicular signal transformation. Compared to the conventional deconvolution

10.18416/ijmpi.2024.2403030

method using parallel receive signals for reconstruction, our method significantly enhances the spatial resolution of the reconstructed images. In addition to resolution improvement, using the transformed perpendicular signals for reconstruction also yields the best shape recovery of the entire line pair phantom among the three methods.

The method proposed in this paper utilizes perpendicular receive coils to capture the perpendicular signal. Theoretically, the perpendicular signal should naturally decouple from the excitation magnetic field. However, in reality, irregularities in the coils and field inhomogeneities can lead to the presence of excitation feedthrough signal, resulting in a decreased signal-to-noise ratio. Additionally, it can cause certain stretching deformations in the PSF. Nevertheless, these challenges do not render the method impractical, as recently developed active compensation methods can effectively address excitation feedthrough and other harmonic interferences[13], [14],[15],[16]. As for the PSF stretching issue, it can be improved by enhancing the coil design[17].

V. Conclusions

In this work, we propose a single-harmonic MPI reconstruction method based on perpendicular signal transformation. This method performs a second-order derivative transform of the raw perpendicular PSF along the direction of the non-excitation field (perpendicular direction) in the image domain to obtain a perpendicular transformed PSF as an inverse convolution kernel for reconstruction. Experimental results demonstrated that our method, compared to the reconstruction using the raw original parallel 3^{rd} harmonic signals and raw perpendicular 3^{rd} harmonic signals, not only effectively improves resolution but also better recovers the shape contour of the phantom. Specifically, the proposed method achieves at least a 2-fold increase in resolution compared to the deconvolution reconstruction by the raw parallel 3^{rd} harmonic signals.

Acknowledgments

This work was supported by the National Natural Science Foundation of China under Grant Nos. 62027901, 62071362, 82272050, 61901342, the National Key Research and Development Program of China under Grant No. 2022YFB3203803, the Natural Science Basic Research Program of Shaanxi Province under Grant Nos. 2021JZ-29, 2021SF-131, 2021SF-169.

Author's statement

Conflict of interest: Authors state no conflict of interest.

References

[1] B. Gleich and J. Weizenecker, “Tomographic imaging using the nonlinear response of magnetic particles,” Nature, vol. 435, pp. 1214–1217, 2005.

[2] P. Ludewig et al., “Magnetic particle imaging for assessment of cerebral perfusion and ischemia.,” Wiley Interdiscip. Rev. Nanomed. Nanobiotechnol., p. e1757, 2021.

[3] X. Yang et al., “Applications of Magnetic Particle Imaging in Biomedicine: Advancements and Prospects,” Front. Physiol., vol. 13, 2022, [Online]. Available: https://api.semanticscholar.org/CorpusID:250180708

[4] P. Vogel et al., “iMPI: portable human-sized magnetic particle imaging scanner for real-time endovascular interventions,” Sci. Rep., vol. 13, 2023, [Online]. Available: https://api.semanticscholar.org/CorpusID:259285238

[5] P. W. Goodwill et al., “X-Space MPI: Magnetic Nanoparticles for Safe Medical Imaging,” Adv. Mater., vol. 24, 2012.

[6] K.-J. Janssen, M. Schilling, F. Ludwig, and J. Zhong, “Single harmonic-based narrowband magnetic particle imaging,” Meas. Sci. Technol., vol. 33, 2022.

[7] D. B. Reeves and J. B. Weaver, “Magnetic nanoparticle sensing: decoupling the magnetization from the excitation field,” J. Phys. Appl. Phys., vol. 47, 2014.

[8] J. B. Weaver, “Perpendicular Magnetic Particle Imaging, pMPI,” IEEE Trans. Magn., vol. 51, pp. 1–4, 2015.

[9] L. Li et al., “Improving single harmonic MPI performance Using perpendicular magnetization,” Int. J. Magn. Part. Imaging IJMPI, vol. 9, no. 1 Suppl 1, 2023.

[10] J. Rahmer, J. Weizenecker, B. Gleich, and J. Borgert, “Signal encoding in magnetic particle imaging: properties of the system function,” BMC Med. Imaging, vol. 9, pp. 4–4, 2009.

[11] X. Liu et al, “Research Progress of Computational Microscopy Imaging Based on Point Spread Function Engineering,” Laser Optoelectron. Prog., vol. 58, no. 18, p. 1811008, 2021.

[12] T. Knopp et al., “Weighted iterative reconstruction for magnetic particle imaging,” Phys. Med. Biol., vol. 55, pp. 1577–1589, 2010.

[13] D. Pantke, N. Holle, A. Mogarkar, M. Straub, and V. Schulz, “Multifrequency magnetic particle imaging enabled by a combined passive and active drive field feed-through compensation approach,” Med. Phys., vol. 46, pp. 4077–4086, 2019.

[14] Y. Gao et al., “2-D magnetic particle imaging based on actively feedthrough fundamental frequency recovery,” Int. J. Magn. Part. Imaging IJMPI, vol. 9, no. 1 Suppl 1, 2023.

[15] M. Fujimoto, N. Futagawa, K. Higashino, T. Sasayama, and T. Yoshida, “Direct Magnetic Field Compensation Circuit for Improved Stability of Magnetic Nanoparticle Tomography,” 2023 IEEE Int. Magn. Conf. INTERMAG, pp. 1–5, 2023.

[16] L. Yin et al., “A Streamlined 3-D Magnetic Particle Imaging System With a Two-Stage Excitation Feed-Through Compensation Strategy,” IEEE Trans. Instrum. Meas., vol. 72, pp. 1–10, 2023.

[17] P. Vogel, T. Kampf, M. A. Ruckert, and V. C. Behr, “Novel Fabrication Method for Nested Saddle Coils,” IEEE Trans. Magn., pp. 1–6, Sep. 2020, doi: 10.1109/tmag.2020.3007358.

10.18416/ijmpi.2024.2403030