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Investigating the Limits of Solid-Liquid Phase Differentiation in Multi-Color Magnetic Particle Imaging

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Abstract

Multi-color Magnetic Particle Imaging (MPI) offers the ability to distinguish magnetic nanoparticles (MNPs) based on their physical states, enhancing its use in functional imaging and interventional guidance. This study explores the limits of solid-liquid phase differentiation in multi-color MPI. A customized MPI setup was used to test mixed-phase samples, highlighting the relationship between the solid-liquid phase differentiation resolution and system detection resolution. Results show that improving solid-liquid phase differentiation requires both point spread function (PSF) optimization and increased system detection resolution.

I. Introduction

Multi-color MPI extends the capabilities of standard MPI by enabling differentiation between various MNPs based on their physical states or properties [1]. This capability is essential for applications such as targeted drug delivery, hyperthermia, and functional imaging. Previous studies have demonstrated that multi-color MPI, achieved by solving system equations, can distinguish between different aggregation states - such as fluid versus solid phases - and differentiate between free and cell-bound nanoparticles [2].

In this study, we used a home-built MPI setup to test solid-liquid mixed Resovist (PDRadiopharma Inc.) samples and applied the previously mentioned approach to reconstruct the particle distributions, with a focus on exploring the solid-liquid phase differentiation limits in multi-color MPI.

II. Methods and materials

II.I. Theory

For the typical MPI image reconstruction problem, assuming the system is linear, the following equation is often used:

$$\mathbf{S} \cdot c = \mathbf{V} \tag{1}$$

where $\mathbf{S}$ is the system matrix, which can be obtained through a measurement-based approach or a model-based approach, c is the particle concentration distribution, and $\boldsymbol{V}$ is the induced MPI voltage signal.

When the MNPs injected into the biological tissue was immobilized, the signal changes accordingly [3], and (1) can be extended as [1]:

$$\begin{pmatrix} \mathbf{S}_{\text{solid}} & \mathbf{S}_{\text{liquid}} \end{pmatrix} \begin{pmatrix} c_{\text{solid}} \\ c_{\text{liquid}} \end{pmatrix} = \mathbf{V} \tag{2}$$

where $\mathbf{S}_{\text{solid}}$ and $\mathbf{S}_{\text{liquid}}$ are the system matrices of the solid and liquid phase samples, respectively. Similarly,

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Table 1: Estimated Concentration of Solid and Liquid Phase

Liquid Concentration relative to Solid	Estimated Solid Concentration / c/278.75 µg	Estimated Liquid Concentration / c/278.75 µg	Solid Estimating Error / µg (relative error)	Solid Estimating Error / µg (relative error)
25%	0.946	0.300	15.094 (5.4%)	13.904 (20.0%)
50%	0.936	0.526	17.929 (6.4%)	7.365 (5.3%)
75%	0.886	0.857	31.787 (11.4%)	29.919 (14.3%)
100%	0.885	1.039	32.174 (11.5%)	10.902 (3.9%)

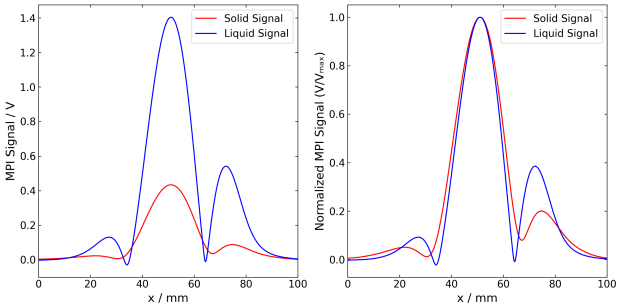

Figure 1: 1 Dimension PSF of Resovist (left) and Normalized MPI Signal (right).

c_{solid} and c_{liquid} are the particle concentration distributions in the solid and liquid phase. Here immobilized MNPs was simulated to the solidified MNPs.

II.II. Experiments

We used a home-built MPI setup to analyze the differentiation resolution for solid and liquid MNPs. The magnetic field gradient along the x-axis was set to 0.4 T/m, and the excitation field had an amplitude of 12 mT at a frequency of 11.48 kHz. Measurements showed that, for 15 µL liquid-phase Resovist samples, the detection resolution of this setup was 10 µg.

We conducted x-axis scans on both solid and liquid Resovist samples to obtain their one-dimensional PSF, as shown in Figure 1. To assess the ability to differentiate between solid and liquid phases in mixed samples, we prepared four sets of samples with varying liquid-phase iron content at 25%, 50%, 75%, and 100% relative to a fixed solid-phase iron content of 278.75 µg. In each sample, resin was used to prepare 150 ml of solid sample in a container, and 50 ml of liquid sample was then injected into the container after the curing process was completed.

III. Results and discussion

III.I. Results

The measured signals are shown in the left of Figure 2. After performing deconvolution using the system matrix constructed from PSFs with a bounded linear least squares method, the reconstructed distributions of solid and liquid MNPs are obtained as shown in Table 1. The errors are calculated as the absolute differences between the reconstructed values and the true iron quantities, confirming the effectiveness of the method.

III.II. Discussion

Our MPI setup has a detection resolution of approximately 10 ug of Resovist. However, when using the proposed solid-liquid phase differentiation approach, the reconstructed iron quantities for solid and liquid phases exhibited an error margin of around 30 ug, which lags behind the system detection resolution.This discrepancy highlights the limitation in the solid-liquid phase differentiation process when applied to mixed samples. While the MPI system itself is sensitive enough to detect smaller amounts of magnetic material, the accuracy of distinguishing between solid and liquid phases is constrained by factors such as signal overlap, differences in PSF, and the challenges associated with deconvolution. We suggest that under fixed system resolution, improvements in PSF and deconvolution methods can only bring the solid-liquid phase differentiation resolution closer to the system detection resolution, but do not yet demonstrate it conclusively. We also acknowledge that other factors - such as imperfect linearity, may contribute to the observed errors.

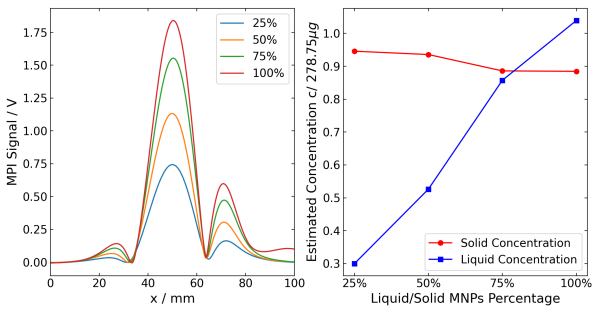

Figure 2: MPI Signal of Hybrid Samples(left) and Reconstructed Distribution of Solid and Liquid MNPs(right)

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IV. Conclusion

This study explored the limits of solid-liquid phase differentiation in multi-color MPI using a home-built experimental setup. By investigating the system's detection resolution and evaluating their impact on distinguishing between solid and liquid phases of MNPs, we identified key factors contributing to solid-liquid phase differentiation errors. Understanding these limits provides valuable insights into enhancing the resolution of solid-liquid phase differentiation in MPI.

Acknowledgments

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study.

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