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Multi-contrast MPI channel leakage reduction using a two-step measurement and reconstruction method

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Abstract

Magnetic particle imaging (MPI) is an imaging modality that measures the response of magnetic nanoparticle tracers to alternating magnetic fields. There has recently been exploration into multi-contrast MPI, in which the signal from different tracer materials or environments is separately reconstructed, resulting in multi-channel images that enable temperature or viscosity quantification. In this work, we investigate the channel leakage in multi-contrast MPI reconstruction and we introduce a two-step measurement and reconstruction method to quantify and reduce channel leakage between multi-contrast MPI channels.

I. Introduction

Magnetic particle imaging (MPI) is a new tomographic medical imaging technique that employs static and dynamic magnetic fields. The magnetization response of magnetic nanoparticles (MNPs) in MPI is recorded, allowing for spatial encoding of MNP distribution using gradient fields [1]. The possibility of multi-contrast MPI has been recently explored, in which the signal from different tracers or tracer environments is separated [2]. In standard single-contrast MPI, the image is reconstructed from the induced voltage signal using a single system matrix. With multi-contrast MPI, multiple system matrices are used to reconstruct multi-channel images. Multi-contrast MPI reconstruction can separate signals from different tracers or different tracer environments, such as material [2], core size [3], temperature [4], or viscosity [5]. A detailed theoretical description of multi-contrast frequency-space MPI can be found in [5].

Multi-contrast MPI reconstruction is quite challenging due to the difficulty of correctly separating the signal into the different channels. This difficulty leads to an exclusive type of artifact for multi-contrast MPI reconstruction, called channel leakage. This work introduces a two-step measurement and reconstruction method to quantify and reduce channel leakage between multi-contrast MPI channels.

II. Methods and materials

II.I. Two-Step Measurement & Reconstruction Method

This two-step method implies modifications to both the measurement scheme and the reconstruction method. For the sake of simplicity, the method is explained in a two-channel multi-contrast scenario while the idea can be generalized for more channels. To start with the measurement scheme, this method introduces an extra prior measurement step where a single channel is measured with the other channel left empty as follows:

$$\begin{pmatrix} S_1 & S_2 \end{pmatrix} \begin{pmatrix} c_1 \\ \mathbf{0} \end{pmatrix} = \tilde{u}. \tag{1}$$

Here, S_1 and S_2 are the system matrices, c_1 is the channel-one phantom, and $\tilde{u}$ is the additional data measurement vector. This additional measurement data $\tilde{u}$ is exploited to quantify the leakage and thus reduce it. After that, the regular experiment measurement scheme is conducted, which is described with the following forward model

$$\begin{pmatrix} S_1 & S_2 \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = u, \tag{2}$$

where c_2 represents the channel-two phantom. Moving to the reconstruction scheme, figure 1 explains the steps of the proposed method. First, the method starts with reconstructing (1) and (2), which results in the solutions shown in the flowchart. $l_{1,2}$ and $l_{2,1}$ represent the leakage in the first and the second channels, respectively. Then, the solution of (1) is subtracted from the solution of (2) as follows

$$\begin{pmatrix} (c_1 + l_{1,2}) - \tilde{c}_1 \\ (c_2 + l_{2,1}) - \tilde{l}_{2,1} \end{pmatrix} \approx \begin{pmatrix} \tilde{l}_{1,2} \\ \tilde{c}_2 \end{pmatrix}. \tag{3}$$

$\tilde{l}_{1,2}$ is an approximation of the leakage from the second channel and $\tilde{c}_2$ is an approximation of channel-two phantom reconstruction with no leakage. Then, subtracting (3) from the solution of (2) gives

$$\begin{pmatrix} (c_1 + l_{1,2}) - \tilde{l}_{1,2} \\ (c_2 + l_{2,1}) - \tilde{c}_2 \end{pmatrix} \approx \begin{pmatrix} \tilde{c}_1 \\ \tilde{l}_{2,1} \end{pmatrix}, \tag{4}$$

where $\tilde{c}_1$ is an approximation of channel-one phantom reconstruction with no leakage and $\tilde{l}_{2,1}$ is an approximation of the leakage from the first channel. Finally, sorting everything together, we get an approximation of a final solution with reduced leakage as shown in the flowchart.

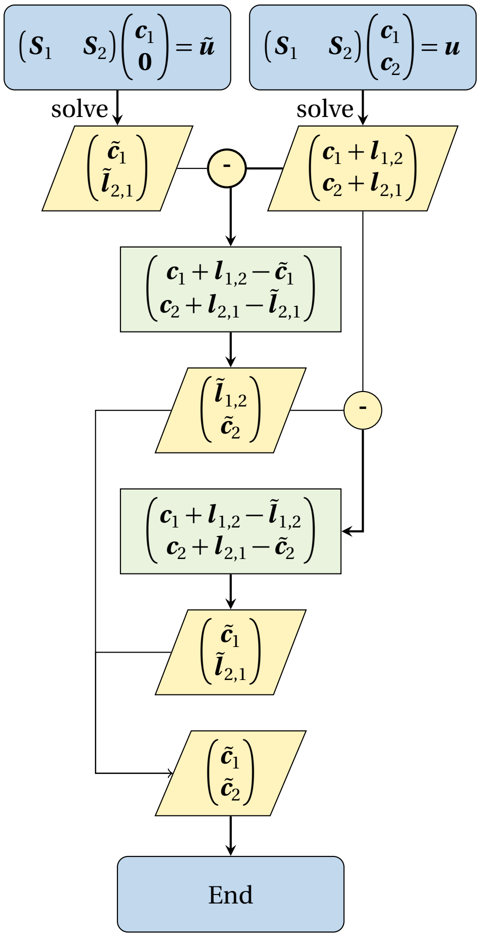

Figure 1: This flowchart describes the two-step measurement and reconstruction method.

II.II. Leakage Reduction Evaluation Tools

Channel leakage represents a kind of artifact in multi-contrast MPI, where part of the reconstructed signal is falsely leaking into the wrong channel. Thus, it is an artifact that is spatially dependent on the particle distribution in the other channels. Creating a leakage measure to quantify the amount of channel leakage in the reconstructed images is considered to evaluate the effectiveness of the proposed method. A mask m_i is created for the phantom in each channel i, where 0 values represent the phantoms and the rest of the mask is filled with 1 values, and applied to the reconstructed images and the mean of the non-zero pixels is summed up to represent the leakage per channel as follows:

$$\mathfrak{L}_i = \frac{\sum_{\text{pixels}} (c_i \times m_i)}{N}. \tag{5}$$

$\mathfrak{L}_i \geq 0$ should be as small as possible for optimal reconstruction results and N is the number of pixels. This leakage measure gives a more accurate approximation of the channel leakage when the reconstruction noise is minimal.

III. Experiments

III.I. Experimental Setup

Immobilized and mobilized perimag-based system matrices S_1 and S_2 are measured using the preclinical MPI scanner (Bruker, Ettlingen, Germany) on a grid of $24 \times 24 \times 24$. The delta sample had a size of $2 \times 2 \times 1\,\text{mm}^3$. The gradient field strength is $1.5\ \text{Tm}^{-1}\mu_0^{-1}$ in z-direction and $-0.75\ \text{Tm}^{-1}\mu_0^{-1}$ in x- and y-directions. The drive

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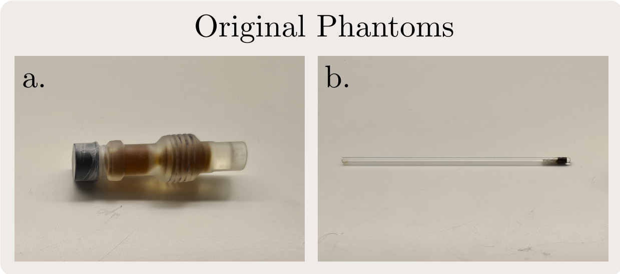

Figure 2: (a) the vessel stenosis phantom. (b) the catheter phantom.

field amplitude is 12 $mT\mu_0^{-1}$ in each direction. This created a FOV of size $24 \times 24 \times 24$mm.

A vessel with stenosis is 3D printed and then filled with perimag tracer as shown in figure 2 (a). This vessel phantom has a length of 40 mm, a maximum inner radius of 13 mm, and a minimum inner radius of 5mm. A thin glass capillary (inner diameter 1.3 mm) is used as a catheter. The glass capillary is filled with a drop of solid perimag tracer as seen in figure 2 (b). The experiment starts with measuring solely the perimag-filled stenosis phantom. Next, the thin glass capillary filled with a dot of immobilized perimag representing the catheter is introduced into the stenosis phantom and then moved back and forth through the FOV. A total of 10 000 frames is measured. The catheter movement is achieved via a custom-built inserting tool while the stenosis phantom is mounted along the scanner bore. This results in two different MPI datasets reconstructed from the two measurements: the dataset of the catheter and the stenosis from the multi-contrast MPI measurements on the one hand, and the dataset of the stenosis and the empty channel from the multi-contrast MPI measurements on the other hand.

IV. Results

Figure. 3 shows the reconstruction results of the experimental data represented above using the standard Kaczmarz method and the proposed two-step method using 10 iterations of the Kaczmarz algorithm. The first row shows the reconstruction results of the first measurement step, where channel 1 displays the stenosis phantom and channel 2 shows the leakage from the first channel. The second row shows the reconstruction results of the second measurement step as described in III.I. The last row shows the reconstruction results using our two-step method. It can be seen that the overall quality of the reconstruction is improved as the leakage in channel 2 is significantly reduced.

The value of leakage in the second channel along the measured frames is considered for evaluating the proposed method. While the mean of the leakage along the

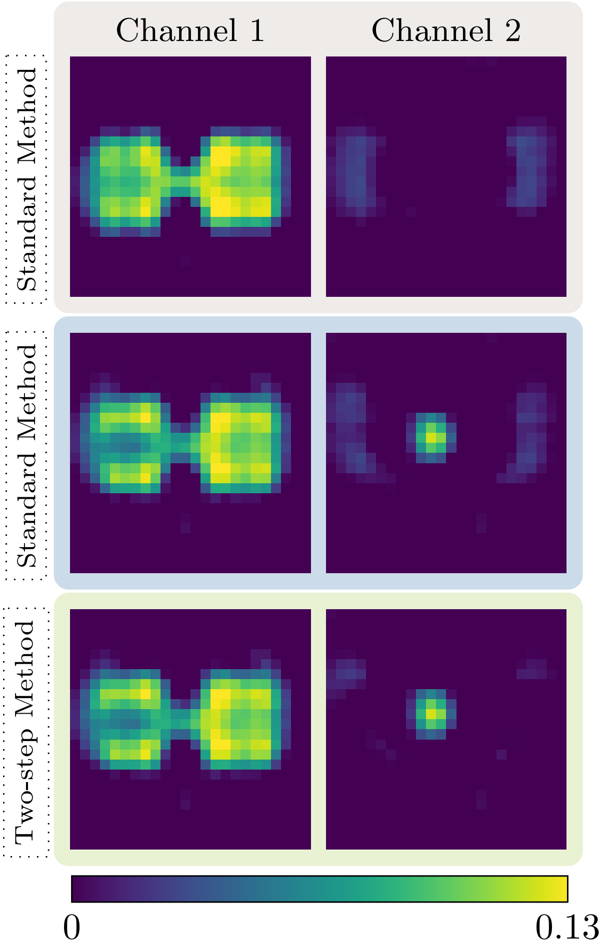

Figure 3: The reconstruction results of the 3D measured data using the standard Kaczmarz method and the proposed two-step reconstruction method.

frames in the second channel equals 2.2×10^{-3} using the regular Kaczmarz solve, it is equal to 7.85×10^{-4} using the proposed two-step method.

V. Conclusions & Discussion

The multi-contrast MPI channel leakage is significantly reduced using the proposed method. However, the method's applicability is limited by its reliance on a specific measurement protocol, which may not be feasible in all potential application scenarios. That being said, the amount of leakage is reduced by a factor of 2.8 when using the two-step method along the measured frames. This method also helps to reduce the number of needed Kaczmarz iterations for convergence, i.e. it speeds up the reconstruction convergence.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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