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Saturation Coil for Localized Signal Suppression in MPI

Ege Kor [a,*] · Musa Tunç Arslan [a,b] · Emine Ulku Saritas [a,b,c]

[a] Department of Electrical and Electronics Engineering, Bilkent University, Ankara, Turkey
[b] National Magnetic Resonance Research Center (UMRAM), Bilkent University, Ankara, Turkey
[c] Neuroscience Program, Sabuncu Brain Research Center, Bilkent University, Ankara, Turkey
[*] Corresponding author, email: ege.kor@ug.bilkent.edu.tr

Abstract

The magnetic nanoparticles (MNPs) used as imaging tracers in magnetic particle imaging (MPI) accumulate in off-target organs such as liver or spleen. The signal from the high-concentration MNPs in these off-target organs may overpower the signals from the nearby low-concentration regions targeted during imaging. In this work, we propose using a saturation coil to suppress the localized high intensity MPI signal from the off-target accumulation organs. The results of the proof-of-concept imaging experiments show that, when the saturation coil is placed over the high-concentration region, it can selectively and completely suppress the signal from that region.

I. Introduction

Magnetic particle imaging (MPI) uses magnetic nanoparticles (MNPs) as imaging tracers [1, 2]. As in other medical imaging technologies, determining the location of a particular target within the human body with high precision is crucial in the diagnosis of diseases using MPI. However, MNPs accumulate in off-target organs such as liver or spleen [3–5]. Since the pixel intensity in MPI images is proportional to MNP concentration, the MPI signal from these off-target organs can overpower the signal from nearby target regions, such as blood vessels during angiographic imaging or tumor tissue during cancer imaging. This problem is further exacerbated by the fact that the imaging point spread function in MPI has relatively long tails, especially in the direction orthogonal to the drive field [6].

One potential solution to image targets near the off-target accumulation organs is to increase the system resolution by utilizing a larger selection field gradient or MNPs with larger effective diameters [6]. However, increasing the gradients comes at the cost of reduced field-of-view (FOV), and larger MNPs can suffer from increased relaxation blur.

In this work, we propose using a saturation coil placed over the off-target accumulation organs to saturate the MNP signal from these organs in a localized fashion. With proof-of-concept imaging experiments on our in-house MPI scanner, we demonstrate that the proposed saturation coil can successfully achieve localized suppression of regions with high-concentration MNPs.

II. Materials and Methods

II.I. Saturation Coil Design

In MPI scanner, the magnetization response of the MNPs is modeled using the Langevin function, formulated as follows [6]:

$$\mathscr{L}\left(\frac{H}{H_{sat}}\right)=\coth\left(\frac{H}{H_{sat}}\right)-\frac{H_{sat}}{H} \quad (1)$$

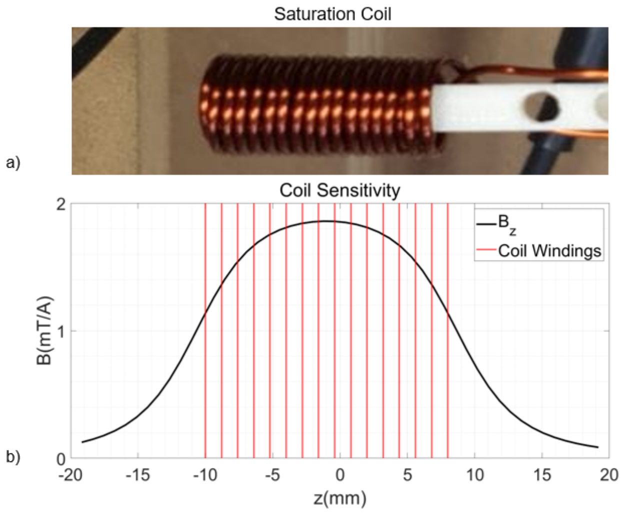

Figure 1: (a) Saturation coil with 10 mm inner diameter. This coil has 2 layers, with 16 windings per layer. (b) Simulated coil sensitivity and coil winding positions. The measured coil sensitivity was 1.6 mT/A near the center of the coil.

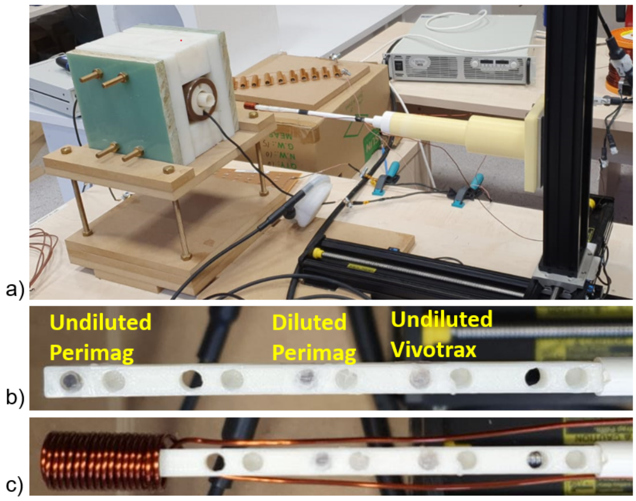

Figure 2: (a) In-house MPI scanner and the experiment setup. (b) Imaging phantom with 10 μL undiluted Perimag, 10-fold diluted 20 μL Perimag, and 20 μL undiluted Vivotrax. (c) Saturation coil was placed over the undiluted Perimag sample to locally suppress its signal.

Here, H is the applied external magnetic field and H_{sat} is the field required to half saturate the MNP magnetization. When we apply a time-varying drive field (DF), the MNPs in the viscinity of the field free point (FFP) induce a large signal in the receive coil. On the other hand, the MNPs far away from the FFP experience a large static field that saturates their magnetization, and hence do not contribute to the MPI signal.

In this work, we propose utilizing an additional saturation coil that applies a static magnetic field in a relatively small volume, causing a localized saturation effect. The saturation coil, shown in Fig. 1(a), was designed and analyzed in MATLAB using the Biot-Savart law. The inner and outer diameters of the coil was 10 mm and 15 mm, respectively. The coil had 2 layers, with 16 windings per layer, wound using a 1.2 mm diameter copper wire. The simulated coil sensitivity along the coil axis is shown in Fig. 1(b). The average coil sensitivity over a central region of interest of 10 mm along the z-direction was measured as 1.6 mT/A.

II.II. Imaging Experiments

The imaging experiments were conducted on our in-house FFP MPI scanner, shown in Fig. 2(a). The selection field gradients were (-4.8, 2.4, 2.4) T/m in (x, y, z) directions, and the DF was at 10 kHz and 14 mT along the z-direction. The free imaging bore diameter of this scanner was approximately 18 mm, such that the imaging phantom with the saturation coil could only be moved along the z-direction. Therefore, 1D images were acquired by scanning a FOV of length 12.7 cm along the z-direction. To move the phantom together with the saturation coil inside the MPI scanner, a linear actuator was used as seen in Fig. 2(a). The speed of the actuator motion was 2.54 cm/sec, and the total scan time was 4.7 sec.

An imaging phantom containing 3 samples was prepared, as shown in Fig. 2(b). To mimic an off-target accumulation organ, a 10 μL undiluted Perimag sample (17 mg Fe/mL undiluted concentration) was utilized. The other two samples represented the targeted regions, and consisted of a 10-fold diluted 20 μL Perimag sample and a 20 μL undiluted Vivotrax sample (5.5 mg Fe/mL undiluted concentration). The center-to-center distance between the undiluted Perimag and the 10-fold diluted Perimag samples was 4.6 cm, and the distance between the 10-fold diluted Perimag and the undiluted Vivotrax samples was 2.3 cm along the z-direction.

Two different imaging experiments were performed, one without the saturation coil and one with the saturation coil. For the second case, 16 A DC current was applied through the saturation coil to create a localized 24.5 mT static field. To ensure stable DC currents, a 1 Ω power resistor was connected in series with the saturation coil. A background measurement was acquired before each imaging experiment, which was then subtracted from the received signal. In the case of the saturation coil, the background measurement was obtained by removing the phantom from the linear actuator but keeping the saturation coil in place and turned on. The same trajectory used during imaging was then applied to record the direct feedthrough in the presence of the saturation coil. For both imaging experiments, x-space based Partial FOV Center Imaging (PCI) algorithm was utilized to reconstruct the MPI images after background subtraction [7].

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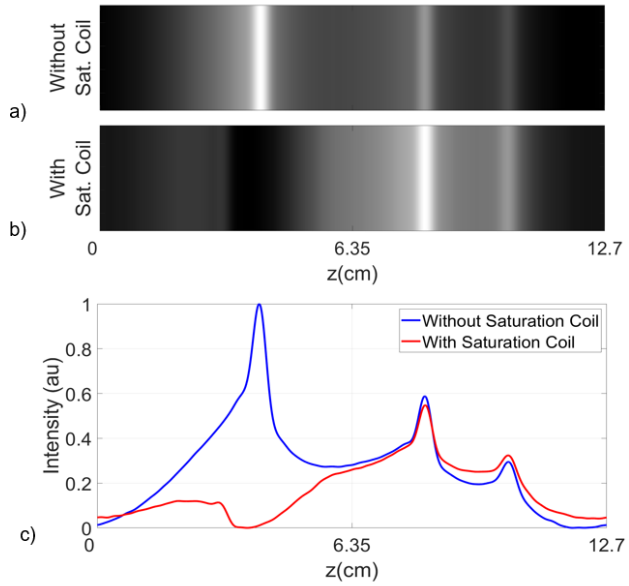

Figure 3: (a) 1D MPI images acquired (a) without and (b) with saturation coil. These images were stacked in the vertical direction for display purposes, and displayed with individual gray-scale windowing to highlight the overpowering effect of the signal from the undiluted Perimag sample (leftmost sample in (a)). (c) 1D cross-section images with and without the saturation coil. The saturation coil successfully suppresses the signal from the undiluted Perimag sample.

III. Results and Discussion

Figure 3 shows the results of the proof-of-concept 1D imaging experiments performed on our in-house MPI scanner. In the absence of the saturation coil, the signal from the undiluted Perimag sample overpowers the other two samples. With the saturation coil turned on and placed over the undiluted Perimag sample, its signal is completely suppressed, as seen in the Fig. 3(b)-(c). Suppressing the signal from this high-concentration sample makes it easier to distinguish the other two samples.

Note that the three samples in the imaging phantom were placed relative far away from each other in these proof-of-concept experiments, to demonstrate the signal suppression effect of the saturation coil. Detailed simulations and experiments should be performed to investigate the performance of the saturation coil when the other samples are placed closer to the saturated region.

IV. Conclusion

In this study, we proposed a saturation coil to suppress the signal from a high-concentration region that can dominate the signal from targeted low-concentration regions. Proof-of-concept 1D imaging experiments on our in-house MPI scanner demonstrate that the saturation coil can achieve localized suppression of a high-concentration sample, making it easier to distinguish lower concentration samples.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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