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X-ray based magnetic particle imaging

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Abstract

Magnetic particle imaging (MPI) is an emerging preclinical imaging modality that offers several notable advantages, including excellent biosafety, high sensitivity, and superior image contrast. To further improve spatial resolution and expand the effective field of view, this study proposes a novel X-ray based MPI approach. In this method, magnetic nanoparticles are employed as contrast agents for X-ray imaging, while an external magnetic field is applied to modulate their X-ray absorption coefficient. Consequently, the spatial distribution of the magnetic nanoparticles can be translated into quantifiable variations in X-ray beam intensity. A proof-of-concept experiment was conducted using a custom-built, simplified device to preliminarily validate the feasibility of the proposed method, and the observed imaging behavior was interpreted within the framework of magnetic dipole–dipole interaction theory. This X-ray based MPI method demonstrates significant potential for practical application, offering a new technical paradigm that may advance the translational development of MPI toward clinical implementation.

I. Introduction

Magnetic particle imaging (MPI) is a novel functional imaging method developed in the 21st century, characterized by its non-toxic, non-ionizing, and non-invasive nature [1]. MPI method relies on the superparamagnetic properties of magnetic nanoparticles to generate strong image contrast and employs an encoded magnetic field to establish a free field point for high-resolution spatial localization [2]. In recent years, researchers have made significant advances in the design of MPI devices, developing a variety of scanning strategies and acquisition methods. However, due to inherent limitations of the MPI method, spatial resolution and imaging field of view remain mutually constrained, as both are governed by the gradient intensity of the spatially encoded magnetic field [3–5].

Recently, we have investigated the use of optical methods to detect magnetic nanoparticles and visualize their spatial concentration distribution [6]. The reconstructed images clearly reveal the spatial distribution of magnetic nanoparticles and demonstrate excellent two-dimensional spatial and temporal resolution, showing greater potential for clinical application compared with conventional magnetic mapping–based MPI. Furthermore, we propose employing magnetic nanoparticles as contrast agents for X-ray imaging. Changes in X-ray absorption arise exclusively from the magnetic nanoparticles under the applied magnetic field, and the grayscale values in the resulting images therefore directly reflect the spatial distribution of the nanoparticles. Consequently, we refer to this approach as X-ray based MPI. This method fully leverages the structural imaging advantages of X-rays while exploiting the magnetic field–dependent modulation characteristics of magnetic nanoparticles.

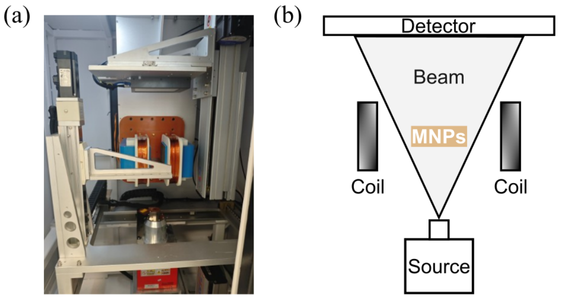

Figure 1: (a) Physical diagram of X-ray MPI device, the electromagnet generates a uniform magnetic field over an area of approximately 50 × 50 mm^2, and the system can achieve an optimal two-dimensional spatial resolution of up to 10 µm; (b) Schematic diagram of the structure of the X-ray MPI device

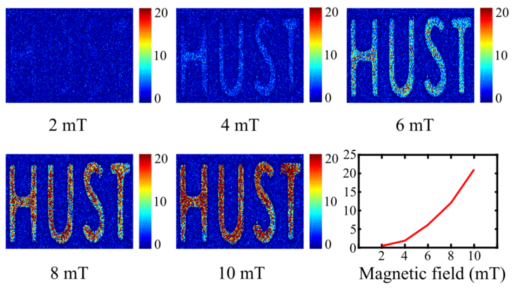

Figure 2: The experimental results of X-ray MPI

II. Principle and method

The X-ray based MPI device consists of an X-ray imaging unit and a pair of Helmholtz coils that generate a uniform magnetic field, as shown in Figure 1. Compared with conventional MPI devices, the X-ray based configuration features a simpler structure and can readily achieve a larger imaging field of view using a flat-panel detector. The spatial distribution of magnetic nanoparticles is determined by monitoring variations in the X-ray absorption coefficient induced by the applied magnetic field, analogous to the principle of X-ray contrast imaging. Consequently, the three-dimensional spatial distribution of magnetic nanoparticles can be reconstructed using well-established computed tomography (CT) algorithms.

III. Results and discussion

The experiment was performed using a “HUST”-shaped phantom uniformly filled with a magnetic nanoparticle suspension. Under magnetic field excitation ranging from 0 to 10 mT, a flat-panel detector was employed to record the transmitted X-ray intensity. The obtained silhouette images were processed by calculating the difference between magnetic field on/off states, as shown in Figure 2. The contrast signal generated by the magnetic nanoparticles is relatively weak, and scattering noise from the flat-panel detector therefore has a pronounced impact on the measured signal, resulting in image blurring.The results indicate that the X-ray absorption of the magnetic nanoparticles varies significantly with the applied magnetic field, and the transmitted intensity exhibits a positive correlation with the square of the magnetic field strength.

At present, no clear saturation behavior is observed at a magnetic field strength of 10 mT. Nevertheless, based on the superparamagnetic nature of magnetic nanoparticles, a saturation tendency is expected as the magnetic field strength further increases. We have also conducted experiments using different nanoparticle concentrations and sample thicknesses, and the signal intensity was found to be proportional to these parameters. In addition, the absorption of magnetic nanoparticles decreases as the X-ray energy increases, which is consistent with the stronger penetration ability of shorter-wavelength X-rays.

The above experimental results are presumed to be associated with the self-organization behavior of magnetic nanoparticles at the mesoscopic scale under an external magnetic field, which is consistent with the phenomenon described in the references [7, 8]. Driven by the combined effects of the magnetic potential energy of the applied field and the dipole–dipole interactions among nanoparticles, the particles tend to align into short chain-like structures along the field direction, thereby altering the local particle concentration within the suspension. This structural rearrangement modifies the X-ray absorption, leading to observable changes in transmitted intensity before and after the application of the magnetic field. Consequently, the X-ray signal carries information about the spatial distribution of magnetic nanoparticles under magnetic field modulation.

Iodine-based and other metallic contrast agents primarily enhance local contrast. In contrast, the magnetic nanoparticles used in this method exhibit magnetic-field–dependent modulation, allowing X-ray absorption to be actively regulated by an external magnetic field and enabling specific differentiation of MNPs from surrounding biological tissues. However, the sensitivity achieved with this method remains relatively low, which we attribute to the comparatively low atomic number of iron. We hypothesize that AC magnetic field could enhance the signal-to-noise ratio.

IV. Conclusion

Magnetic nanoparticles exhibit unprecedented imaging effects in X-ray imaging, offering a novel concept for X-ray based MPI and opening new prospects for its clinical application.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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