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Shape-optimized soft-hard tandem tracers for enhanced magnetic particle imaging

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Abstract

Magnetic Particle Imaging (MPI) is a leading molecular imaging technique with unmatched potential for disease diagnosis, offering high contrast and sensitivity without radiation. However, current MPI tracers, such as Vivo Trax and Resovist, have a detection threshold of 100 µM, far from the theoretical 20 nM limit. To address this, we propose a Soft-Strength Tandem (SST) magnetic control strategy using octahedral-IONPs (O-IONPs) to enhance MPI performance. Our O-IONPs reduce surface spin disorder, increasing saturation magnetization (M_s), and their shape influences coercivity (H_c), addressing the balance between these properties. The octahedral shape impacts atomic magnetic moments and surface magnetic anisotropy (K_s). Our tracers achieve comparable imaging to Vivo Trax at significantly lower doses, setting a new paradigm for shape-mediated MPI tracers and unlocking MPI's full diagnostic potential.

I. Introduction

Magnetic Particle Imaging (MPI) has emerged as a revolutionary molecular imaging modality, offering unparalleled potential in diagnosing a broad spectrum of diseases. It excels in directly visualizing biocompatible iron oxide nanoparticles (IONPs) with high contrast and sensitivity, outperforming other imaging techniques[1]. MPI is distinguished by its absence of radiation, high specificity and sensitivity, lack of background signal interference, and its ability to perform quantitative, linear measurements for clear image contrast[2]. Despite these advantages, the current detection threshold of MPI, at 100 µM with existing IONPs like Vivo Trax and Resovist, falls short of the theoretical 20 nM limit proposed by Gleich and Weizenecker. This discrepancy underscores the need for innovative tracers.

To address this challenge, our study introduces a novel Soft-Strength Tandem (SST) magnetic control strategy using octahedral-IONPs (O-IONPs). This approach significantly enhances MPI performance by reducing surface spin disorder, which increases saturation magnetization (M_s), and reduce coercivity (H_c). The SST strategy not only improves MPI performance but also establishes a new paradigm for developing shape-mediated MPI tracers.

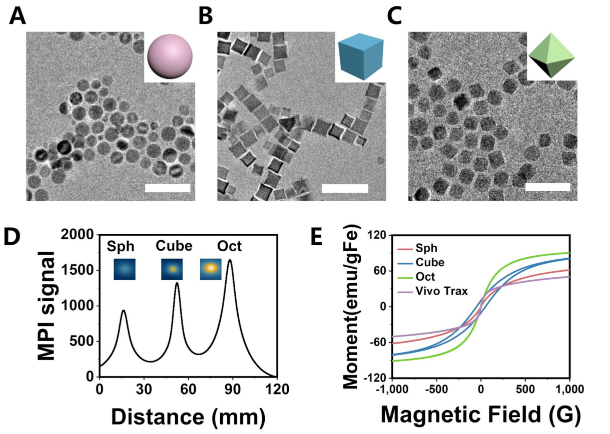

Figure 1: (A-C) TEM images of S-IONP, C-IONP and O-IONP (scale bar = 50 nm). (D) MPI performance of IONPs with the same Fe mass of 50 μg.in 50 μL water. (E) Hysteresis loop of IONPs.

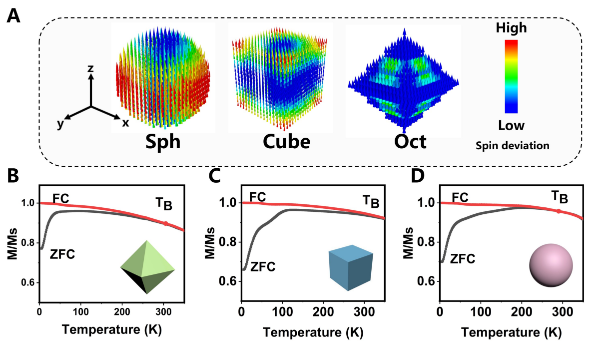

Figure 2: (A) Simulated magnetic spin states of IONPs by OOMMF program. (B-D) ZFC and FC magnetization curves of IONPs.

II. Methods and materials

Different shape IONPs were synthesized via the thermal decomposition method using iron acetylacetonates, with oleic acid and oleylamine acting as surfactants.

III. Results and discussion

Transmission electron microscopy (TEM) images illustrate the diverse shapes of the synthesized IONPs, such as spheres (Figure 1A), cubes (Figure 1B), and octahedra (Figure 1C). Then, the water-dispersible O-IONPs affords a higher MPI signal than that determined for the S-IONPs and C-IONPs (Figure 1D). A vibrating sample magnetometer (VSM) was firstly employed to ascertain the magnetic properties of these IONPs (Figure 1E). Notably, the M_s of the O-IONPs was observed to be 98.9 emu/g Fe, surpassing that of the S-IONPs (82.4 emu/g Fe) and C-IONPs (98.1 emu/g Fe). Meanwhile, the O-IONPs exhibited a markedly reduced H_c, indicating a superior magnetic response and lower energy barrier for magnetization reversal.

M_s exhibits a positive correlation with μ_{sp}. Furthermore, at the nanoscale, where there is a large surface-to-volume ratio, the impact of surface spin disordered (SSD) effects on magnetic properties becomes notably pronounced[4]. The Object Oriented Micromagnetic Framework Program (OOMMF, developed by NIST) was employed to visualize the orientations of the overall magnetic spin structures of these three shaped IONPs. Visual analysis revealed that in the O-IONPs group (Figure 2A), the spins exhibit minimal orientation change in response to the external magnetic field (B_0).

Moreover, surface magnetic anisotropy (K_s) stems from discrepancies in spin orientation and is associated with the spin state. Furthermore, the K_s values for the aforementioned distinct IONPs were determined by assessing their respective blocking temperatures (T_B) of 288 K for S-IONPs, 305 K for O-IONPs, and 404 K for C-IONPs, as shown in Figures 2B-2D. The K_s for the cube, at 9.3×10^{-5}, exceeds those of S-IONPs (5.5×10^{-5}) and O-IONPs (6.4×10^{-5}). Hence, IONPs with the aforementioned traits, particularly low K_s, are well-suited for MPI applications.

IV. Conclusion

In conclusion, we successfully synthesized various IONPs, with octahedral-IONPs (O-IONPs) showing the most promise as MPI tracers due to their higher M_s and lower H_c. The SST strategy achieved a balance between M_s and H_c, enhancing MPI signal contrast. The O-IONPs offer a promising pathway for developing high-performance MPI tracers.

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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. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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