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A trace doping strategy for developing magnetic nanoparticles magnetic particle imaging and magnetic hyperthermia properties

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Abstract

Magnetic particle imaging-guided magnetic hyperthermia therapy (MPI-MHT) allows direct imaging, quantification and prediction of heat production of magnetic nanoparticles at focal sites, guiding target mapping, dose planning and efficacy monitoring of subsequent magnetic hyperthermia therapy, which greatly improves the safety and effectiveness of magnetic hyperthermia therapy. However, due to the performance contradiction between magnetothermal therapy and MPI itself, the currently available magnetic particles fail to balance the needs of both in performance regulation, which greatly hinders the construction of MPI-MHT integrated platform. In this work, we proposed a trace doping strategy to synthesize the magnetic spin ordered and anisotropic tunable nanoprobes. It has been tested to demonstrate unprecedented MPI-MHT capability. It brings great prospects for the construction of MPI-MHT integrated diagnosis and treatment platform, effectively avoiding the harm caused by the increased burden of over-diagnosis and over-treatment.

I. Introduction

Nanotheranostics, which integrate diagnostic and therapeutic functions, has made remarkable progress in recent years in guiding local treatment, planning drug administration, and stratifying patients for optimal treatment. Among them, magnetic hyperthermia therapy (MPI-MHT) allows direct imaging, quantification and prediction of heat production of magnetic nanoparticles at focal sites, guiding target mapping, dose planning and efficacy monitoring of subsequent magnetic hyperthermia therapy, which greatly improves the safety and effectiveness of magnetic hyperthermia therapy [1]. However, due to the inability to balance the contradictory effects of relaxation time on the both properties, it is difficult to prepare magnetic nanoparticles with both properties at present. which greatly hinders the construction of MPI-MHT integrated platform [2]. In this work, we proposed a trace doping strategy to synthesize a series of the magnetic spin ordered and anisotropic tunable nanoprobes by modulating the segregation of Co atoms in the anti-spinel lattice. In which particle with trace doping effectively neutralized the signal-to-noise ratio loss caused by the increase in relaxation heat production. Our synthetic cobalt trace doping Fe_3O_4 (TCIO=$Co_{0.05}Fe_{2.95}O_4$) has been tested to demonstrate unprecedented MPI-MHT capability.

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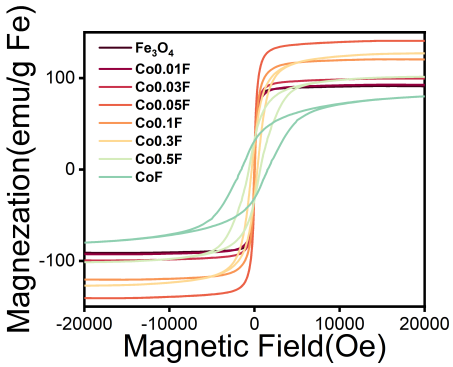

Figure 1: Magnetization curves (M-H) of CoxFe3-xO4 MNPs at 300 K.

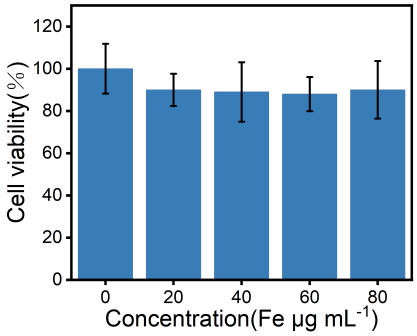

Figure 3: Cell viability of RAW264.7 cocultured with TCIO for 24 h. n = 3 independent experiments.

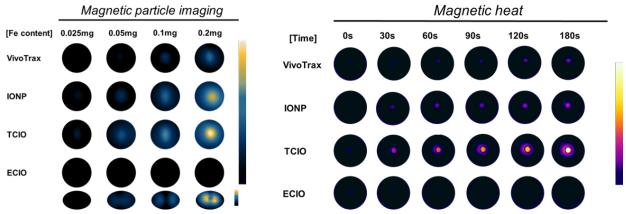

Figure 2: MPI-MHF properties study, (a) MPI phantom images of VivoTrax, Fe_3O_4, TCIO (Co0.05Fe2.95), and ECIO(Co0.3Fe2.7), respectively. (b) Infrared thermal images of VivoTrax, Fe_3O_4, TCIO, and ECIO under AMF (f = 364 kHz).

II. Methods and materials

MPI performances of magnetic tracers were investigated using the magnetic particle imaging system (Magnetic Insight, Inc., USA). The frequency of MPI is 45 kHz; the magnetic gradient strength of MPI is 5.7 T m^{-1}. The measurement of the heat generation from nanoparticles was performed by a high-frequency induction heating equipment (SPG400K2).

III. Results and discussion

The magnetic characteristics of magnetic nanoparticles modulated by $Co_xFe_{3-x}O_4$ atoms were studied by vibrating magnetometer (VSM), and the field-dependent magnetization (M-H) curve measured at 300 K. As shown in Figure 1, the saturation magnetization and coercivity of $Co_xFe_{3-x}O_4$ showed changes.

In previous studies on iron oxide doping, it is generally believed that Co^{2+} will replace the Fe^{2+} at octahedral sites in the antispinel structure [3] since the magnetic moment of Co^{2+} is $3\mu_B$ lower than that of Fe^{2+}. This has a negative effect on the magnetic moment of magnetic particles. In our study, however, the introduction of trace Co^{2+} led to an increase in magnetic moment. We speculated that the surface segregation of Co atoms would preferentially occupy the vacant O_h site on the particle surface. This effect introduced additional spin magnetic moment and improved the inherent surface spin tilt effect, and finally presented a magnetic saturation state.

Further, we used a commercial MPI scanner and a high-frequency magnetothermal therapy apparatus to further investigate the performance of the particles (Figure 2). With the introduction of Co, the MPI and magnetothermal capacity of the particles have a trend of first increase and then decrease.

In addition, because the amount of our Co doping is extremely small, our particles did not show obvious cytotoxicity in the cell co-culture experiment (Figure 3).

IV. Conclusion

In summary, we utilized a trace doping of Co strategy to successfully fabricate a series of the magnetic spin ordered and anisotropic tunable nanoprobes. By modulating the segregation of Co atoms in the antispinel lattice, the resulting TCIO($Co_{0.05}Fe_{2.95}O_4$) showed improved saturation magnetization and moderate relaxation time, achieving the synchronization of MPI-MHT.

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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