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Influence of magnetic nanoparticles interactions on the magnetic particle imaging performance

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Abstract

The here presented study investigated the influence of magnetic particle-particle interactions within the MPI tracer on the imaging performance of the tracers. To realize a proper separation and to increase the distances between the individual magnetic nanoparticles (MNP) within the tracer (which results in reduced particle-particle interactions), the MNP were diluted by non-magnetic SiO_2 spacers in the nanometer range. The obtained MNP/SiO_2 mixtures were characterized and used to build up measurement phantoms by embedding the mixture into a long-term stable polymer matrix. In MPS and MPI measurements it was found that reduction of the magnetic interactions encompassed by increasing the MNP distances leads for the tested tracer system to a weaker decrease of higher harmonics in the MPS spectra after immobilization of the particles and thereby, a higher spatial MPI resolution can be achieved.

I. Introduction

Optimized magnetic nanoparticles (MNP) as tracers for magnetic particle imaging (MPI) are crucial to exploit the achievable spatial and temporal resolution during imaging and thus a necessity for a potential establishment of MPI in medicine.

From other applications of MNP in medicine it is well known that the magnetic interactions of the single cores in an ensemble of MNP influence the effective magnetic properties of the used particles [1]. Strong magnetic dipole-dipole interactions due to the very close distances between the individual MNP lead to a reduced magnetization, coercivity, remanence, and finally to a lower heating performance during magnetic hyperthermia [2,3].

The impact of magnetic interactions on the resulting imaging performance of an MPI tracer has been scarcely investigated, so far [4]. Thus, we carried out a study where the magnetic interactions between the MNP were controlled by adjusting their (mean) distances. This was achieved by a solid phase dilution of the individual MNP without agglomeration.

From the obtained improved tracer materials, long-term stable measurement phantoms similar to those described before [5] were prepared and investigated regarding the achievable spatial resolution in comparison to phantoms of the same MNP concentration but without reduced MNP interactions.

II. Material and methods

To realize a proper separation and to control the distances between the individual MNP, the MNP were diluted by non-magnetic spacers in the nanometer range.

As tracers, perimag® (micromod Partikeltechonlogie,

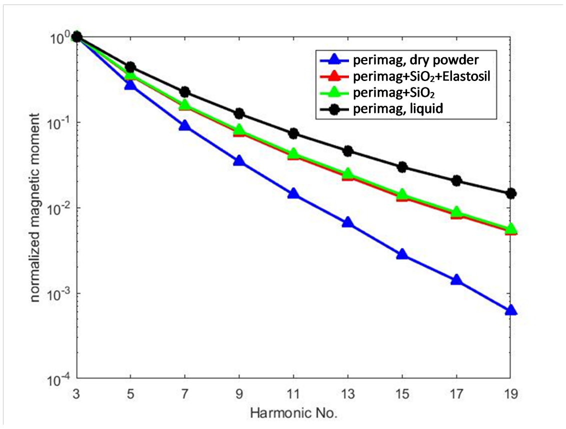

Figure 1: MPS measurements of liquid and immobilized perimag® MNP as well as the MNP/SiO_2 mixture (MNP:SiO_2 ratio = 1:10), before and after dispersion into Elastosil.

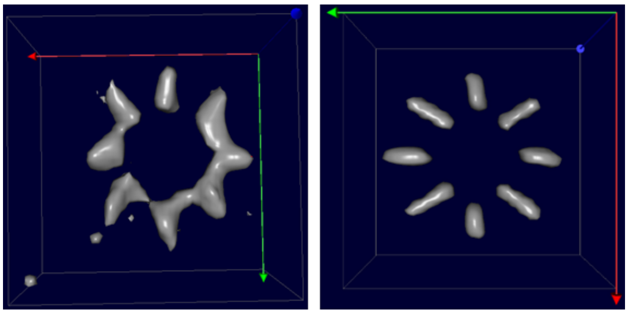

Figure 2: Reconstructed MPI images of the phantom. The structures are filled with perimag® dispersed in Elastosil: (left) without and (right) with non-magnetic spacers made of SiO_2 (MNP:SiO_2 ratio = 1:10). Shown are the volume images with an applied lower threshold of 30 % of the reconstructed maximum value.

Rostock, Germany) was used because this material shows very good MPI performance and has already been used in our previous measurement phantom studies [5,6]. For the dilution of the single MNP and to control the distances between the particles, perimag® was mixed with SiO_2 nanoparticles (Aerosil Pharma®, Evonik Ressource Efficiency, Essen, Germany) with MNP:SiO_2 ratios from 1:1 to 1:10^4. For the mixing process, different strategies were developed and tested. To test the resulting properties of the diluted tracer, the mixtures were dried to powders and investigated by magnetic particle spectroscopy (MPS) using a commercial MPS spectrometer (MPS-3, Bruker, Ettlingen, Germany) operating at an excitation frequency of 25 kHz and an amplitude of 25 mT. We analyzed changes in the amplitudes of the lower odd harmonics of the MPS spectrum between original MNP and after mixing with SiO_2 nanoparticle in the mixing range from 1:1 to 1:10^4.

From the most promising tracer material of the dilution series, long-term stable measurement phantoms were built up and evaluated. For this, the MNP/SiO_2 powder was dispersed into a long-term stable matrix material (Elastosil, Wacker Chemie, München, Germany) with iron concentrations up to c(Fe)=200 mmol/L. The MNP loaded Elastosil was filled into our 3D printed mold with eight, radially arranged notches (2 x 2 mm^2 rectangular cross section, 5.4 mm length) following the procedure described in [5]. The influence of reduced dipole-dipole interactions on the imaging performance by increasing the particle distances was visualized by MPI using a field-free-point MPI scanner (MPI 25/20FF, Bruker, Ettlingen, Germany). The results were compared to the results of a study with phantoms of plain perimag® dispersed in Elastosil [5].

III. Results and discussion

A procedure was developed to prepare MNP/SiO_2 powder mixtures with a homogeneous distribution of the MNP within the SiO_2 powder. These powders were dispersed successfully in long-term stable Elastosil, serving as the matrix for building up phantoms.

The MPS measurements revealed a decrease of the higher harmonics after mixing the MNP with SiO_2 nanoparticles and drying it to a powder as well as after embedding this powder into Elastosil (see Fig. 1). A much stronger decrease of higher harmonics is observed for the plain dried perimag® MNP. Thus, a better imaging performance for the MNP diluted in SiO_2 powder is expected due to reduced interactions between the individual MNP cores and this material and was used to prepare the measurement phantoms at an iron concentration of c(Fe)=200 mmol/L.

Next, the phantoms were imaged by MPI (see Fig. 2). The MPI reconstructions show the entire geometry of the phantom. From Figure 2 it can be seen, that for phantoms at the same iron concentration, a reduction of the magnetic particle-particle interactions leads to a much better imaging performance of the tracer, clearly visible by the higher spatial resolution.

IV. Conclusions

In this study we demonstrated the significant influence of dipole-dipole interactions on the resulting MPI tracer performance. A reduction of the magnetic interactions encompassed by increasing the MNP distances leads for the tested tracer system to a weaker decrease of higher harmonics in the MPS spectra after immobilization of the particles compared to the MNP suspended in their stock carrier liquid. Thereby, a higher spatial MPI resolution can be achieved.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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