Impact of local SPIO concentration on the Magnetic Particle Imaging signal

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Introduction

Recently, **M**agnetic **P**article **I**maging (**MPI**) has been presented as a new imaging method that potentially offers 3D real-time imaging of the concentration distribution $c(\mathbf{x})$ of superparamagnetic iron oxide (SPIO) particles in biological systems at high spatial resolution [1].

A sample containing SPIOs at concentration c is exposed to a harmonically oscillating magnetic field $H(t)$ at frequency ω_0. The MPI signal is the Fourier spectrum of the response field, which contains higher harmonics $N \cdot \omega_0$, due to the nonlinear magnetization curve $M(H, c)$ of the sample in the range of the irradiated field strength, which is on the order of $10\,\mathrm{mT}/\mu_0$.

In essence, $M(H, c)$ transposes input to output and therefore is the key quantity to calculate the MPI signal for a known configuration. For tomographic purposes, the quantity $c(\mathbf{x})$ has to be reconstructed from the MPI signal. Hence, **the quality of the theory describing the impact of concentration c on the magnetization curve is essential for image reconstruction.**

Recent publications only considered Langevin's single particle model of paramagnetism (**SPM**) for reconstruction [e.g. 2]. Thus, magnetic inter particle coupling was neglected, which is valid for $c < 0.2\,\mathrm{mol/l}$, as can be seen in Fig. 1. When particles agglomerate in cell vesicles, as is the case for SPIO labeled cells, concentrations much higher than $0.2\,\mathrm{mol/l}$ are reached [3].

From SPM's point of view, the magnetic coupling then leads to an effective particle diameter d_{eff} which is significantly higher than the real one.

We investigated the impact of particle concentration on the MPI signal spectroscopically as well as in simple 1D MPI experiments. Regarding the latter case, we analyzed two different imaging techniques: the "frequency mixing method" (**FMM**) [4] and the "drive field method" (**DFM**) [1].

References

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Methods

Besides SPM, we consider second order modified mean-field theory (**MMF2**) to include concentration effects. This theory is a second order extension of a modified Curie-Weiss mean-field model [5]. **MMF2 incorporates particle coupling and generates expressions for $M(H, c)$, which reflect experimental results best of all tested models in** [6].

All presented data are acquired using simulations performed with Matlab (The MathWorks, Inc.). For both imaging methods, reconstruction of the distribution of concentration from simulated MPI signal is based on numerical inversion kernels. In case of FMM, we built a PSF from the SPM theory applying a defined d_{eff}. Image reconstruction is performed using the Matlab implementation of a Wiener filtered deconvolution. Regarding DFM, we produced a transfer matrix M from the SPM theory (with defined d_{eff}). Here, image reconstruction is done by applying M to the nonlinear part of the acquired DFM time signal.

In all simulations Magnetite (Fe_3O_4) is used as tracer material.

Results and Discussion

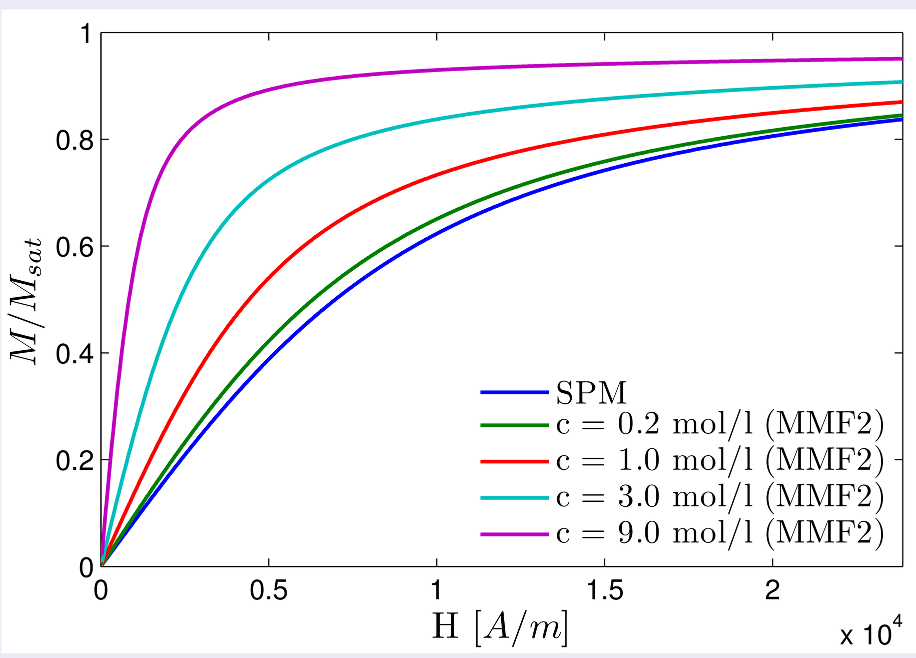

Figure 1: Normalized magnetization curves (particle diameter $d = 15\,nm$) for different concentrations c, calculated using MMF2 theory; in comparison with SPM. M_{sat} is the saturation magnetization of the corresponding sample.

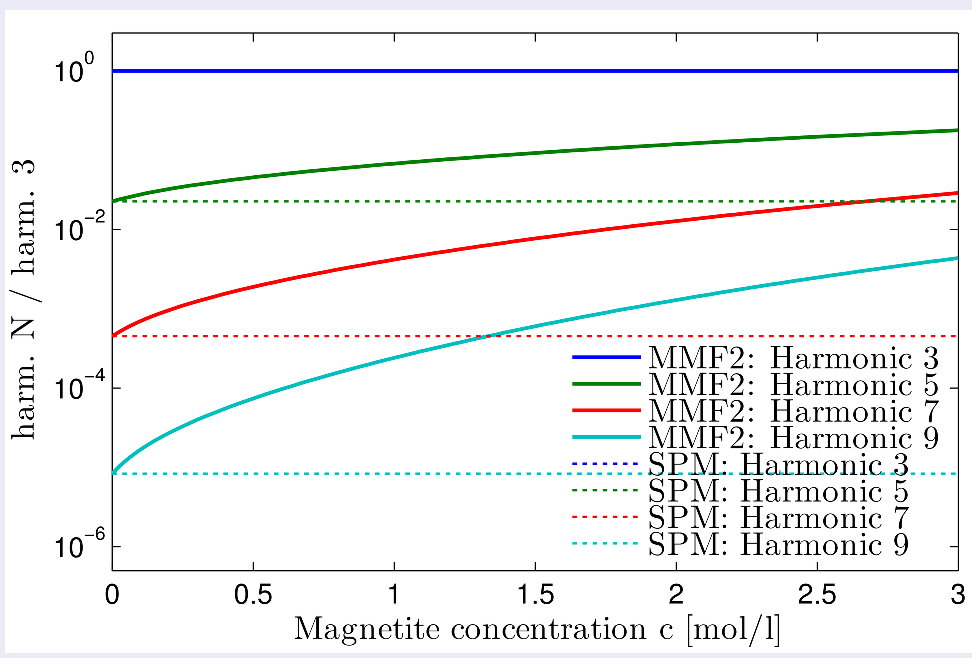

Figure 2: Normalized signal amplitudes of a spectroscopic MPI experiment in dependence of c, the concentration of the sample ($d = 15\,nm$). Signal obtained by MMF2 and SPM in comparison. Harmonics $N = 3; 5; 7; 9$ are normalized to $N = 3$.

Fig. 1 shows the magnetization curve becoming steeper with increasing SPIO concentration. For $c \to 0$, MMF2 converges to SPM. Fig. 2 shows the variation of the higher harmonics of a spectroscopic MPI experiment, while increasing the concentration of a rectangular sample. In case of MMF2, the amplitudes and their ratio change with increasing c.

In Fig. 3 and 4 we show how a wrong estimation of the effective particle diameter d_{eff} may influence image reconstruction. For optimal reconstruction, d_{eff} is gained from the best fit of the SPM model to MMF2 for a given concentration. Two other values for d_{eff} are used to vary the argument of the Langevin function by $\pm 20\%$.

For both DFM and FMM, the optimal inversion yields best reconstruction. Considering an underestimated d_{eff}, in both cases $c_{reco}(x)$ has largest deviations from $c(x)$. Underestimation of d_{eff} means neglecting coupling effects when high concentrations are used. Overestimating d_{eff} results in smaller deviations from $c(x)$.

As shown by our results, **large concentrations may have a severe impact on the quality of reconstruction using the unmodified SPM.** This issue can be overcome by introducing an effective particle diameter fitting SPM to MMF2. Our simulations suggest that a slight overestimation of the effective diameter is less critical than its underestimation.

Considering large variations of concenatration in the field of view, the reconstruction using SPM will probably fail, because the effective diameter d_{eff} is not spatially independent.

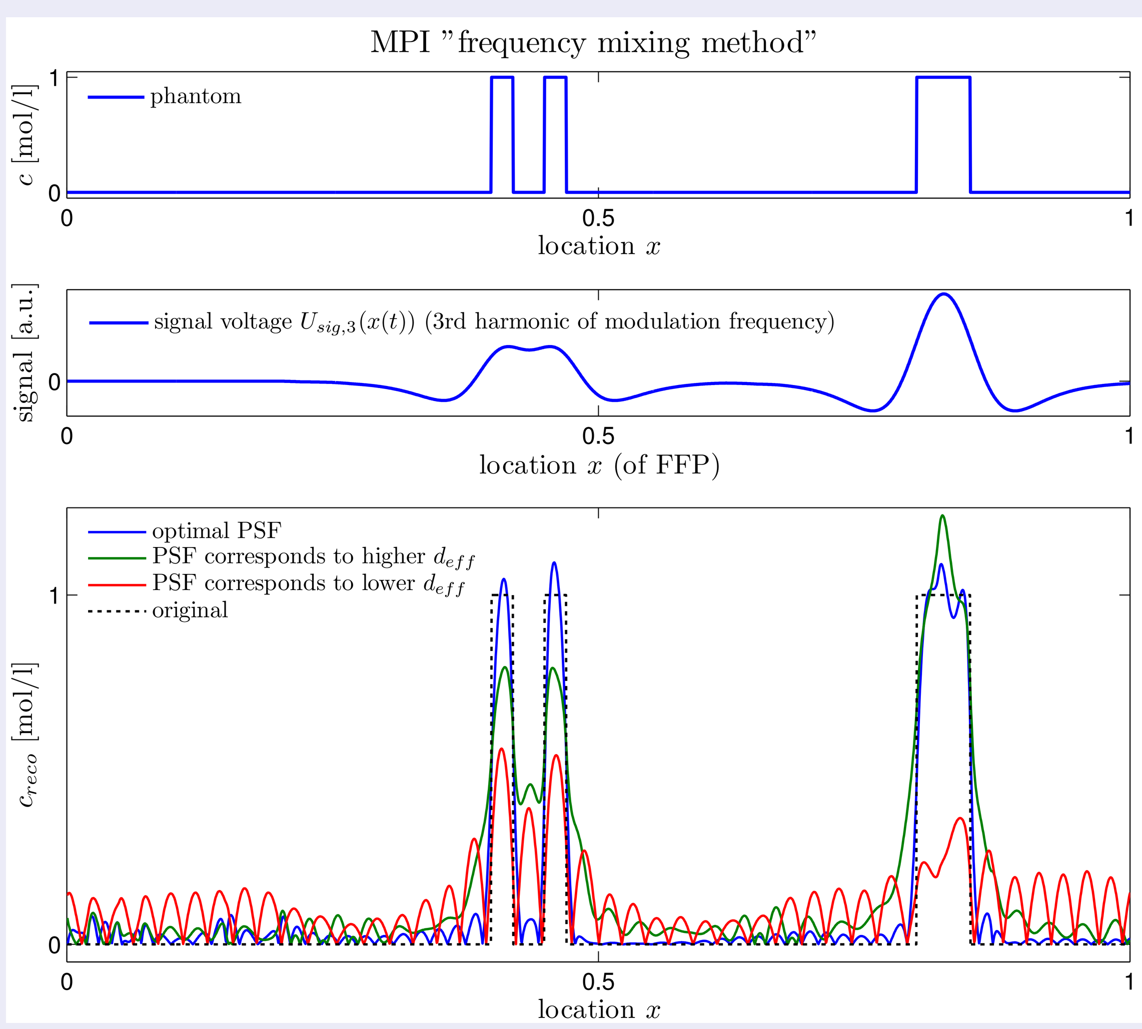

Figure 3: **top:** Phantom $c(x)$. **center:** 3rd harmonic amplitude of the signal voltage for each location; acquired by moving the field free point (**FFP**) over the phantom (with the trajectory $x(t)$). **bottom:** Reconstructed phantom $c_{reco}(x)$; calculated via deconvolution with different PSFs.

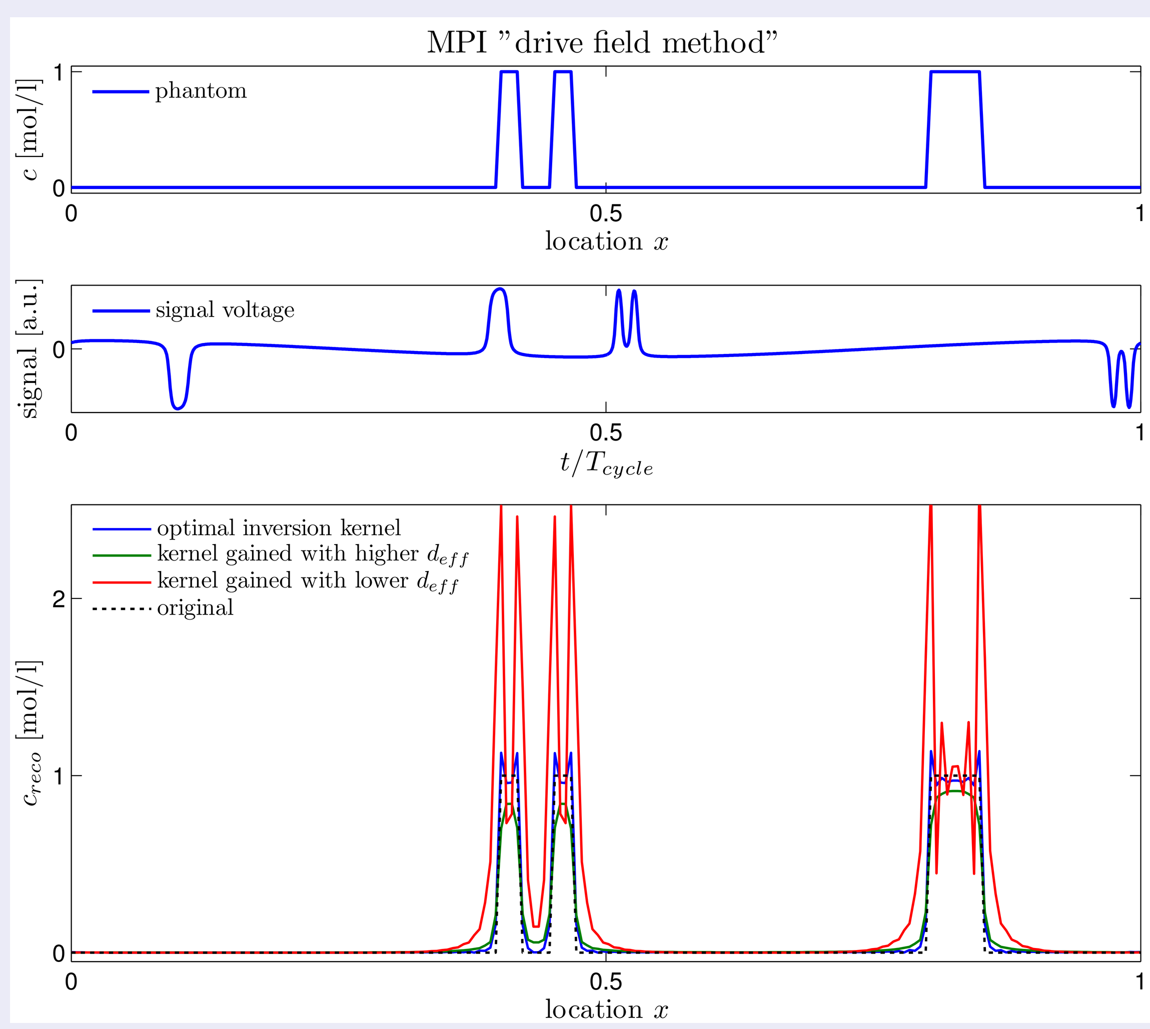

Figure 4: **top:** Phantom $c(x)$. **center:** nonlinear part of the of the MMF2-simulated signal voltage; acquired during 1 period (T_{cycle}) of drive field trajectory $H(x, t)$. **bottom:** Reconstructed phantom $c_{reco}(x)$ using different inversion kernels.