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# Changing iron content and excitation field: Comparative study of Synomag® nanoparticles

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**Abstract**

Magnetic nanoparticles (MNPs) are widely used to facilitate magnetic particle imaging (MPI) which has the potential to become the leading diagnostic instrument for biomedical imaging. This comparative study assesses the effects of changing iron content and excitation frequency on point-spread function (PSF) representing the effect of magnetization reversal. PSF is quantified by features of interest for MPI: i.e. gradient amplitude and full-width-at-half-maximum (FWHM). A superparamagnetic quantifier (SPaQ) is used to assess differential magnetic susceptibility of two commercially available MNPs: Synomag®-D50 and Synomag®-D70. For both MNPs, the signal output depends on increase in drive field frequency and amount of iron oxide, which might be hampering the sensitivity of MPI systems that perform on higher frequencies. Nevertheless, there is a clear potential of Synomag®-D for a stable MPI resolution, especially in case of 70 nm version, that is independent of either drive field frequency or amount of iron oxide.

## I. Introduction

Magnetic nanoparticles (MNPs) are widely used to facilitate new imaging technology, magnetic particle imaging (MPI) [1], that has the potential to become the leading diagnostic instrument for biomedical imaging [2]. MPI enables real-time imaging with high spatial resolution (paramount for simultaneous high sensitivity and specificity) by detecting the non-linear magnetization responses of MNPs. The most frequently used MNPs are superparamagnetic iron oxide nanoparticles (SPIONs) with a slightly different response to the applied magnetic field compared to the surrounding tissue. As illustrated in Figure 1-right, shape of the point-spread function (PSF) represents the magnetization reversal to the applied magnetic field which is governed by two distinct relaxation processes: Brownian relaxation and Néel relaxation [3]. Brownian relaxation is governed by the physical rotation of the MNP hydrodynamic volume, whereas Néel relaxation refers to the fluctuation of magnetic moment ruled by the magnetic core of a MNP. As illustrated in Figure1-left, the dominant relaxation mechanism depends primarily on the MNP size [4] with a clear range in iron core sizes (15-25 nm) where the influence of both Brownian and Néel are relevant. Similarly, Tay et al discovered that MPI resolution follows the steady-state prediction, i.e.

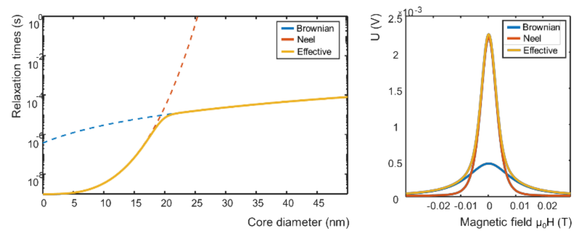


Figure 1: Individual components of relaxation as a function of core diameter (left) and the corresponding PRF (right).

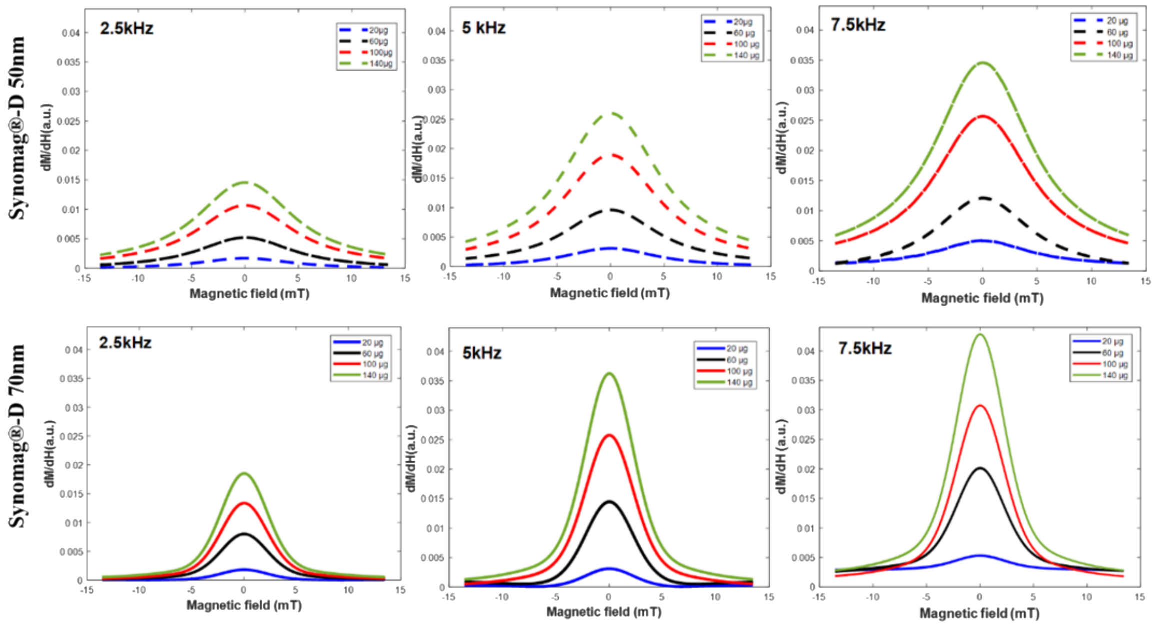


**Figure 2:** PSF for different iron contents measured under different expiation frequencies for Synomag®-D50 (first raw) and Synomag®-D70 (second row).

improves with increasing magnetic core size up to approximately 25 nm where Brownian relaxation becomes leading [5]. MNP with a core size larger than 25 nm experience increased drag, slowing their magnetization response and limiting MPI resolution [6]. The sensitivity and resolution of MPI systems is driven primarily by the shape of PSF for each specific nanoparticle. I.e., gradient amplitude is responsible for the sensitivity and full-width-at-half-maximum (FHWM) is responsible for the resolution. Therefore, this study compares Synomag®-D nanoparticles (Micromod Partikeltechnologie GmbH, Germany) in terms of their potential as MPI tracer in terms of drive field amplitude and FWHM.

# II. Material and methods

## II.I. Magnetic nanoparticles

Samples containing Synomag®-D nanoparticles with different nanoflower sizes were used in this study: i.e. 50 nm (6.1 x $10^{+12}$ Particles per mg) and 70 nm (2.2 x $10^{+12}$ Particles per mg). The plain Synomag®-D nanoflowers are dextran coated iron oxide nanoparticles (mixture of $\gamma$-$Fe_2O_3$ and $Fe_3O_4$) synthesized by a polyol method [7]. For both Synomag®-D nanoflowers, series of four samples were diluted in water to contain 20, 60, 100 and 140 µg iron oxide in a total volume of 140µl.

## II.II. SPaQ

The magnetic properties of the samples were characterised using SPaQ which is a custom differential susceptometry device used to measure the magnetisation response of nanoparticles to an applied alternating magnetic field [9]. The SPaQ combines a low-amplitude alternating magnetic field with a gradual DC offset field to measure the dynamic magnetisation curve [10]. An alternating field magnitude of 1.33 mT was ramped with an offset field (swept between -13.3 and +13.3 mT) in 1s. The excitation frequency was set to 2.5, 5 and 7 kHz. The sample temperature during these measurements was maintained at 20°C.

# III. Results and discussion

For both types of Synomag®-D, Figure 2 illustrates the magnetic differential susceptibility assessed by SPaQ at three different excitation frequencies.

The resulting changes in the differential magnetic susceptibility PSF is illustrated in Figure 3. Synomag®-D50 has a larger FWHM at the same amount of iron oxide. The amplitude of the PSF signal increases with the increasing amount of iron oxide and with the increase of the excitation frequency.

The influence of increasing amount of iron content in nanoflower samples is illustrated in Figure 4. For both nanoflowers, the gradient amplitude linearly increases with the amount of iron oxide for both particles with a slightly steeper incline for Synomag®-D70. Higher excitation frequency caused increased slope even more. In terms of FWHM, both nanoflowers are reasonably steady as a function of excitation frequency and are independent of amount of MNPs. The FWHM of Synomag®-D50

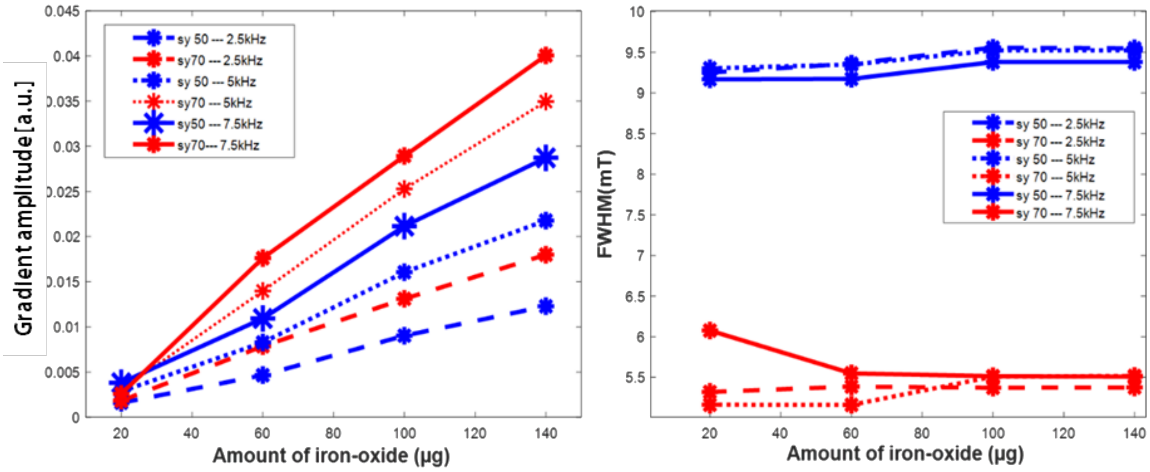


Figure 3: Gradient amplitude (left) and FWHM (right) as a function of iron oxide mass

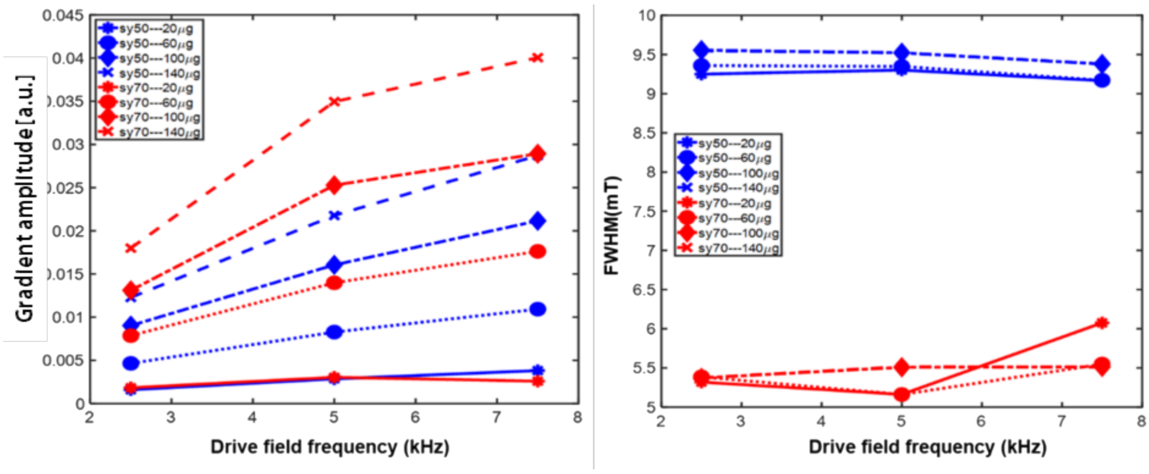


Figure 4: Comparison between Synomag®-D50 and Synomag®-D70 for different field frequencies in terms of gradient amplitude (left) and FWHM (right)

is significantly higher (nearly double) than FWHM of Synomag®-D70.

Figure 5 illustrates the comparison between Synomag®-D50 and Synomag®-D70 for different field frequencies in terms of gradient amplitude (left) and FWHM (right). The amplitude change for the increasing frequency of the excitation field is relatively low for the low iron content samples. The dependency of the excitation frequency is more prominent for samples containing more iron oxide. In terms of FWHM, both nanoflower MNPs are steady and not changing significantly for increasing excitation frequency.

## IV. Conclusions

In conclusion, both Synomag®-D show promising potential as MPI tracer. The signal output depends on both increase in gradient frequency and amount of iron oxide. There is a clear advantage of Synomag®-D, especially in case of 70 nm version, illustrated in a stable resolution independent of either gradient frequency or amount of iron oxide.

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## Author's statement

Authors state no conflict of interest.

 

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