Evaluation of harmonic magnetization properties of clinical magnetic nanoparticles for magnetic particle imaging

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1. Introduction

Magnetic nanoparticles (MNPs) have been widely studied due to their potential use in biomedical applications such as drug delivery, hyperthermia and magnetic particle imaging (MPI). Recently, MPI is attracting extensive attention as a new modality for imaging the spatial distribution of MNPs [1]. In this paper, we first overview the basic principle of MPI and MPI scanner. We then evaluate the harmonic magnetization properties, which are directly related to the sensitivity and spatial resolution in MPI, of clinical MNPs.

2. MPI scanner and Magnetic Nanoparticles

MPI, which was first proposed by Gleich and Weizenecker in 2005, is a new modality for the imaging of the spatial distribution of MNPs, especially for in-vivo diagnostics [1]. In MPI, harmonic magnetizations of MNPs under an AC excitation field are sensitively detected to avoid interference between the excitation field and detection coil. To achieve MPI images with a high spatial resolution, a DC gradient field (selection field), which generates the field free point (FFP), as well as an AC excitation field (drive field) are used. MNPs located around FFP generate rich harmonic magnetizations since relatively large AC excitation field and small or zero DC field are applied. On the other hand, all other MNPs located far from the FFP do not generate harmonic magnetizations since they are exposed to large static field. Thus, high spatial resolution can be achieved by scanning the FFP though field of view (FOV). So far, two MPI scanners have been commercialized [2), 3)]. Figure 1 shows an MPI scanner developed in Kyushu University. The setup is composed of an AC coil for drive field, Nd-Fe-B permanent magnets for selection field, and pickup coil. The amplitude and the frequency of the uniform AC drive field is 3.5 mT and 3 kHz, respectively. The strengths of gradient selection field are 1 and 2 T/m for *x*- and *y*-directions, respectively. The third harmonic magnetization from MNPs located around FFP is detected via pickup coil as an MPI signal.

Experiments were performed using water-based maghemite nanoparticles (CMEADM-004, CMEADM-023, CMEADM-033, and CMEADM-033-02). These nanoparticles were supplied by Meito Sangyo Co. Ltd., Kiyosu, Japan. These MNPs were coated by carboxymethyl-diethylaminoethyl dextran, and their core and hydrodynamic diameters are listed in Table 1. Carboxymethyl-diethylaminoethyl dextran-coated iron oxide nanoparticles are negatively charged and are used as a blood-pooling contrast agent [4].

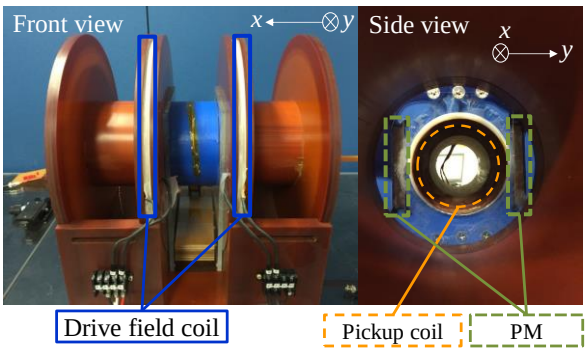

Fig. 1　MPI scanner.

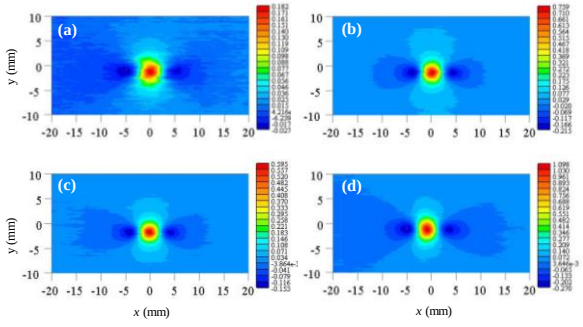

Fig. 2　2D MPI images of the (a) I:CMEADM-004, (b) II:CMEADM-023, (c) III:CMEADM-033, and (d) IV:CMEADM-033-02.

3. Results and Discussion

Figure 2 shows the intensity of the third harmonic magnetization (MPI signal) map of each sample when the sample was mechanically scanned. The FFP is located at the center of each map. The value of maximal intensity and the full width at half maximum (FWHM) of the MPI signal are listed in Table 1. These values are normalized by those of Sample I. The maximal third harmonic intensity of Sample II was higher than that of Samples I and III because the core diameter, d_c, of Sample II is larger than those of Samples I and III [5]. The measured MNP samples are composed of the particles divided into three types of the structures such as the single-core, multi-core, and chain [5]. In particular, the multi-core structure promotes the magnetization and third harmonic signal because of the large size of the effective core [6]. The typical effective core sizes, d_{c_eff}, estimated from the static *M-H* curves are listed in Table 1. The third harmonic intensity of Sample IV was higher than that of Sample II whereas d_c is smaller than that of Sample II. This indicates that large portion of Sample IV is composed of multi-core particles with large d_{c_eff}. Actually, Sample IV was prepared by collecting the MNPs with large d_{c_eff} by magnetic separation from Sample III [5]. This can be found from the value of d_{c_eff} for Sample IV, i.e., 21.3 nm.

In Table 1, the third harmonic magnetization normalized by the fundamental magnetization, M_3 / M_1, is listed. For the estimation of M_3 / M_1, the AC magnetization signal was measured when an excitation field intensity of 10 mT and frequency of 10 kHz was applied. The measurements and estimations of M_3 / M_1 were performed at Yokohama National University and Shizuoka University. As shown in Table I, the FWHM correlates with the M_3 / M_1. Sample IV shows the highest M_3 / M_1 and the smallest FWHM among all four samples. In particular, M_3 / M_1 of Sample III was higher than that of Sample II and the FWHM of Sample III was smaller than that of Sample II, although the maximal intensity of the MPI signal of Sample III was lower than that of Sample II. It suggests that the difference in the structures of Samples II and III influences the maximal intensity and the FWHM of the MPI signal.

Table 1 Parameters of measured MNP samples. Effective core size d_{c_eff} was estimated from static *M-H* curve. Maximal intensity of MPI signal and FWHM were normalized by those of Sample I:CMEADM-004.

Sample # : Measured MNP	d_c (nm)	d_{c_eff} (nm)	d_h (nm)	Maximal intensity of MPI signal	FWHM	M_3 / M_1
I : CMEADM-004	4	5.4	38	1	1	0.0728
II: CMEADM-023	8	7.4	83	3.9	0.86	0.0975
III: CMEADM-033	5-6	5.6 (21.3)	54	3.1	0.81	0.115
IV: CMEADM-033-02	6	21.3	64	6.1	0.76	0.123

4. Conclusions

In this paper, we first overviewed the basic principle of MPI and MPI scanner. We then evaluated the third harmonic magnetization (MPI signal) properties of clinical MNPs. We showed that MNP sample with appropriate core size generates large MPI signal. We also showed that the FWHM, which is directly related to the spatial resolution of the MPI image, correlates with the M_3 / M_1.

Acknowledgement

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Reference

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