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Heat dissipation characteristics of magnetite nanoparticles and their application to macrophage cells

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Abstract

We report the results of the study undertaken to determine relative contributions of Néel and Brownian relaxations on magnetic heat dissipation by investigating the physical, magnetic and heating characteristics of magnetite suspension dispersing particles ranging in average diameter from 10.0 to 15.7 nm. Heating characteristics depended on the primary particle size and the viscosity of the medium. In the case of the sample with average diameter of 12.5 nm, the effective specific absorption rate dropped by 27 % (22.9×10^{-9} to $16.8 \times 10^{-9} \text{ Wg}^{-1} \text{Oe}^{-2} \text{Hz}^{-1}$). In contrast, the decrease of 67 % (29.5×10^{-9} to $9.7 \times 10^{-9} \text{ Wg}^{-1} \text{Oe}^{-2} \text{Hz}^{-1}$) was observed for the sample with average diameter of 15.7 nm. The potential of these particles as thermal seeds was tested by feeding the macrophage and exposing them to an alternative current magnetic field strength and frequency of 40 Oe and 600 kHz, respectively. The uptake of magnetite particles by the macrophage was adequate to raise the temperature of cell suspension by 8 °C required for thermal necrosis.

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1. Introduction

Magnetic fluid hyperthermia (MFH) is a technique that annihilates cancer cells through the elevation of cell temperature above 43°C. The heat dissipation of magnetite nanoparticles exposed to alternative current (AC) magnetic field is originated from Néel and Brownian relaxations [1]. Among various magnetic oxides, magnetite (Fe_3O_4) has been considered suitable due to its biocompatibility and easiness to synthesize and surface modifications. In addition, their heating efficiencies at various AC magnetic field strength and frequencies have been tested. The sizes of particles that could dissipate heat through the Néel and Brown motion of the magnetic vector has been

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estimated theoretically [2]. However, the contribution of each relaxation to heat dissipation in any sample should be determined to generate anticipated heat in *in-vivo* experiments.

In this study, we have focused the specific heat absorption characteristics of magnetite, especially the relative contributions of Néel and Brownian relaxations, by considering the physical and magnetic properties of samples with different mean diameters. Then, we have investigated the heating ability of these particles by using the macrophage cells.

2. Experimental

Stable water-based magnetite suspensions were supplied by Ferrotec Corporation. The particles were synthesized by coprecipitation method, coated with a surfactant and dispersed in water or oil. We fabricated the high viscosity samples by adding polymer in oil or dispersing particles in polyvinyl alcohol (PVA) hydro-gel. The preparation method of PVA hydro-gel is written in a literature [3].

The crystal structure and the crystallite size of the samples were measured using X-ray diffractometer (XRD). The particle morphology was observed by a transmission electron microscope (TEM). AC magnetic characterization was carried out using the physical properties measuring system. The AC magnetic susceptibility measurements were performed at frequencies 10, 57, 320, 1788, 9977 Hz in the temperature range between 5 and 265 K. Heat evolution experiments were carried out by introducing the suspensions dispersing 8.0 wt. % of magnetite in the medium into a test tube and by placing the same at the center of the solenoid coil that generated a magnetic field strength of 40 Oe at 600 kHz. The ESAR values were calculated using Eq. (1).

$$ESAR = \frac{\sum_i c_i m_i}{m_{\text{Fe}_3\text{O}_4}} \frac{\Delta T}{\Delta t} \frac{1}{H_{\text{applied}}^2 f} \quad (1)$$

c : specific heat, m_i : weight of each particle, $m_{\text{Fe}_3\text{O}_4}$: weight of magnetite nanoparticle, T : temperature, t : time, f : frequency of applied AC magnetic field, H_{applied} : strength of applied AC magnetic field. The specific heat of water was assumed $4.2 \text{ JK}^{-1}\text{g}^{-1}$. The specific heat of PVA hydro-gel was estimated to be $2.76 \text{ JK}^{-1}\text{g}^{-1}$ from the measurement of differential scanning calorimetry (DSC). The temperature increment rate ($\Delta T/\Delta t$) was evaluated from the temperature-time curve obtained for a measurement time of initial 60 s.

The thermal dissipation potential of the particles that dissipate heat through Néel relaxation was examined by carrying out *in vitro* experiments using macrophage cells (RAW 264.7). Water dispersion of magnetite nanoparticles was introduced into culture fluid after filtering and sterilizing the same. Then, the magnetite concentration was adjusted to 1.0 mg/mL and about 7.5×10^6 of RAW 264.7 was introduced into the culture media and cultured at 37°C . After centrifuging, magnetite uptaken cell and free magnetite were separated. The calorimetric analysis using KSCN was carried out to evaluate the Fe^{3+} uptake concentration per cell. On the contrary, the macrophage cell was exposed to various concentrations of magnetite for different durations to obtain macrophage with different loads of magnetite particles. Then, about 1.5×10^7 of RAW 264.7 containing culture media with different magnetite uptake concentrations were exposed to the AC magnetic field to measure the temperature rise against time.

3. Results and Discussion

The XRD profiles of the samples (figure not shown) confirmed the presence of Fe_3O_4 with spinel structure. The crystallite sizes estimated by Scherrer's equation are shown in Table 1. The average particle diameters of the samples obtained from measuring 1,000 particles from TEM micrograph were also given in Table 1. Representative TEM micrographs of samples A and E are shown in Fig. 1. These results suggest that the particle diameters of the samples from A to E are in the increasing order.

According to the results obtained from the AC magnetic susceptibility measurements, the blocking temperature (T_B) at the χ'' maximum for the samples were estimated as follows; 30.0 (sample A), 80.0 (sample B), 120.1 (sample C), and 204.9 K (sample D) at the measurement frequency of 10 Hz. Since χ'' value of the sample E continued to increase with increasing temperature, the T_B of the sample E should be higher than room temperature (RT). When we increased measuring frequencies, T_B shifted towards higher temperatures, while the T_B values measured at 9977

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