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The heating effect of magnetic fluids in an alternating magnetic field

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Abstract

The heating mechanism and influencing factors of magnetite particles in a 63 kHz alternating magnetic field and 7 kA/m were studied. The results from in vivo heating experiments suggest that magnetite particles can generate enough energy to heat tumor tissue and perform effective hyperthermia. A novel model for predicting power losses has been proposed.

Keywords: Specific power absorption rate (SAR); Hyperthermia; Magnetic fluids; Néel relaxation; Magnetite; Oleic acid; Octane

1. Introduction

Magnetic fluids are stable colloidal suspensions that are composed of single-domain magnetic nanoparticles dispersed in appropriate solvents. They have some peculiar properties, one of which is that they can generate heat in an alternating magnetic field. Thus they become promising materials for tumor hyperthermia, which takes advantage of higher sensitivity of tumor tissue to heat than normal tissue [1–3]. Magnetic fluid hyperthermia involves the introduction of magnetic particles into the tumor tissue and irradiation with an external alternating magnetic field to increase the temperature in the tumor to 42–46 °C. Consequently, large power losses of the magnetic materials are desirable in order to reduce the amount of material to be applied to a patient. The study of the mechanism of power loss is of intense interest currently with the aim to enhance the heating power of magnetic materials. Generally, the heat effect of magnetic particles with diameters around 10 nm in an alternating magnetic field is considered to be caused by relaxation

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processes [1,4,5], which are the gradual alignment of the magnetic moments during the magnetization process. These relaxation processes of a magnetic fluid may take place through two distinct mechanisms simultaneously, the Brownian relaxation and the Néel relaxation.

The Brownian relaxation time is given by the following relationship [4]:

$$\tau_B = \frac{3\eta V_H}{kT} \tag{1}$$

and the Néel relaxation time is [6]

$$\tau_N = \tau_0 \exp \frac{KV}{k_b T}, \tag{2}$$

where η is the viscosity of the carrier liquid, V_H the hydrodynamic volume of the particle, k_b the Boltzmann constant, T the absolute temperature, τ_0 the time constant, $\tau_0 \sim 10^{-9}$ s, K the anisotropy constant, and V the volume of particle core.

The power loss corresponding to Néel or Brownian relaxation is approximately given by [4]

$$P = \pi \mu_0 \chi_0 H_0^2 f \frac{2\pi f \tau}{1 + (2\pi f \tau)^2}, \tag{3}$$

where μ_0 is the permeability of vacuum, χ_0 the equilibrium susceptibility, and H_0 are the amplitude and f the frequency of the applied alternating magnetic field.

According to formulas (1)–(3), specific power absorption rate (SAR) values of magnetic fluids strongly depend on the alternating magnetic field and the nature and structure of magnetite fluids.

In fact, the experimental results of many research groups revealed that the heating power strongly depends on the parameter of magnetic field and the nature of the materials, such as particle size and size distribution, anisotropy constant, saturation magnetization and surface modification [2,3,5].

The purpose of this work was to further investigate the factors that influence heating effects of the magnetite fluids, such as the amplitude of alternating magnetic field, magnetic particle sizes, dispersion state, surface treatment, the concentrations of magnetite particles, and the viscosity of carrier liquids. The mechanism of power losses of magnetite particles under an alternating magnetic field was primarily studied by experimental and theoretical analysis. Magnetite samples with different particle sizes were prepared, and their SAR values (which were used to represent the power losses of materials) were tested in an alternating magnetic field with a frequency of 63 kHz and amplitude of 7 kA/m.

2. Experimental

2.1. Material synthesis and characterization

Magnetite particles were prepared according to the method of Molday [7]. By varying precipitation temperature and reactants concentrations, different magnetite particles were synthesized by coprecipitation, dried into a powder at 50 °C under vacuum, mixed with deionized water and sodium oleic acid and heated at 80 °C for 2 h. The final particles covered with oleic acid could be dispersed in toluene, benzene, octane, styrene and oleic acid in an ultrasonic generator to receive a series of magnetic fluids. The particle sizes and shape of magnetite particles were determined by transmission electron microscopy (JEM-100; JEOL Co., Ltd., Japan). The diameters of magnetite particles agglomerate were determined by Zetasizer (HPP5001; MALVERN Co., Ltd., Great Britain). The crystalline phase of the magnetite particles were determined by the X-ray diffraction (XRD) pattern (D_{MAX}RB; RIGAKU Co., Ltd., Japan).

2.2. Measurement of SAR values

SAR values of these magnetic fluids were measured referring to Hilger's technique [5]. For fair comparison, these measured results were normalized to a frequency of 1 MHz and amplitude of 100 Oe (i.e., 8 kA/m) according to Chan's technique [2]. The experimental setup is shown schematically in Fig. 1. The frequency and amplitude of the magnetic field are 63 kHz and 7 kA/m, respectively. Unless otherwise noted, all samples were composed of magnetic particles with a diameter of 10 nm dispersed in octane with the

concentration of 2% (w/w), and were well dispersed before measurements.

2.3. Heating experiment in vivo

To assess in vivo heating effects of magnetite particles, a New Zealand rabbit with a single VX2 liver carcinoma of 2 cm diameter was used. A total of 0.1 ml magnetic fluid that contained 50 mg magnetite particles with an average diameter of 10 nm dispersed in iodinated oil was injected into the center of the tumor. Then optical fiber thermometer probes (FTI-10; FISO Co., Ltd., Canada) were inserted into the tumor core and tumor rim. The rabbit was put in the coil and irradiated with a 55 kHz, 20 kA/m magnetic field for 900 s.

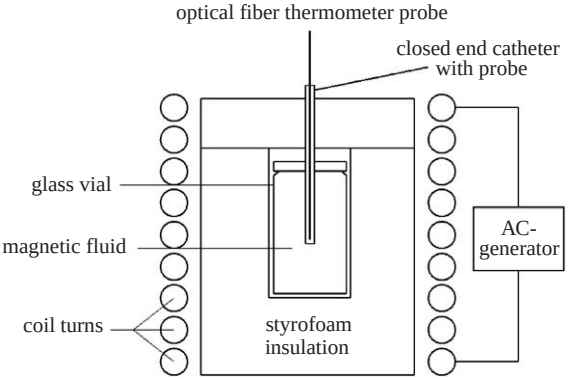

Fig. 1. Experimental setup for SAR values measurements.

3. Results and discussion

3.1. Characterization of materials

Transmission electron microscopy of the prepared samples showed that particles had average diameters of about 6, 8, 10 nm, respectively, just as shown in Fig. 2(A)–(C). XRD patterns of three samples indicated that they were indeed Fe_3O_4. As a typical example, the XRD pattern of sample C is shown in Fig. 3. These materials laid a good foundation for further research work.

3.2. Influences of materials on the SAR values

The material properties are important factors on the SAR values of magnetite particles. We investigated the influence of particle size, surface

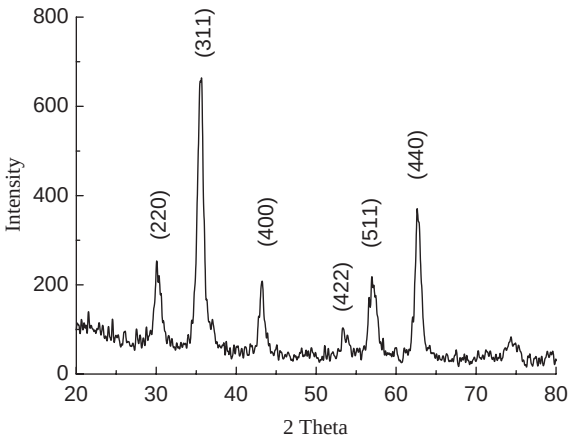

Fig. 3. XRD spectrum of synthesized Fe_3O_4 (sample C).

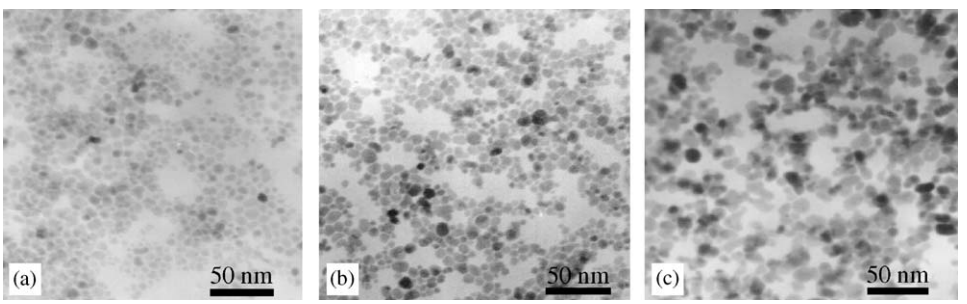

Fig. 2. TEM micrographs of magnetite particles with a diameter of (a) 6 nm (sample A), (b) 8 nm (sample B), and (c) 10 nm (sample C).

treatment, dispersion state, magnetite concentration and viscosity of carrier liquids on SAR values of magnetite particles synthesized by coprecipitation.

Table 1 shows that magnetite particles with larger average size generated higher SAR values. At lower frequencies ($2\pi f\tau \ll 1$), formula (3) could be simplified as

$$P = 2\pi^2 \mu_0 \chi_0 \tau H_0^2 f^2. \quad (4)$$

As can be deduced from the above formula, power losses increase with τ, in other words, increase with particles diameters. While $2\pi f\tau \gg 1$, power losses decrease with particles diameters. The transition between these two regimes would take place near $2\pi f\tau = 1$, where the power loss has its maximum. Values of $f = 63\,\text{kHz}$, $\tau_0 = 10^{-9}\,\text{s}$, $T = 298\,\text{K}$, $k_b = 1.38 \times 10^{-23}\,\text{J/K}$ and $K = 10^4\,\text{J/m}^3$ led to a calculated diameter of about 18.3 nm which makes $2\pi f\tau_N = 1$ and $P_{\text{Néel}}$ reach a maximum. Most magnetite particles which are used presently are smaller than 10 nm, which means that there are still large improvements in SAR values possible by means of increasing particle diameters.

In Table 2, agglomeration factors, which are the quotient obtained by dividing the diameter of magnetite particle agglomerates by the average particle diameter, were applied to characterize the dispersion states of magnetite particles. As can be seen from Table 2, agglomerated particles decrease the SAR values greatly. As two extreme cases, the SAR value of the sample that was not treated by a dispersing process was only about a tenth of the highest value in which the sample was completely monodispersed. These results could be attributed to the interparticle interactions due to agglomeration of particles. Both Néel and Brownian models ignore the dipole–dipole interaction between magnetic particles. In fact, in an agglomerated state, the interaction cannot be omitted as can be deduced from these results. As a result of the interaction, the relaxation behavior would be restrained. Therefore, the heat effect would decrease.

In Table 3, SAR values of magnetite particles were enhanced greatly by means of surface treatment by surfactants, and varied with different surfactants. The last sample in Table 3 was covered with a surfactant bilayer, the inner surfactant was oleic acid, and the outer one was sodium dodecyl benzene sulfonate (SDBS). By contrasting SAR values of the last two samples, we can deduce that the power losses were only dependent on the inner surfactant. This result suggests that increasing SAR values of magnetite particles covered with surfactant maybe due to the interaction between the magnetic particles and organic molecules. Morrish et al. reported that this kind interaction increased the surface anisotropy, and that this increase varied with different surfactants [8]. As can be deduced from the above formula, power losses increase with τ, in other words, increase with the values of K.

Table 1
Influence of magnetite particle diameter on SAR values

Sample	Average particle diameter (nm)	Carrier liquid	SAR values (W/g)
A	6	Octane	50
B	8	Octane	78
C	10	Octane	123

Table 2
Influence of dispersion states on SAR values

Agglomeration factor	3	4.3	6.8	52	80	Not dispersed
SAR values (W/g)	198	123	113	97	91	17

Table 3
SAR values of magnetite particles covered with different surfactants

Surfactants	None	Aminosilane	Oleic acid	Oleic acid + SDBS
Carrier liquids	Water	Water	Oleic acid	Water
SAR values (W/g)	21	77	126	120

Results in Fig. 4 suggested that magnetic particle concentrations showed no influence on SAR values, even though the concentration was as high as 32% (i.e. 6% volume fraction). In principle, increasing concentration would decrease the distance between adjacent magnetic particles, and the interparticle interaction might affect the relaxation behavior. However, the results show that the distance between adjacent magnetic particles seems far enough to omit this interaction. If the distance is very close, such as in agglomerated state, the interaction must be taken into account.

Table 4 demonstrates the influence of carrier liquids on SAR values of magnetite particles. Sample C (diameter of 10 nm) was dispersed in different carrier liquids and SAR values of different samples were measured. The results suggest that heat effects are independent of the carrier liquids used, and further implies that Brownian relaxation maybe not the dominant cause that results in relaxation losses.

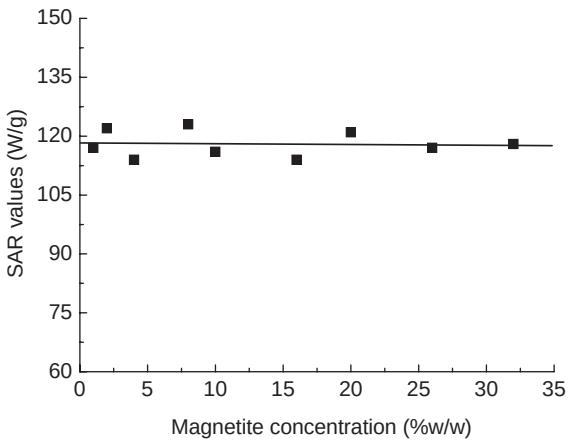

Fig. 4. The SAR values of sample C with different magnetite concentrations and according fit.

3.3. Influence of alternating magnetic field on SAR values

As shown in Fig. 5, SAR values of magnetite particles were proportional to the square of the magnetic field amplitude. This relation is in agreement with theoretical predictions of Rosenweig's model, and also found by Hiergeist and Hergt [9,10]. Since the amplitudes of existing alternating magnetic field are not high, increasing amplitudes can greatly improve SAR values besides optimizing the particle properties.

3.4. Heating experiment in vivo

Experimental temperature profiles inside a rabbit tumor under the influence of an alternating magnetic field are shown in Fig. 6. The temperature in the tumor core increased rapidly over 45 °C after 300 s, and stayed at 45.1 °C after 360 s, whereas the temperature in the tumor rim never

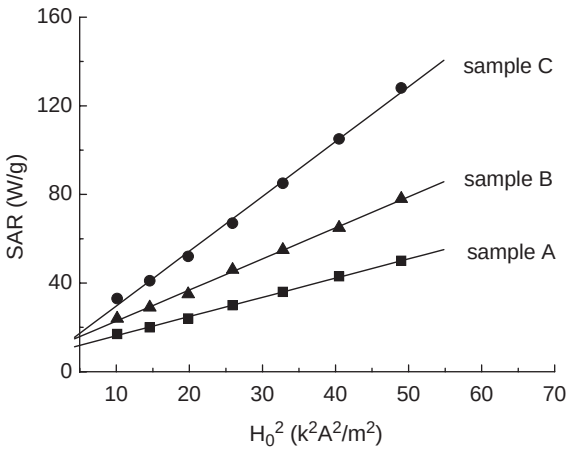

Fig. 5. Experimental data of SAR in dependence on the square of the magnetic field amplitude for three magnetic fluids and according fits.

Table 4
Influences of carrier liquids on SAR values

Carrier liquids	Octane	Toluene	Benzene	Styrene	Oleic acid
Viscosity of carrier liquids (mPa s)	0.545	0.586	0.601	0.696	38.8
SAR values (W/g)	123	127	135	124	126

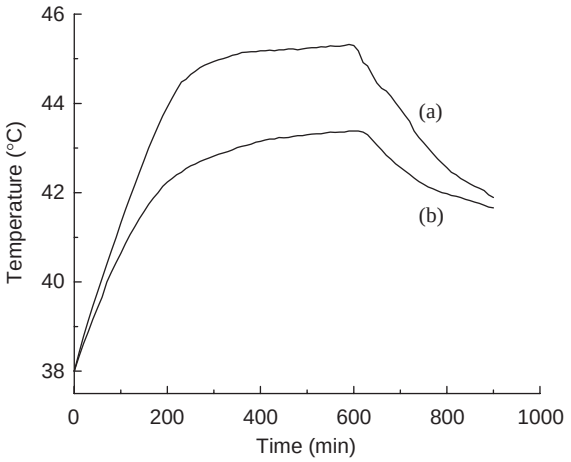

Fig. 6. Temperature curves of magnetite dispersion over time (a) in the tumor core and (b) around the tumor edge.

exceed 43.3 °C. After 600 s, the magnetic field was switched off, and the temperature dropped sharply. The results prove that the magnetite particles can generate enough energy to heat the tumor tissue for the effective hyperthermia.

3.5. Heating mechanism

The above results that heat effect of samples was independent of carrier liquids implied that Brownian relaxation may not be the dominant cause of relaxation losses. To further elucidate the heating mechanism, a series of experiments was performed.

Magnetite particles with 10 nm diameters were dispersed in a mixture of styrene and divinylbenzene. These two monomers were then polymerized and formed a crosslinked copolymer with a three-dimensional network, in which magnetic particles were tightly bound. Brownian relaxation could thus be excluded. SAR values of the sample before and after copolymerization were measured. Meanwhile, an applied field of 16 kA/m was employed to study the action of the external magnetic field on the relaxation behavior. As can be seen from Table 5, the power losses before and after polymerization were almost equal, which proved that it was Néel relaxation instead of Brownian relaxation that contributed most to the heating effect. Additionally, the results showed that the applied field reduced both SAR values greatly. In fact, the introduction of external magnetic field increased the energy barrier for magnetization reversal, consequently restraining Néel relaxation. The result also revealed that it was Néel relaxation that caused losses.

Table 5
Influences of external magnetic field and surroundings of magnetite particles on SAR values

Applied magnetic field (kA/m)	SAR values before polymerization (W/g)	SAR values after polymerization (W/g)
0	123	120
16	55	49

Furthermore, parameters of magnetite particles and the viscosity of octane were used to calculate τ_B and τ_N according to formulas (1) and (2). Values of $\tau_0 = 10^{-9}$ s, $T = 298$ K, $k_b = 1.38 \times 10^{-23}$ J/K, $K = 10^4$ J/m^3, $\eta = 5.45 \times 10^{-4}$ Pa s, $r_M = 5 \times 10^{-9}$ m and $r_H = 15 \times 10^{-9}$ m led to calculated Néel relaxation time of about 2.20×10^{-9} s and Brownian relaxation time of about 5.61×10^{-6} s. If both relaxation processes take place in parallel, the shorter one tends to dominate in determining the effective relaxation time [4], so calculated results also indicate that Néel relaxation is the dominant relaxation mechanism.

The Néel model that was cited in the above was used to calculate the relaxation time for magnetization reversal in single-domain monodiperse and non-interacting particles with uniaxial anisotropy in zero field. But in real systems, as could be seen in the above experimental results, the interparticles interaction cannot be ignored, and in some cases, external magnetic fields must be taken into account. All these factors can be analyzed starting from the energy E of particles in a real system. According to Fanning mode, this energy could be expressed as

$$E = E_{ms} + E_p = -\frac{\mu^2}{a^3}(1 + \cos^2\theta) + 2\mu H \cos\theta, \tag{5}$$

where μ is the magnetic moment of the particle, a the mean distance between the magnetic moments

corresponding to each particle, θ the angle of the magnetic moment to the line between the two adjacent particles, and H the amplitude of applied magnetic field.

So real Néel relaxation time τ_{re} could be expressed as

$$\tau_{re} = \tau_0 \exp\left[\frac{-(\mu^2/a^3)(1+\cos^2\theta) + 2\mu H\cos\theta}{k_b T}\right]. \quad (6)$$

From formulas (3) and (6) the power loss is expressed as

$$P = \pi\mu_0\chi_0 H_0^2 f \frac{2\pi f\tau_{re}}{1+(2\pi f\tau_{re})^2}. \quad (7)$$

Generally, the interparticle interactions or external magnetic field would increase τ_{re} greatly ($2\pi f\tau \gg 1$), so formula (7) could be simplified as

$$P = \frac{\mu_0\chi_0 H_0^2}{2\tau_{re}}. \quad (8)$$

As can be deduced from the above formula, power losses decrease with τ_{re}, in other words, decrease with d or H. So the new model can explain the influences of agglomeration of materials or external magnetic fields on the SAR values. At this time, the model is preliminary and needs further confirmation.

4. Conclusions

The factors that influenced SAR values of magnetic fluids were investigated. The results showed that SAR values of magnetic fluids were affected by the amplitude of alternating magnetic field and the material properties, such as particles sizes, surfactants, dispersion state and external magnetic field. Based on these experimental results and theoretical calculations, an excellent magnetic fluid with high SAR values can be prepared by means of increasing the amplitude and frequency of alternating magnetic field, increasing the particle diameter, enhancing surface treatment by surfactants, improving the dispersion state of particles, and so on. Our experimental heating results in vivo suggest that such magnetite particles can generate enough energy to heat tumor tissue to an effective hyperthermia temperature.

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