Effects of Mn concentration on the ac magnetically induced heating characteristics of superparamagnetic $Mn_xZn_{1-x}Fe_2O_4$ nanoparticles for hyperthermia

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The effects of Mn^{2+} cation concentration on the ac magnetically induced heating characteristics and the magnetic properties of superparamagnetic $Mn_xZn_{1-x}Fe_2O_4$ nanoparticles (SPNPs) were investigated to explore the biotechnical feasibility as a hyperthermia agent. Among the $Mn_xZn_{1-x}Fe_2O_4$ SPNPs, the $Mn_{0.5}Zn_{0.5}Fe_2O_4$ SPNP showed the highest ac magnetically induced heating temperature ($\Delta T_{ac,mag}$), the highest specific absorption rate (SAR), and the highest biocompatibility. The higher out of phase susceptibility (χ''_m) value and the higher chemical stability systematically controlled by the replacement of Zn^{2+} cations by the Mn^{2+} cations on the *A*-site (tetrahedral site) are the primary physical reason for the promising biotechnical properties of $Mn_{0.5}Zn_{0.5}Fe_2O_4$ SPNP. © *2010 American Institute of Physics*. [doi:10.1063/1.3430043]

Magnetic hyperthermia (MH) using a superparamagntice nanoparticle agent (SPNA) has recently drawn huge attraction due to its clinical promises.[1,2] Accordingly, the interests to utilize the ternary phase of SPNPs, MFe_2O_4 (M=Fe, Co, Ni, and Mg), with a mean diameter below 10 nm for a MH agent has increased dramatically. However, despite their promising chemical, physiological, biotechnical, and physical properties suitable for SPNA applications,[3] an insufficient $\Delta T_{ac,mag}$ and low specific absorption rate (SAR) at the physiologically tolerable range of frequencies and magnetic fields ($f_{appl}<100$ kHz, $H_{appl}<200$ Oe) are still revealed as the technical challenges to be overcome for a real clinical MH.[4,5] Thus, a great deal of research activity is being conducted in order to develop a functional SPNA and to improve the efficiency of currently used ferrite SPNAs. The quarterly phase of bulk $Mn_xZn_{1-x}Fe_2O_4$, which is one of the softest (or the highest permeability) ferrite materials, is considered to be a potential material for MH agent. The main physical reason is that it has a good electrical field absorption and a large power loss (500–200 W/m^3) at a low frequency (<100 kHz) which is due to its low electrical resistivity (0.02–20 Ω m).[6,7] Furthermore, its magnetic properties, i.e., saturation magnetization, M_s, and magnetic susceptibility ($\chi_m=\chi'_m+i\chi''_m$, particularly χ''_m), which are directly relevant to the $\Delta T_{ac,mag}$ characteristics, can be easily controlled by adjusting the relative concentration of Mn^{2+} and Zn^{2+} cations in the $Mn_xZn_{1-x}Fe_2O_4$.[6,8,9] However, all of the works relevant to the $Mn_xZn_{1-x}Fe_2O_4$ done so far were entirely focused on magnetoelectronics device applications.[10] There have been no systematic studies on the magnetic properties, $\Delta T_{ac,mag}$ characteristics, and the biocompatibility of $Mn_xZn_{1-x}Fe_2O_4$ SPNPs for MH agent applications until now.

In this paper, we report on the effects of Mn^{2+} cation concentration on the magnetic properties and the $\Delta T_{ac,mag}$ characteristics of $Mn_xZn_{1-x}Fe_2O_4$ SPNPs to explore its feasibility as a MH agent. The physical correlation between the magnetic properties of $Mn_xZn_{1-x}Fe_2O_4$ SPNPs controlled by the Mn^{2+} cation concentration and $\Delta T_{ac,mag}$, characteristics including power loss mechanism were systematically investigated at different ac H_{appl} and f_{appl}. In addition, the cell viability of $Mn_xZn_{1-x}Fe_2O_4$ SPNPs with different Mn^{2+} cation concentrations were quantitatively analyzed to evaluate the biocompatibility for *in vivo* MH agent applications.

The spinel ferrite $Mn_xZn_{1-x}Fe_2O_4$ nanoparticles (NPs) with different Mn^{2+} cation concentration were synthesized using a modified high temperature thermal decomposition (HTTD) method, where ramping up rate and heat treatment time were changed to 8.5 °C/min and 25 min, respectively, compared to a conventional HTTD method.[11] The Mn^{2+} cation concentration of $Mn_xZn_{1-x}Fe_2O_4$ NPs was systematically controlled from x=0.2 to 0.8 during the synthesis. The crystal structure, the particle size, and the distribution of $Mn_xZn_{1-x}Fe_2O_4$ NPs were analyzed by using a Cu-kα radiated x-ray diffractometer (XRD) and a high resolution transmission electron microscopy (HRTEM). The $\Delta T_{ac,mag}$ characteristics and the ac magnetic hysteresis of the solid state $Mn_xZn_{1-x}Fe_2O_4$ NPs were measured by using an ac solenoid coil system, which is connected to a capacitor. The f_{appl} and the H_{appl} were varied from 30 kHz to 210 kHz and from 60 Oe to 140 Oe, respectively. The dc magnetic properties of the

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