Published in final edited form as:

Nanoscale. 2014 November 21; 6(22): 13463–13469. doi:10.1039/c4nr04884a.

Monodisperse Magnetofluorescent Nanoplatforms for Local Heating and Temperature Sensing

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Abstract

Monodisperse multifunctional MnFe₂O₄/dye/silica core/shell nanoparticles have been designed and developed. The magnetic cores act as nano-heaters in biological systems under RF field excitation and the encapsulated dyes work as local temperature probes. The silica shells enable the water-solubility and biocompatibility of the NPs and protect the encapsulated fluorophores from photobleaching.

There is great interest in multifunctional nanoparticles (NPs) for novel diagnostic and therapeutic applications. Superparamagnetic NPs are being explored as agents for hyperthermia cancer treatment, biological separation, targeted drug delivery and controlled release, and as magnetic resonance imaging (MRI) contrast agents.¹ Recently, we and others have shown that heating of super-paramagnetic NPs in radio-frequency (RF) magnetic fields is sufficiently localized to remotely trigger temperature-sensitive ion-channels and stimulate protein synthesis *in vivo*.^{2–3} These applications call for stable, biocompatible NPs with maximal heating power. MnFe₂O₄ NPs have very high magnetization and are stable against oxidation. For maximal RF-heating the NPs should be monodisperse with high crystallinity, with their size controlled relaxation frequency matched to the RF frequency (Here, we used stimulation at 425 kHz and 40 MHz.), which is best achieved by synthesis in organic solvents.⁴ However, the resulting NPs are hydrophobic and require surface modification by either polymer ligand-exchange or inorganic surface coating (silica or carbon).⁵ Silica coating has been proven to be an effective method to create non-toxic, biocompatible, and stable NPs which can be further functionalized.⁶ Silica coated NPs may be synthesized either by the modified Stöber method or by reverse microemulsion method.⁷ Furthermore, the silica shell provides a location to embed fluorescent markers, which allows not only tracking and imaging, but also local temperature sensing. Although the synthesis of silica coated iron oxide NPs has been reported previously, they lack the precise control over the core size and shell thickness necessary for efficient RF field heating and temperature sensing.² Earlier work often demonstrated either thick silica shells with multiple cores, empty silica NPs free of magnetic core, or very thin silica shells that are not adequate to

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Electronic supplementary information (ESI) available: The synthesis, characterization, and oxidation rates of Fe and Fe/SiO₂ NPs

encapsulate desirable to develop a multifunctional nanoplatfrom consisting of monodisperse magnetic/dye/silica NPs with tunable dimensions.⁸

Here, we present our results on design, synthesis and characterization of monodisperse MnFe_2O_4 /dye/silica multi-functional NPs. The superparamagnetic MnFe_2O_4 core with its size tuned to match its relaxation frequency with the driving frequency of the RF field ensures highly efficient heating. The silica shell stabilizes the NPs in aqueous solution and reduces the fluorescence bleaching. The thickness of the shell is optimized to achieve sufficient heating and adequate dye loading for sensitive temperature measurement. The fluorophore embedded in the silica shell retains its temperature dependent luminescence properties, which makes them suitable for sensing local temperature changes inside cells.²

RF heating requires the magnetic core to possess high saturation magnetization for strong interaction with magnetic fields, yet to lack remnant magnetization (*i.e.* being superparamagnetic) to allow delivery of NPs to their *in vivo* targets without agglomeration. The main NP parameters affecting the power loss due to magnetic relaxation are the magnetic susceptibility χ_0 and the relaxation time τ .⁸ χ_0 is proportional to the saturation magnetization and NP size. Therefore particles should have highest possible magnetization. MnFe_2O_4 fulfills this condition and is stable against oxidation. The relaxation time, on the other hand decreases with increasing particle size. The two relaxation mechanisms are Néel relaxation (magnetic domain rotation) and Brownian relaxation (physical rotation of the particle). However, when the NPs are tethered to the cell surface for specific applications, physical rotation is prevented and Brownian relaxation irrelevant. MnFe_2O_4 is a rather soft magnetic material. In order to maximize the heating, we aimed to synthesize the largest cores, which could form a stable colloidal suspension in water. We observed that 18 nm MnFe_2O_4 cores were stable, but that 20 nm cores would aggregate. We added two silica shell thicknesses to the 18 nm MnFe_2O_4 core: 4 nm or 7 nm. We use rhodamine B isothiocyanate ($\lambda_{exc} = 555$ nm) as the fluorophore for temperature sensing. The isothiocyanate group enables stable chemical bonding of the dye molecules to the silica shell on the surface of the NPs.

The synthesis is outlined in Scheme 1. Monodisperse magnetic NPs up to 18 nm were synthesized through thermal-decomposition in organic solutions. The silica shells were coated on the NPs by reverse microemulsion method. During coating, dye molecules pre-bonded with 3-aminopropyltriethoxysilane (APTES) were added to form water-soluble magnetic/silica core/shell NPs with encapsulated fluorescent dye molecules in the silica shells. The magnetic cores can be removed by dilute hydrochloric acid (HCl), resulting in hollow silica NPs with dye molecules remaining intact.

MnFe_2O_4 NP seeds (8 nm) were synthesized through the thermal decomposition of iron acetylacetonate and manganese acetyl-acetonate with surfactants in a high-boiling point solvent such as benzyl ether at 300 °C.⁹ MnFe_2O_4 NPs larger than 10 nm were then obtained by seed-mediated growth method. Figure 1a shows a typical transmission electron microscopy (TEM) image of monodisperse MnFe_2O_4 NPs with an average diameter of 18 nm. EDX analysis shows that the Fe to Mn ratio equals to 2:1, close to the stoichiometry ratio of MnFe_2O_4 (Figure S1). The uncoated NPs were well dispersed in nonpolar solvents

such as hexane or chloroform. Silica coating of the magnetic NPs was performed by reverse microemulsion method.¹⁰ In order to preserve the excellent response of NPs to a RF magnetic field, a thin silica shell (< 10 nm) coating on a larger magnetic core is desirable. Varying the reaction conditions, such as the amount of magnetic NP seeds, ammonia and TEOS, controls the thickness of the silica shell. Raising the amounts of TEOS and ammonia increases the shell thickness, while increasing the amount of seed NPs exhibits the opposite effect (experimental section). Figure 1b shows MnFe₂O₄ NPs (18 nm) with 7-nm silica shells. Doubling the amount of MnFe₂O₄ NPs results in a thinner shell of 4 nm (Figure 1c). It is worth pointing out that in order to achieve single-core per particle coating without free silica particles, it is critical to match the number of magnetic NP seeds with that of the micelles in the emulsion. Therefore, in our synthesis, we used appropriate amount of seeds, much more than what was reported in previous work.¹⁰ Similarly, we also obtained silica coated Fe NPs using Fe NPs as seeds during the coating. We observe that all silica shells are thin and extremely uniform, with each shell containing exactly one magnetic core and no presence of core-free silica particles in a large area (Figure S2). To encapsulate dye molecules into the silica shell, the dye molecules were first bonded to a silica precursor.¹¹ The reaction was allowed to proceed overnight in the dark with shaking. The freshly made dye-APTES complex was added during the silica coating step. After reaction, the NPs were collected and washed by centrifugation and redispersion several times to ensure the removal of free dye molecules.

The magnetic hysteresis loops reveal that both the uncoated MnFe₂O₄ and silica-coated magnetic NPs are superparamagnetic at room temperature. The 18 nm MnFe₂O₄ NPs show saturation magnetization σ_s of 75.0 emu g⁻¹ in the presence of surfactants. The surfactants remaining on the NPs was determined to be 11.8 wt% by thermogravimetric analysis (TGA). The calibrated net σ_s of MnFe₂O₄ NPs is thus obtained to be 85.0 emu g_{NPs}⁻¹, (Figure 2a). This is very close to the bulk value of 90 emu g⁻¹ for MnFe₂O₄, suggesting excellent crystallinity. The slightly reduced magnetization may be due to surface spin disorder.¹² The σ_s of the MnFe₂O₄/dye/SiO₂ core/shell NPs with a 7-nm thick silica shell is measured to be 40 emu g⁻¹ (Figure 2b). The weight percentage of the MnFe₂O₄ NPs in the core/shell NPs was determined to be 48.8% by removing the silica shell using ammonium solution. Calculating the net σ_s of MnFe₂O₄ NPs per NP and metal content yields 82 emu g_{NPs}⁻¹, respectively, comparable to the values for uncoated NPs. This clearly shows that the magnetic properties are not affected by silica coating, suggesting the excellent stability of MnFe₂O₄ NPs. The low field (to 2000 Oe) hysteresis loops show that before and after silica coating, the NPs are superparamagnetic (Figure S3). Based on the calculated volume and measured weight percentage of the amorphous SiO₂ shell we can estimate the porosity of the silica shell to be about 22%. The porous nature of SiO₂ shell is beneficial if the NPs are to be used for MRI contrast agents, since they would allow water protons to diffuse as close to the surface of the magnetic core as possible for the dipole field to influence the spin relaxation of protons. However, the porosity reduces the ability of the shell to protect the core against oxidation and corrosion (see below).

After silica coating, the resulting core/shell NPs are water-soluble and aqueous dispersions remain stable without precipitation for months. The NP solution is black in color due to the absorption of MnFe₂O₄ cores (Figure 1b, inset). UV-Vis absorption and photoluminescence

spectra show that the dye molecules have been encapsulated into the silica shell. The UV-vis absorption spectrum of the NP aqueous solution indicates that the dye-encapsulated NPs have a broad absorption with peak at about 550 nm (Figure 3a). The broad background absorption is attributed to the magnetic MnFe_2O_4 cores. To remove this background, the magnetic cores were etched away by a dilute hydrochloric acid (2N) aqueous solution, leading to the formation of hollow fluorescent SiO_2 NPs. Figure 1d shows the TEM image of dye-encapsulated hollowed silica shells after the removal of magnetic cores from the NPs shown in Figure 1b.

All ferrite cores were removed by acid etching, showing that the silica shells are sufficiently porous to allow the hydrochloric acid to penetrate. EDX analysis reveals that there is no heavy metal ions to the limit of the instrument resolution were detected after etching (Figure S4). These hollow SiO_2 NPs disperse well in water to form a pink aqueous solution (Figure 1d inset). The color is the same as that of free rhodamine B aqueous solution. The broad background absorption is removed, resulting in a clear absorption with a peak at 560 nm (Figure 3b). The absorption is identical to that of free dyes in aqueous solution (Figure 3c) except for a few nanometer shift of the peak position to longer wavelengths. The average number of encapsulated dye molecules per NP was determined by integrating the area below the absorption curve of hollow NPs and comparing it with that of pure dye molecule solution of a known concentration. A 7-nm thick shell as shown in Figure 1d contains around 90 dye molecules; while a 4-nm thick shell hosts only 15 dye molecules.

This shows that we can use the thickness of the silica shell to control the amount of dye molecules encapsulated. The photoluminescence spectra of all samples were measured. The peak of the emission spectrum of the dye-encapsulated NPs and hollow silica NPs are near the 585 nm of free rhodamine B, while the uncoated magnetic NPs solution has no emission peak (Figure 3d). Encapsulating the rhodamine B fluorophore in silica reduces photobleaching about eight-fold (to $0.018\% \text{ min}^{-1}$) compared to free rhodamine B (about $0.138\% \text{ min}^{-1}$) (Figure 4). A small amount (5%) of fluorophores bleaches as fast as in water, which may indicate that those molecules are at the surface of the silica matrix. Earlier Wiesner and coworkers also demonstrated that encapsulating dye molecules with a SiO_2 shell increased their photostability.¹³ In addition, the silica shell also helps to deter the oxidation of the inner cores as demonstrated by comparing the magnetization drop rates of the as-synthesized Fe NPs and silica coated Fe NPs. Our results show that the silica shell reduces the speed of Fe oxidation several folds yet cannot prevent it completely (Figure S6). The details of the synthesis of Fe NPs, characterization and the magnetization measurement are also shown in the supplemental section.

We examined next the heating efficiency of the core/shell NPs in bulk solution. A 10-mg ml^{-1} solution of rhodamine B encapsulated $\text{MnFe}_2\text{O}_4/\text{SiO}_2$ NPs was subjected to an RF magnetic field of 425 kHz and 370 Gauss or 40 MHz and 22.4 G. The resulting temperature changes of the solution were measured by a fiber optic temperature probe, and compared to heating of mPEG-2000 coated MnFe_2O_4 NPs of the same ferrite core size and that of water (Fig. 5). It is shown that the rhodamine B encapsulated NPs heat the solution significantly above background, though less than that of mPEG-2000 coated NPs. Since the 7-nm silica shell essentially doubles the weight of the $\text{MnFe}_2\text{O}_4/\text{dye}/\text{SiO}_2$ NPs, we compare the specific

absorption rate (SAR) of 10 mg ml⁻¹ silica coated NPs to 10 mg ml⁻¹ and 5 mg ml⁻¹ mPEG-2000 coated NPs (Figure 5 and Table 1). For the nominally same concentration of magnetic material, the SAR of the silica coated NPs is about 60% of the value for mPEG-coated NPs, despite having nearly identical magnetization at room temperature. In our experiments, polymer-coated and silica-coated NPs have identical magnetic cores, so they should have the same magnetic power loss. Therefore, the difference in solution temperature must be due to the difference in the coating layer thickness and properties. The hydrodynamic radius of the silica coated NPs is estimated to be 6 nm larger than that of the PEG coated NPs. However, according to our earlier discussion, Néel relaxation, determined by the magnetic NP volume, dominates the relaxation time, so the increase of hydrodynamic radius alone does not explain the different SAR. A possible explanation could be the 50-fold lower thermal conductivity of silica compared to water, which may create an appreciable temperature gradient across the shell. However, further studies will be required to determine the exact cause of the reduced SAR of the silica coated NPs. Table 1 shows also that the 18nm MnFe₂O₄ NPs fulfill the resonance condition better at 40 MHz. Despite $f \times H^2$ being only one third at 40MHz, the measured SAR is about twice that measured at 425 kHz. This is expected for a magnetically soft material.

To confirm that the fluorophores embedded in the silica shells can be used for temperature sensing, we measured the fluorescence lifetime of dye-encapsulated NPs as a function of temperature. Figure 6a shows that between 25 °C to 45 °C, the fluorescence lifetime of encapsulated rhodamine B decreases with increasing temperature. For this small biologically relevant temperature range the decrease can be approximated by a linear function with a rate of -1.43% °C⁻¹. This temperature dependence is similar to that of free dyes in aqueous solutions, whose fluorescence lifetime decreases at a rate of -1.55% °C⁻¹. Prior measurements of free Rhodamine B in solution showed that the temperature dependence of the quantum yield changes over a larger range of temperatures, and disappears for low temperatures.¹⁴ The fluorescence absorption and emission spectra are temperature independent. Earlier work had proposed that the temperature dependence is the result of torsional flexibility within the fluorophore,¹⁴ which may well explain our observations. The quantum yield shows the same temperature dependence. Hence, fluorescence lifetime, quantum yield, and relative changes of fluorescence intensity for a given sample can be used for nanoscale local temperature sensing near the NP surface. Figure 6a shows further that at any particular temperature, the fluorescence lifetime of encapsulated rhodamine B is longer than that of free rhodamine B. This indicates that the encapsulation in silica eliminates some non-radiative recombination processes, most likely by protecting the fluorophore from solvent quenching.

The fluorescence signal from rhodamine B embedded in the silica shell is used to measure the local temperature near the NP surface. Figure 6b shows that the local temperature change, as measured by the fluorescence intensity of rhodamine B, is significantly (4 °C after 2 min heating) higher than that in the bulk solution monitored simultaneously by a fiber optic temperature probe. This temperature difference between NP surface and bulk water is similar to our previously published measurements using protein coated 7nm MnFe₂O₄ NPs.¹⁰ Our data also agree with results of Riedinger et al.³⁵ who used the temperature

dependent release of a fluorophore to measure the temperature profile. However, precise quantification of the temperature profile near the nanoparticle is extremely challenging because the spacer linking the probe to the nanoparticle is typically an unstructured polymer with broad length distribution, which affects the hydrodynamic radius. Using fluorophores embedded in a silica shell offers a few advantages to measure the local temperature profile: (a) instant readout, (b) the probe remains on the NP, so it may be performed inside cells, and (c) by growing the silica shell in sequential layers to create NP with the same hydrodynamic radius but fluorophore at varying distance from the magnetic NP surface. In addition, the actual thermal gradient in a biological system may be very different, depending on the thermal conductivity of the environment and the spatial distribution of the NPs. Our previous experiments showed that a dense array of NPs attached to the cell membrane can create significantly more localized heating. Therefore, it is extremely useful to have a fluorophore embedded in the NP surface as molecular temperature sensor. The heating rate of a solution containing hollow silica shells is also measured as a control experiment. The SAR is much lower than that of the NPs with MnFe_2O_4 . This residue SAR value may be contributed by the ferrite cores not completely etched away.

In conclusion, we have synthesized monodisperse silica coated superparamagnetic NPs containing fluorophores in their shells. These NPs are water-soluble, biocompatible, and preserve both stable magnetization and fluorescence. RF magnetic field heating experiments showed that these NPs act both as nano-heaters and local temperature probes. The silica coating protects the dye molecules from photobleaching, deters the oxidation of magnetic cores, and facilitates further biofunctionalization. The amount of encapsulated dye molecules can be well controlled by the silica shell thickness. Such multifunctional nanoprobe are promising for magnetic hyperthermia and other applications where a RF magnetic field can be used to remotely trigger a biological response.

Materials and Methods

Iron(III) 2,4-pentanedionate [$\text{Fe}(\text{acac})_3$], manganese(II) 2,4-pentanedionate [$\text{Mn}(\text{acac})_2$], oleic acid (OA), Iron(0) pentacarbonyl ($\text{Fe}(\text{CO})_5$) and 1-octadecene (ODE) from Alfa Aesar; Polyoxy-ethylene(5) nonylphenyl ether (Igepal CO-520), benzyl ether, tetra-ethylorthosilicate (TEOS), 3-aminopropyltriethoxysilane (APTES), and rhodamine B isothiocyanate (RITC) from Sigma; Oleylamine (OAm) from Acros Organics.

Synthesis of 8 nm MnFe_2O_4 NPs

10 mmol of tetradecanediol, 2mmol of Fe(III) acetylacetonate and 1 mmol of Mn(II) acetylacetonate were mixed together in 20 ml benzyl ether, and 6 mmol of oleic acid (OA) and oleylamine (Oam) were added as surfactants. The solution was heated to 120 °C and kept at that temperature for 1 h before further heated to 210 °C for 2 h. Then, the mixture was brought up to 298 °C and refluxed for 1h, before cooled down to room temperature by removing the heating mantle. The black NPs were collected by adding ethanol and centrifugation, and were redispersed in hexane.

Synthesis of 13-18 nm MnFe₂O₄ NPs

10 mmol of tetradecanediol, 2 mmol of Fe(III) acetylacetonate and 1 mmol of Mn(II) acetylacetonate were mixed in benzyl ether, and 2 mmols of OA and OAm were added as surfactants. The solution was heated to 120 °C for 1 h. To synthesize 13 nm MnFe₂O₄ NPs, 60 mg of 8-nm MnFe₂O₄ NPs in 2 ml hexane were. The mixture was kept at 120 °C for 0.5 h and then heated to 210 °C for 1 h, and finally brought up to 298 °C and refluxed for 0.5 h. After cooling to room temperature, the NPs were cleaned by adding ethanol and centrifugation, and redispersed in hexane. For 18 nm MnFe₂O₄ NPs, the synthesis is similar, except that 30 mg of 8-nm MnFe₂O₄ seeds were used.

Conjugation of Dye with APTES

Rhodamine B isothiocyanate (RITC, Aldrich) (5 mg) was dissolved in 0.5 ml ethanol and reacted with 44 µL of 3-aminopropyltriethoxysilane (APTES, Sigma, 98%) (molar ratio of dye:APS of 1:20) overnight in the dark.

Silica and Dye/Silica coating of magnetic NPs

For 7-nm silica coating, 40 ml cyclohexane and 2.3 ml Igepal CO-520 were mixed and 40 mg magnetic NPs in 5 ml cyclohexane were added while stirring. 0.4 ml ammonium hydroxide (29%) was, followed by 0.3 ml TEOS. The solution was stirred at room temperature for 24 h and the resulting magnetic NPs/dye/SiO₂ core/shell NPs were precipitated by adding ethanol and centrifugation. The collected particles were washed in ethanol and water twice and precipitated by centrifugation and finally redispersed in water. To encapsulate dye molecules into the silica shell, 16 µl APTES-conjugated dye solution were added into the reaction after the addition of TEOS, while others conditions were kept the same. The thickness of silica shell can be tuned by varying the reaction conditions. For example, by increasing the amount of magnetic NPs seeds to 80 mg, a 4-nm silica coating was obtained. Doubling of the TEOS amount (0.8 ml) leads the formation of 10 nm silica shell. With the reduction of the ammonia amount to 0.1 ml, a very thin shell of 2 nm was generated.

Formation of hollow silica NPs

The MnFe₂O₄/SiO₂ NPs were precipitated by centrifugation, and 2 N HCl solution was added to remove the magnetic core. The NPs were redispersed by stirring in the dark for 24 h. The resulted hollow NPs were washed in water.

Fluorescence lifetime measurements

The fluorescence lifetimes of free rhodamine B in aqueous solution and of rhodamine B/silica NPs were measured using a Zeiss LSM 710 confocal microscope with an In-Tune laser and time-correlated photon-counting (Becker & Hickl). An incubation chamber controlled the temperature of the solution.

SAR measurements

100 µL of a 10-mg ml⁻¹ NP solution was placed within a glass cuvette, thermally insulated with styrofoam and placed inside a heating coil (425-kHz, 370 Gauss). The temperature of

the solution was measured by a fiber optic temperature probe (Neoptix). The SAR values were obtained by multiplying rate of temperature increase during the initial 10 s by the specific heat of water.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

We thank R. Munshi for assistance with SAR measurements and I. Castellanos-Rubio for simulations. The research was supported in part by grant R01 MH094730-03 from NIH/NIMH, RGP0052/2012 from HFSP, and 51171121 from NFS of China.

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Figure 1.

TEM images of (a) uncoated 18 nm MnFe_2O_4 NPs deposited from hexane; (b) 18 nm MnFe_2O_4 NPs coated with a 7-nm silica shell and rhodamine B encapsulated in the shell, deposited from water; (c) 18 nm MnFe_2O_4 NPs coated with a 4-nm silica shell deposited from water; (d) and hollow dye/ SiO_2 shells obtained by removing the MnFe_2O_4 cores from samples shown in (b). Insets in (b) and (d) show photos of the MnFe_2O_4 /dye/silica NPs and the dye/silica shells, respectively.

Figure 2.

The magnetic hysteresis loops of (a) as-synthesized 18 nm MnFe_2O_4 NPs and (b) 7-nm silica coated 18 nm MnFe_2O_4 NPs.

Figure 3.

UV-vis absorption spectra of (a) rhodamine B embedded in the shell of MnFe_2O_4 (18 nm)/ SiO_2 (7 nm) core/shell NPs; (b) rhodamine B embedded in hollow SiO_2 shells and (c) free rhodamine B in aqueous solution with a concentration of $8.35 \times 10^{-7} \text{ mol} \cdot \text{ml}^{-1}$; (d) fluorescence emission of free rhodamine B (red circles), rhodamine B embedded in the shell of MnFe_2O_4 (18 nm)/ SiO_2 (7 nm) core/shell NPs (pink crosses) and of the hollow silica shells by removing the magnetic cores (blue triangles), and that of NPs without fluorophore (black dash line). The excitation wavelength is 540 nm.

Figure 4.

The photobleaching of rhodamine B in the silica shell of $\text{MnFe}_2\text{O}_4/\text{dye/silica}$ NPs (circles) and of free rhodamine B in solution (crosses) under identical illumination and imaging conditions. In both cases, there is a small fraction ($< 5\%$) of quickly bleaching molecules. The majority of rhodamine B molecules in the silica shell of $\text{MnFe}_2\text{O}_4/\text{dye/silica}$ NPs is bleached at a rate of 0.018 % per minute, which is significantly lower than the rate of 0.138% per minute for free Rhodamine B in solution.

Figure 5.

Temperature rise measured in aqueous suspensions of 18 nm MnFe₂O₄ NPs at 5 mg ml⁻¹ (solid blue line), 18 nm MnFe₂O₄ NPs with 7-nm SiO₂ shells at 10 mg ml⁻¹ (equivalent to 5 mg ml⁻¹ of magnetic cores, dotted red line) and pure water (dashed black line), during the application of a RF magnetic field (425 kHz, 370 Gauss).

Figure 6.

(a) Temperature dependence of the fluorescence lifetime of free rhodamine B solution (crosses) and rhodamine B embedded in the shell of MnFe₂O₄/SiO₂ NPs with 7-nm shell (open squares). (b) The temperature changes of a 1 mg ml⁻¹ NP solution in response to the application of RF magnetic field (40 MHz, 22.4 Gauss, note: frequency and field used different from table 1 to accommodate the microscopic imaging). The solid line shows the local temperature changes at the MnFe₂O₄/SiO₂ NP surface measured by rhodamine B fluorescence in the silica shell. The temperature changes in the bulk solution of the same NPs suspension as measured with a fiber optic temperature probe is shown as dash-dotted line. The bulk solution heating of rhodamine B embedded hollow SiO₂ shells (dashed line) as well as free rhodamine B solution (dotted line) in response to the same RF magnetic field are shown for comparison. The RF magnetic field was applied between 0 s and 120 s.

Scheme 1.

The scheme of the synthesis of MnFe₂O₄/dye/SiO₂ core/shell NPs and the generation of hollow dye/SiO₂ NPs.

Table 1

Specific absorption rates (SAR) of NP aqueous suspensions normalized per gram of magnetic core material. The PEG-2000 coated 18nm MnFe_2O_4 are measured at two concentrations to show that the SAR per g magnetic material is independent of the concentration. In the case of silica-coated MnFe_2O_4 NPs, the magnetic core accounts for 51.2% of the total particle weight. The SAR of the silica-coated MnFe_2O_4 NPs is also measured at 40MHz for comparison with figure 6.

NP core	NP shell coating	NP conc [mg/ml]	RF field	SAR per core [W/g]
MnFe_2O_4 (d=18 nm)	PEG-2000	10	425 kHz 370 G	196
MnFe_2O_4 (d=18 nm)	PEG-2000	5	425 kHz 370 G	212
MnFe_2O_4 (d=18 nm)	SiO_2 (t=7 nm)	10	425 kHz 370 G	123
MnFe_2O_4 (d=18 nm)	SiO_2 (t=7 nm)	1	40 MHz 22.4 G	252