Size-tunable NaGdF₄ nanoparticles as T₂ contrast agents for high-field magnetic resonance imaging†

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It is important to get high-quality magnetic resonance images at high magnetic field (>3 T) for medical diagnoses. However, the efficiency of the commonly used magnetic resonance imaging (MRI) contrast agents (CAs) always decrease with the increasing of magnetic field intensity. Thus, it is necessary to design MRI CAs with high relaxivity at high magnetic field. In this study, the hydrophilic and biocompatible NaGdF₄@SiO₂ nanoparticles (NPs) were feasibly synthesized and exhibited highly effective T₂ contrast imaging at 7 T magnetic field. Furthermore, the obtained NPs had a higher r₂/r₁ value than the other typical T₂ CAs (such as Dy-based NPs and Fe-based NPs) at high magnetic field. The observed large r₂ of the current NaGdF₄@SiO₂ was mainly ascribed to the increased particle sizes. For in vivo application, 250 nm NaGdF₄@SiO₂ (with the highest relaxivity) as T₂-weighted MRI CAs was further assessed. Toxicity studies demonstrated that NaGdF₄@SiO₂ NPs exhibited little toxicity both in vitro and in vivo. Therefore, NaGdF₄@SiO₂ NPs with appropriate size could be used as high-performance T₂ CAs in the high magnetic field.

Lanthaneide-based nanoparticles can be used as ideal building blocks for CAs because of their unique magnetic properties.10–14 Among the lanthanide elements, paramagnetic gadolinium (Gd), which has seven unpaired electrons, is usually considered as excellent T₁-weighted MRI CAs.15 Recently, gadolinium ion-doped nanoparticles (Gd-NPs), such as upconversion nanoparticles (UCNPs),16–19 GdPO₄,20,21 GdF₃ (ref. 22 and 23) and Gd₂O₃24,25 have attracted increasing attention as promising T₁ MRI CAs, more and more studies have been performed to describe how Gd-NPs affect the longitudinal relaxation rate (r₁) and have demonstrated that the surface-coating and the size of the Gd-NPs are key factors influencing the relaxation rate.26–28 Unfortunately, many previously reported Gd-NPs including Dy-NPs and Fe-NPs have high r₁ or r₂ values but the r₂/r₁ value is not so satisfied. Furthermore, one of the major limitation of the present CAs is their decreased efficiency at higher magnetic fields, for example, the T₁ imaging ability of Gd ion complexes is optimal at fields below 1 T.6,29,30 The other kind of T₂ CAs (superparamagnetic iron oxide nanoparticles) are known to saturate their magnetization at about 1.5 T. Therefore, the development of CAs (with high r₂ and high ratio of r₂/r₁) that are more efficient at high magnetic field is urgently needed to take full advantage of contrast enhanced MRI at ultrahigh fields and to meet the ever-growing performance demand on scientific research and clinical diagnosis.31

In this work, we report a simple and feasible approach to prepare the NaGdF₄ NPs by direct nanoprecipitation method for high efficiency T₂ MRI CAs. This synthesized method allows for...
regulating crystal growth by changing the density of chelator to
obtain different sizes of NaGdF₄ NPs in the range of 100–220 nm. Then NaGdF₄ NPs with different size distribution
were coated with the same thickness of silica (~12 nm), forming
a highly biocompatible and hydrophilic rigid sphere with the
diameter from 120 to 250 nm. The T₂ relaxivity measurements
were performed at 0.5 T and 7 T. The r₂ values were 129–
159 mM⁻¹ s⁻¹, and the r₂/r₁ values were as high as 173–586 (7 T) when the size of the NPs was increased. The magnetization
plots (M–H) of the NaGdF₄@SiO₂ show that NPs are paramagnetic and the observed large r₂ of the current NaGdF₄@SiO₂
was mainly ascribed to the particle sizes increase. The toxicities
of these NPs in vitro and in vivo were further evaluated using
WST-8 assays and pathology staining methods to demonstrate
the non-toxicity with the NaGdF₄@SiO₂ NPs. The T₂-weighted
MRI contrast effect in vivo was also investigated. In short, this
work will provide a new method for the application of Gd-NPs as
high efficiency T₂ MRI CAs.

Experiments

Materials

All of the chemicals used were of analytical grade and were used
without further purification unless otherwise stated. Gadolinium
oxide (Gd₂O₃, 99.9%) was purchased from China Min-
metals Corporation Co. Ltd. Na₄ nitritoltriacetic acid (Na-NTA,
99.9%) and sodium fluoride (NaF) were obtained from
Aldrich. Tetraethyl orthosilicate (TEOS) was purchased from
Alfa-Aesar. Aqueous ammonia solution (25 wt%), perchloric
acid (HClO₄), and ethanol were purchased from Beijin
Chemical Factory (China). Dulbecco's modified Eagle's medium
(DMEM, HyClone, United States), Cell Counting Kit-8 (CCK-8),
penicillin/streptomycin (PS), and fetal bovine serum (FBS,
HyClone, USA) were all purchased from Biodoe Co. Ltd., Beijing
(China). This study was performed in strict accordance with the
NIH guidelines for the care and use of laboratory animals (NIH
publication no. 85-23 Rev. 1985) and was approved by IACUC
(Institutional Animal Care and Use Committee) of Capital
Medical University (Beijing, China).

Preparation of NaGdF₄ nanoparticles

NaGdF₄ NPs were synthesized as follows. In brief, Gadolinium
oxide (1 mmol) and a measured amount of perchloride were
mixed together in a 50 mL flask heated to 80 °C until a clear
solution formed. The gadolinium perchloride solution was
cooled to room temperature and concentrated to 5 mL
(0.2 mol L⁻¹) by vacuum rotary evaporation. Next, 15 mL of
different concentrations of trisodium citrate (0.6 mol L⁻¹ for
120 nm NPs, 0.3 mol L⁻¹ for 190 nm NPs and 0.2 mol L⁻¹ for
250 nm NPs) was quickly injected into the flask, the mixture
was stirred for 10 min. Then, NaF (5 mL, 0.5 mol L⁻¹) was quickly
injected into the flask with vigorous magnetic stirring at room
temperature for 4 h and a milk white solution formed. Subse-
sequently, the milk white solution was centrifuged at 8000 rpm
and washed twice with ethanol and water. The NPs were finally
dispersed in 15 mL of water.

Preparation of silica-coated NaGdF₄ nanoparticles

NaGdF₄@SiO₂ core/shell nanoparticles were prepared by the
reverse microemulsion method. The preparation was typi-
cally performed as follows: under vigorous stirring, 1 mL of
aqueous NaGdF₄ solution was introduced into a liquid system
containing 10 mL of ethanol, the volume of aqueous ammonia
solutions and TEOS were added differently along with different
size of NaGdF₄@SiO₂ NPs: for 120 nm NaGdF₄@SiO₂ NPs, 40 µL
aqueous ammonia solutions were added dropwise, after about
5 minutes, another 50 µL TEOS were introduced dropwise into
the flask, for 190 nm and 250 nm NaGdF₄@SiO₂ NPs, the
procedures were the same as 120 nm NaGdF₄@SiO₂ NPs, but
the volume that were: 60 µL aqueous ammonia solutions and
80 µL TEOS for 190 nm NaGdF₄@SiO₂ NPs, 80 µL aqueous
ammonia solutions and 100 µL TEOS for 250 nm NaGdF₄@SiO₂
NPs. Then, the reaction system was sealed and kept under
stirring in a dark at room temperature for different times (4 h,
d = 120 nm; 5 h, d = 190 nm; 6 h, d = 250 nm). Isopropanol
was used to terminate the reaction, and the resultant precipitate
of NaGdF₄@SiO₂ composite particles was subsequently washed in
sequence with ethanol and water. The particles suspended in
liquid media were typically collected by centrifugation and then
dispersed in pure water for further characterization.

Characterization

Transmission electron microscopy (TEM) images were obtained
on a JEM-2100F microscope (JEOL, Japan) at an operating
temperature of 100 K. Samples were prepared by spreading a drop
of sample on copper grids, followed by evaporation under vacuum.
Powder X-ray diffraction (XRD) measurements were taken with
a Rigaku D/MAX-2000 diffractometer (Japan) with a slit of 1°/2°
at a scanning rate of 2° min⁻¹ using Cu Kα radiation (λ = 0.15406
nm). The dynamic light scattering (DLS, Malvern, UK)
measurements were performed at 25 °C. The scattering angle
was fixed at 90°. Samples were filtered through a 0.45 µm pore
size membrane before DLS measurement.

Cell culture

Human lung cancer A549 cells were provided by peking union
medical college hospital (Beijing, China). A549 cells were
cultured in DMEM supplemented with 10% fetal bovine serum
(FBS), streptomycin (100 µg mL⁻¹) and penicillin (100 U mL⁻¹)
at 37 °C in a humidified 5% CO₂ atmosphere.

Cellular toxicity

To investigate the cellular toxicity of NaGdF₄@SiO₂, the A549
cells were seeded in a 96-well culture plate with DMEM for 24 h.
Then, the aged culture medium was replaced with freshly
prepared culture medium that contained NaGdF₄@SiO₂ solu-
tion in a series of gradient Gd⁺⁺ concentrations and incubated
for another 24 h (n = 6). Subsequently, the culture medium was
removed, and 100 µL of DMEM without phenol red and 10 µL of
Cell Counting Kit-8 (CCK-8; DOJINDO, Kumamoto, Japan) were
added to each well. After incubation for another 1 h, the
absorbance of each treated well was measured at 450 nm using a microplate reader (iMark microplate reader, Bio-RAD, USA).

Relaxivity measurement in vitro
To evaluate the contrast enhancement of the obtained NaGdF₄@SiO₂, the relaxivities r₁ and r₂ were measured at 0.5 T and 7 T. For 0.5 T NM120 analyst, using a spin-echo pulse sequence with pulse repetition time D₀ = 300 ms. For 7 T analyst, the MR signal intensity in the tubes was ascertained by the average intensity in the defined regions of interests (ROI) using a 7 T (BioSpec70/20USR, Bruker, Germany) in conjunction with a volume coil. Dilutions of NaGdF₄@SiO₂ in water were placed in a series of 0.5 mL tubes. The T₁ WI and T₂ WI were acquired with T₁-flash and T₂-turbo-RARE sequences, respectively. The T₁-flash parameters were as follows: TR/TE = 150/1.8 ms, NEX = 3, flip angle = 80°, FOV = 40 × 40 mm, MTX = 256 × 256; T₂-turbo-RARE: TR/TE = 2500/53.38 ms, NEX = 1, flip angle = 90°, FOV = 40 × 40 mm, MTX = 256 × 256. The T₁ and T₂ values were measured with T₁ map-RARE and T₂ map-MSME sequences, respectively. The T₁ map-RARE parameters were as follows: TR/TE = 189, 400, 800, 1200, 2500/6.1 ms, NEX = 1, flip angle = 90°, FOV = 40 × 40 mm, MTX = 128 × 128; T₂ map-MSME: TR/TE = 2500/6.67 (16 echo times, the step is 6.67 ms), NEX = 1, flip angle = 90°, FOV = 40 × 40 mm, MTX = 128 × 128.

Magnetic resonance imaging in vivo
H22 cells were grown in DMEM medium that was supplemented with 10% FBS and 1% PS at 37 °C in 5% CO₂. Balb/c mice (five weeks, 18–22 g) were purchased from Beijing Xing Long Biological Technology Co., Ltd (China). Each mouse was subcutaneously injected in the flank with approximately 8 × 10⁶ H22 cells that were suspended in 100 μL of PBS. Approximately 8 d after inoculation, 200 μL of the complex solution at a dose of 4 mM Gd³⁺ was intravenously injected into the tail vein and mice were imaged with a rat head coil on a 7 T MRI instrument. The T₂ WI was acquired with T₂-turbo-RARE sequence. The parameters were as follows: TR/TE = 3000/50 ms, NEX = 2, flip angle = 90°, FOV = 40 × 40 mm, MTX = 256 × 256.

H&E staining
For hematoxylin and eosin (H&E) staining, the heart, liver, spleen, lung, and kidney were harvested from mice after intravenously injected with different sizes of NaGdF₄@SiO₂ NPs (n = 3, dose = 4 mM, 200 μL, test group) and the un-treated mice as control. The tissues were fixed in 4% paraformaldehyde solution and embedded in paraffin. They were then sectioned and stained with hematoxylin and eosin. The histological sections were tested for in vivo toxicity and observed under a Nano-Zoomer-SQ slide scanner (Hamamatsu, Japan).

Results and discussion
Synthesis and characterization of NaGdF₄ NPs
NaGdF₄ NPs were first formed by the aggregation model and were prepared in the presence of a chelator (trisodium citrate). By changing the concentration of trisodium citrate from 0.2 M to 0.6 M, the sizes of obtained NaGdF₄ NPs were ranged from 100 nm to 220 nm (Fig. S1†). According to the reported literature, the formation of the NPs is primarily controlled by the aggregation of the primary Gd ion. Smaller particles were achieved by the presence of the chelator trisodium citrate and its variation ion concentration. This change probably resulted in the adsorption of chelators onto the NaGdF₄ nanoparticles and influenced the repulsive force between the primary Gd ions, preventing the primary Gd ions from forming large particles but generating uniform NPs by aggregation. The water-dispersible NaGdF₄ NPs were then coated with silicon dioxide, as shown in Fig. 1A–C. The silica-coated NaGdF₄ NPs were well dispersed in water. By changing the ratio of TEOS to ammonia, different sizes of NaGdF₄ were coated with the same thickness of silica, and the thickness of the silica layer could be easily observed by TEM as approximately 12 nm. The average hydrodynamic diameters of the NaGdF₄@SiO₂ NPs were ranged from 120 nm to 250 nm measured by dynamic light scattering (DLS, Fig. 1D–F), which was consistent with those observed with TEM. The surface zeta potential of NaGdF₄@SiO₂ with the size of 250 nm was −30 ± 0.6 mV, −32 ± 0.8 mV for 190 nm NPs and...
versus Relaxivity measurements and phase was detected.

No impurity ion concentration of the NaGdF4@SiO2 NPs dispersions was determined using ICP-MS a † versus

Relaxivity measurements and T2-weighted MRI in vitro

To evaluate the impact of size on MRI relaxivity properties, the r1 and r2 relaxivity of NaGdF4@SiO2 NPs were investigated in water at 0.5 T and 7 T. To calculate the ionic relaxivities, the Gd ion concentration of the NaGdF4@SiO2 NPs dispersions was determined using ICP-MS after digesting the NPs with concentrated nitric acid and hydrochloric acid (v/v = 1:3) at 100 °C overnight. The ionic relaxivity values {r1, r2} with an equivalent Gd ion concentration range of 0–2.5 mM at 0.5 T and 7 T were obtained from the slope of the linear regression fit from the relaxivity plots (Fig. 3). In addition, r1 and r2 relaxivity values of NaGdF4@SiO2 were shown in Table S1.† At 0.5 T, r1 relaxivities decreased with the increase of particle size, from a value of 1.4 mM−1 s−1 (120 nm particles) to 0.39 mM−1 s−1 (250 nm particles). At 7 T, r1 relaxivities decreased from a value of 0.75 mM−1 s−1 (for the 120 nm particles) to 0.27 mM−1 s−1 (for the 250 nm particles). Conversely, at both 0.5 T and 7 T, r2 relaxivities increased dramatically with increasing particle size, from a value of 4.36 mM−1 s−1 for the 120 nm particles to 8.55 mM−1 s−1 for the 250 nm particles at 0.5 T, and from a value of 129.7 mM−1 s−1 for the 120 nm particles to 159.6 mM−1 s−1 for the 250 nm particles at 7 T. Clearly, the r2 values were highly increased at high field strengths. The r2 value is as high as some reported Dy3+-based NPs and some of clinically used T2 CAs8,34–40 (Table 1).

According to the r2 relaxivities measured at both 0.5 T and 7 T, larger size of NaGdF4@SiO2 NPs show higher relaxivity than the smaller ones. The magnetic hysteresis loop plot (M–H) obtained by different size of NPs showed that NPs are paramagnetic and the observed high r2 of the current NaGdF4@SiO2 mainly be ascribed to the particle sizes increase (Fig. S2†). To further analyze the observed enhancement of ionic relaxivity with increasing NP size, the relaxivities, based on the mass concentration of NPs (r1/M) and CAs concentration of NPs (r1/NP), were calculated from the ionic relaxivity (r1/[Gd3+]) (Table S2†).

The r2/NP values correspond to per CA relaxivity, and the relaxivity increases from 1.56 × 109 mM−1 s−1 for the 120 nm particle to 1.73 × 1010 mM−1 s−1 for the 250 nm particles at 7 T. Because the total number of Gd ions is higher in larger particles, the r2/NP values increase with size. Clinical complexes typically contain one Gd ion per CA, and their unit CA relaxivity is the same as their ionic relaxivity. Thus, the relaxivity offered by each NaGdF4 NPs can be calculated here is approximately 1 × 109 times that of clinical agents, which allows enhanced local contrast and was highly beneficial for targeted imaging. Moreover, because of the coating of silica on the NaGdF4, bundles of multiple Gd ions in a crystalline NPs are less likely to leak. ICP-MS analysis of the bulk water after dialysis of the NPs showed no appreciable amount of free Gd ions in solution, indicating

Table 1 Comparison of NaGdF4@SiO2 NPs and the clinically used MRI T2 CAs

![Fig. 3 Relaxation rate r1 (1/T1) versus Gd3+ concentration at different magnetic field strengths, 0.5 T (A) and 7 T (C). Relaxation rate r2 (1/T2) versus Gd3+ concentration at different magnetic field strengths, 0.5 T (B) and 7 T (D). Blue triangle stands for sample 1; red circle stands for sample 2 and black square stands for sample 3.](Image)
that no leaking of ions from the NP occurred. Thus, these NPs are good scaffolds for integrating multiple Gd ions without compromising Gd ion binding.

The ability of CAs to be used as $T_2$ agents was also governed by the ratio of their transverse relaxivity to longitudinal relaxivity, high $r_2/r_1$ ratios were considered ideal. The $r_2/r_1$ ratio for the 120 nm NPs was approximately 157, and the 250 nm NPs was as high as approximately 587 (Fig. 4A), which to the best of our knowledge, was the highest value reported for Gd-based nanoparticle CAs thus far.

For $T_2$-weighted MRI in vitro, the $T_2$-weighted phantom MR images between the three types of NaGdF$_4@$SiO$_2$ NPs were obtained at 7 T. As shown in Fig. 4B, the images of three types NPs (all at a 0.1 mM Gd$^{3+}$ concentration) became shallow as the size gets smaller (from left to right). The 250 nm NaGdF$_4@$SiO$_2$ NPs, which had shown the highest relaxivity and may suit for biological applications were chosen for concentration-dependent (0.6–0.009 mM Gd$^{3+}$) phantom images to examine the feasibility of the NPs for in vitro MRI imaging. As we can easily find that (Fig. 4C), with Gd ion concentrations decreased (from left to right), the $T_2$-weighted.

MRI images became shallow continuously. It is evident that these NPs have excellent $T_2$-weighted MRI imaging ability and can easily be tuned by adjusting the size and concentration of the NPs.

$T_2$-weighted MRI in vivo

Due to the excellent $T_2$ magnetic resonance effect of NaGdF$_4@$SiO$_2$ NPs, the applicability as a $T_2$-weighted MRI CAs in vivo was further assessed. Therefore, 250 nm NaGdF$_4@$SiO$_2$ NPs (with the highest $r_2$ relaxivities) were chosen for intravenous injection in tumor-bearing (H22) mouse model. Compared with the MR images of tumor and normal tissue before 7 h and 24 h post-injection, remarkable negative contrast enhancement was observed in the tumor region, whereas hardly any changes appeared in the normal tissue (Fig. 5). According to the MR images, NPs could accumulate in the tumor and decreased in 24 h. It demonstrated silica coated NaGdF$_4$ NPs have good biocompatibility and can be accumulated at the tumor position through the enhanced permeability and retention (EPR) effect. These result indicated that NaGdF$_4@$SiO$_2$ NPs (250 nm) could act as high-performance $T_2$-weighted MRI CAs on H22 tumor in vivo. Furthermore, NaGdF$_4@$SiO$_2$ NPs (250 nm) in the main organs at different time points post-injection have been investigated. After they were intravenously injected with the NPs, the mice were sacrificed at 2 h, 7 h, 24 h, and 30 day post-injection. The distribution of Gd$^{3+}$ in each organ was shown in Fig. 6. The results exhibited that 250 nm NaGdF$_4@$SiO$_2$ NPs mainly accumulated in the lung, liver and spleen and reached a maximum at 7 h post-injection in the tumor, which was consistent with the above MRI results. After 30 day post-injection, the Gd$^{3+}$ residues were nearly undetectable in the organs via ICP-MS, showing that most of the NPs were excreted from the body of the mice.
in these major organs compared with the control (Fig. 8). This phenomenon has previously been observed in other rare-earth fluoride hosts. However, further long-term study is still needed to evaluate the toxicity of NaGdF₄-based MRI probes.

**Conclusion**

In summary, we have prepared different sizes of NaGdF₄@SiO₂ NPs (from 120 nm to 250 nm), compared with Dy-based and Fe-based NPs, NaGdF₄@SiO₂ exhibited excellent high r₂ value and ultrahigh r₂/r₁ values at the high magnetic field (7 T). Furthermore, the results of toxicity studies indicated that NaGdF₄@SiO₂ NPs showed good compatibility and low cytotoxicity to the living systems. Our study demonstrated that Gd-based NPs with appropriate size could be used as potential T₂ CAs in an ultrahigh field.

**Conflicts of interest**

There are no conflicts to declare.

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**Toxicity of NaGdF₄@SiO₂**

To evaluate the toxicity of silica-coated NaGdF₄ NPs, the cell growth and viability of A549 cells incubated with NaGdF₄@SiO₂ at different Gd³⁺ concentrations (up to 600 μM) for 24 h were evaluated. The WST-8 assay showed that no significant differences in the proliferation of A549 cells were observed in the absence or presence of NaGdF₄@SiO₂ within 24 h (Fig. 7). Even at the concentration of 600 μM, the cell viability was estimated to be approximately 80%. The WST-8 assay results demonstrated that NaGdF₄@SiO₂ NPs showed low cytotoxicity to A549 cells.

Toxicity was further investigated by pathology assessments of tissue obtained from the tested mice at 7 days post-injection. The major organs such as heart, liver, spleen, lung and kidney were harvested for histological analysis. Despite the high-concentration injection of water dispersible NaGdF₄@SiO₂ NPs at an equivalent Gd³⁺ concentration of 4 mM, no noticeable signs of organ damage or inflammatory lesions were observed in these major organs compared with the control (Fig. 8). This phenomenon has previously been observed in other rare-earth fluoride hosts. However, further long-term study is still needed to evaluate the toxicity of NaGdF₄-based MRI probes.

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**Fig. 7** Viability of A549 cells after treatment with different concentrations of NaGdF₄@SiO₂ NPs with different Gd³⁺ concentrations (0, 100 μM, 200 μM, 300 μM, 400 μM, 500 μM and 600 μM) for 24 h. The viability was determined by CCK-8 assay. Error bar represents the standard error of 6 trials.

**Fig. 8** H&E-stained tissue (heart, liver, spleen, lung, kidney). Scale bar: 250 μm sections from mice intravenously injected with sample 1 (A), sample 2 (B), sample 3 (C) (200 μL 0.9% NaCl control) and (200 μL dose = 4 mM NaGdF₄@SiO₂, test).
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