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Al(OH)$_3$ facilitated synthesis of water-soluble, magnetic, radiolabelled and fluorescent hydroxyapatite nanoparticles†

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Magnetic and fluorescent hydroxyapatite nanoparticles were synthesised using Al(OH)$_3$-stabilised MnFe$_2$O$_4$ or Fe$_3$O$_4$ nanoparticles as precursors. They were readily and efficiently radiolabelled with $^{18}$F. Bisphosphonate polyethylene glycol polymers were utilised to endow the nanoparticles with excellent colloidal stability in water and to incorporate cyclam for high affinity labelling with $^{64}$Cu.

Molecular imaging techniques, including magnetic resonance imaging (MRI), positron emission tomography (PET), single photon emission computed tomography (SPECT) and fluorescence optical imaging, play an increasingly important role in clinical diagnosis and management of disease, as well as medical and biological research. Multimodal imaging recently has gained attention because of its potential to overcome the limitations of individual imaging modalities and to provide more accurate and complete physiological information at sites of disease.¹⁻³ Numerous nanoparticles (NPs) have been studied as multimodal imaging contrast agents due to their multi-functionality and potential for surface modification.⁴⁻⁷ An adequate multimodal particulate contrast agent must be multifunctional, biocompatible and colloidal stable. The NPs should be uniform in morphology and size, so that they share similar in vivo behaviour, and chemically stable to ensure that the signal of each modality reflects the same anatomic position.

Hydroxyapatite (HA) has attracted much interest as the basis of multifunctional probes very recently,⁸⁻¹¹ because of its biocompatibility and high affinity for fluoride which allows facile labelling with the positron emitter $^{18}$F. Fluorescent HA can be obtained by either doping with rare earth cations⁸,¹¹ or by conjugation with organic dyes.¹⁰ HA is not an ideal fluorescent host matrix, so luminescent rare earth doped HA nanocrystal requires up to 20% replacement of OH$^-$ by F$^-$ (maximum theoretical value for fluoride substitution), to minimise the quenching of the excited state of rare earth cations.⁸,¹²,¹³ As a result, such HA is no longer suitable for $^{18}$F radiolabelling. It has been reported that magnetic iron oxide NPs can be deposited on the surface of HA aggregates or NPs via thermolysis¹¹ or a wet chemistry approach.⁹ One problem that remained unsolved for both synthetic approaches is how to effectively isolate the desired Fe$_3$O$_4$–HA composites from the unwanted iron oxides and HA nanoparticles. Moreover, all these multifunctional HA NPs suffer from the problem of aggregation or large size to some extent, which is an obstacle for their biological or medical applications. In this work, we present a novel synthesis of magnetic and fluorescent HA nanocomposites with uniform size and morphology, and excellent colloidal stability in water by using Fe$_3$O$_4$ nanoparticles stabilised with Al(OH)$_3$ as a template. The radiolabelling, magnetic and optical properties were investigated, to demonstrate potential for application as tri-modal probes for MR, PET and optical imaging.

Our strategy is to synthesise HA using water-soluble magnetic Fe$_3$O$_4$@Al(OH)$_3$ or MnFe$_2$O$_4$@Al(OH)$_3$ NPs as templates. The advantages of this approach is the small hydrodynamic size of the template particles and their excellent colloidal stability, provided by the Al(OH)$_3$ layer as reported previously.¹⁴ More importantly, the layer of Al(OH)$_3$ can be readily removed as it is soluble under basic pH conditions. The design incorporated bisphosphonate polyethylene glycol (BP-PEG) polymers (Scheme 1) to stabilise NPs after the formation of HA on the surface, to take advantage of the outstanding binding affinity of bisphosphonates to HA.
Bisphosphonate amine 1 was obtained via a slightly modified version of the previously reported protocol.\textsuperscript{15} PEG carboxylic acids were obtained by oxidation of corresponding PEG polymers with CrO\textsubscript{3}/H\textsubscript{2}SO\textsubscript{4} via the reported protocol.\textsuperscript{16} The bisphosphonate (BP) or 1,4,8,11-tetraazacyclotetradecane (cyclam) were grafted to PEG via amide formation mediated by N,N\textsuperscript{′},N\textsuperscript{′}′-dicyclohexylcarbodiimide (DCC).\textsuperscript{17} BP-PEG-Me\textsubscript{2} and BP-PEG-cyclam 3 were purified by dialysis for over 24 h using a membrane with a cut-off size of 3500 Da to remove unconjugated small molecules such as bisphosphonate amine 1 and 1,4,8,11-tetraazacyclotetradecane. The conjugation of bisphosphonate and PEG was confirmed by the change in chemical shift in the \textsuperscript{31}P NMR spectrum (from 20 ppm for free bisphosphonate to 12.8 ppm for BP-PEG, see ESI†).

NP particulate precursors MnFe\textsubscript{2}O\textsubscript{4}@[Al(OH)\textsubscript{3}] and Fe\textsubscript{3}O\textsubscript{4}@Al(OH)\textsubscript{3} were obtained via a method reported by our group previously.\textsuperscript{14} Typically, 4 ml Fe\textsubscript{3}O\textsubscript{4}@Al(OH)\textsubscript{3} colloids (concentration of Fe\textsubscript{3}O\textsubscript{4}, ca. 8 mg ml\textsuperscript{−1}) and 200 mg BP-PEG-Me polymers 2 were placed in a 500 ml flask containing 300 ml water. Under stirring, 4 ml 0.1 mol 1\textsuperscript{−1} Na\textsubscript{2}HPO\textsubscript{4} and 4 ml 0.2 mol 1\textsuperscript{−1} CaCl\textsubscript{2} aqueous solutions were added sequentially. This light brown solution was refluxed overnight after the addition of 30 ml 28% ammonia water. The NPs were collected by centrifugation at 2000 g for 30 minutes, re-dissolved in 10 ml water and freeze dried. The NPs were collected by centrifugation at 2000 g for 30 minutes, re-dissolved in 10 ml water and freeze dried. TEM images (a) and (b) and size distribution (c) and (d) (major and minor axis, respectively) of Fe\textsubscript{3}O\textsubscript{4}@HA NPs synthesised from Fe\textsubscript{3}O\textsubscript{4}@Al(OH)\textsubscript{3} in the presence of BP-PEG-Me; (e) TEM image of MnFe\textsubscript{2}O\textsubscript{4}@HA NPs synthesised in absence of BP-PEG-Me; (f) TEM image of pure HA NPs.

The X-ray powder diffraction (XRD) pattern of NPs indicates co-existence of HA and Fe\textsubscript{3}O\textsubscript{4} (or MnFe\textsubscript{2}O\textsubscript{4}). TEM images show an olive-like morphology for Fe\textsubscript{3}O\textsubscript{4}@HA and MnFe\textsubscript{2}O\textsubscript{4}@HA NPs, which is significantly different both in size and in morphology from pure HA NPs synthesised under the same conditions (Fig. 1). Particle analysis by TEM gave a mean size of 60.3 nm (major axis) × 29.7 nm (minor axis) for Fe\textsubscript{3}O\textsubscript{4}@HA NPs (Fig. 1c and d). MnFe\textsubscript{2}O\textsubscript{4}@HA NPs displayed a similar aspect ratio to Fe\textsubscript{3}O\textsubscript{4}@HA NPs, but the size was almost doubled. These results indicate an important role of BP-PEG-Me in reducing particle size.

The hydrodynamic size of NPs during the synthesis was monitored by dynamic light scattering (DLS) experiments. No obvious change was observed after adding the solutions of Na\textsubscript{2}HPO\textsubscript{4} and CaCl\textsubscript{2} into the solution of Fe\textsubscript{3}O\textsubscript{4}@Al(OH)\textsubscript{3} NPs, and it remained around 80 nm. This leads to a hypothesis that phosphate anions adsorb on the highly positive charged surface of Fe\textsubscript{3}O\textsubscript{4}@Al(OH)\textsubscript{3} NP and then react with the subsequently added Ca\textsuperscript{2+} to form calcium phosphate around the NPs. At the elevated temperature and basic solution environment, the outer layer of calcium phosphate was converted to crystallised HA, meanwhile the Al(OH)\textsubscript{3} was dissolved, resulting in the formation of Fe\textsubscript{3}O\textsubscript{4}@HA NPs. The diminished peak due to OH around 3300–3500 cm\textsuperscript{−1} in the IR spectrum, together with XRD patterns, confirm the replacement of Al(OH)\textsubscript{3} layer by HA. The changes in surface potential of NPs could not be monitored by measuring the zeta potential during the process, since the polymeric PEG imposes a thick hydration layer on NP surface and zeta potential no longer correlates to the surface potential. Therefore the surface potential was monitored in the absence of BP-PEG-Me, and a significant decrease in zeta potential was observed after the addition of Na\textsubscript{2}HPO\textsubscript{4} solution, from 42.5 mV to 24.9 mV. This is presumed to be due to the adsorption of phosphate anions on the surface, since the changes in pH should be negligible in this case. The zeta potential slightly increased back to 27.1 mV after adding the CaCl\textsubscript{2} solution, indicating a reaction of calcium cations and phosphate anions. Similar results were also observed for MnFe\textsubscript{2}O\textsubscript{4}@HA NPs. In this synthesis approach, the positively charged Al(OH)\textsubscript{3} layer is essential for the formation of MnFe\textsubscript{2}O\textsubscript{4}@HA or Fe\textsubscript{3}O\textsubscript{4}@HA. Using the MnFe\textsubscript{2}O\textsubscript{4} NPs colloids instead of MnFe\textsubscript{2}O\textsubscript{4}@Al(OH)\textsubscript{3} as precursors, a simple mixture of magnetic MnFe\textsubscript{2}O\textsubscript{4} and non-magnetic HA NPs was obtained, identifiable as two kinds of NPs with apparently different morphology and size on TEM images.

Both MnFe\textsubscript{2}O\textsubscript{4}@HA and Fe\textsubscript{3}O\textsubscript{4}@HA NPs were coated by BP-PEG-Me polymers 2 during the synthesis, as confirmed by ca. 18% mass loss on thermogravimetric analysis (TGA). Due to the strong interactions between the bisphosphonate group of 2...
and MnFe₂O₄@HA and Fe₃O₄@HA NPs, both NPs exhibit long-term colloidal stability in aqueous solution, even in high ionic strength environment such as PBS. The hydrodynamic size of Fe₃O₄@HA and MnFe₂O₄@HA NPs remained at 50.7 nm and 60.3 nm, respectively, for over two months (Fig. 2a). The excellent colloidal stability and small hydrodynamic size of MnFe₂O₄@HA and Fe₃O₄@HA make them potentially suitable for biological or medical applications.

Unsurprisingly, because of the high affinity of fluoride for HA, both NPs exhibit a high radiolabelling efficiency with ¹⁸F-fluoride, up to 88.3 ± 0.5% for 0.3 mg MnFe₂O₄@HA NPs and 92.1 ± 0.1% for 0.3 mg Fe₃O₄@NaYF₄ NPs (Fig. 2b). Labelling and purification was readily achieved in less than 23 minutes. To provide a means of incorporating the positron emitter ⁶⁴Cu, the NPs were sonicated in 1 mg ml⁻¹ BP-PEG-cyclam solution for 30 minutes to allow replacement of a fraction of BP-PEG-Me by BP-PEG-cyclam, and free BP-PEG-polymer were removed by centrifugation before mixing with radioactivity. The resulting particles showed a high ⁶⁴Cu radiolabelling efficiency in a short time (<5 minutes) (Fig. 2b). Both NPs display essentially the magnetic properties of Fe₃O₄ or MnFe₂O₄ NPs and are active on MR images (Fig. 2c and d). The transverse (r₂) and longitudinal (r₁) relaxivities of Fe₃O₄@HA NPs were measured to be 150.2 ± 3.2 mM⁻¹ s⁻¹ and 1.9 ± 0.1 mM⁻¹ s⁻¹, respectively, at 3 T magnetic field. As expected, the relaxivities of NPs could be improved by altering the ratio of magnetic component and non-magnetic HA, since r₂ is proportional to the volume fraction of magnetic component. For example, the r₂ of MnFe₂O₄@HA NPs could be dramatically improved from 105.7 ± 3.5 mM⁻¹ s⁻¹ to 246.5 ± 15.9 mM⁻¹ s⁻¹ by doubling the amount of MnFe₂O₄@Al(OH)₃ while keeping the amount of NaH₂PO₄ and CaCl₂ solutions the same during the synthesis. High transverse relaxivity of these magnetic hydroxyapatite NPs as well as a high ratio of r₂/r₁ demonstrate their potential application as T₂ contrast agents on MR imaging.

Fig. 2 (a) DLS size distribution of 1 mg ml⁻¹ Fe₃O₄@HA NPs in aqueous solution; (b) radiolabelling of MnFe₂O₄@HA and Fe₃O₄@HA NPs with ¹⁸F-fluoride and ⁶⁴CuCl₂ (the latter after sonicating the particles with BP-PEG-cyclam); (c) T₁ and T₂ weighted MR images of the solution containing Fe₃O₄@HA NPs, and (d) relaxivities of Fe₃O₄@HA NPs. Concentration of iron in the solution was measured by ICP-MS.
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Notes and references