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## Simple hybrid polymeric nanostructures encapsulating macro-cyclic Gd/Eu based complexes: luminescence properties and application as MRI contrast agent†

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Lanthanide-based macrocycles are successfully incorporated into hybrid polyionic complexes, formed by adding a mixture of zirconium ions to a solution of a double-hydrophilic block copolymer. The resulting nanoobjects with an average radius of approximately 10–15 nm present good colloidal and chemical stability in physiological media even in the presence of competing ions such as phosphate or calcium ions. The final optical and magnetic properties of these objects benefit from both their colloidal nature and the specific properties of the complexes. Hence these new nanocarriers exhibit enhanced T1 MRI contrast, when administered intravenously to mice.

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### 1. Introduction

Magnetic resonance imaging (MRI) is a powerful medical diagnostic tool, the efficiency of which is significantly enhanced by the use of exogenous contrast agents (CAs). Among these, CAs based on the gadolinium ions with seven unpaired electrons, paramagnetic properties and a high magnetic moment are most commonly employed as  $T_1$  or positive contrast agents. To mitigate their cytotoxicity,<sup>1–3</sup> gadolinium ions are generally chelated with linear (MAGNEVIST®,<sup>4</sup> OMNISCAN®,<sup>5,6</sup> OPTIMARK® and MultiHance®<sup>7</sup>) or macrocycle multifunctional ligands (PROHANCE®, DOTAREM®, GADOVIST®).<sup>8</sup> However, molecular complexes possess limitations, such as residual toxicity and reduced efficiency at the higher magnetic fields of modern MRI instruments.<sup>5,9,10</sup> Consequently, in 2017 European medicine agency suspended the authorization of the intravenous linear Gd-based CAs. Therefore, there is an

ongoing need for new CAs with enhanced properties such as extended circulation lifetime or higher relaxivity.<sup>11</sup>

The immobilization of Gd-chelates onto macromolecules or nano-objects is one approach to provide more efficient CAs.<sup>12–14</sup> Indeed, Gd ions located within the colloidal species will rotate at the same low rate as the entire nanoparticles (NPs), thereby increasing the observed relaxivity  $r_1$  (the longitudinal relaxation rate  $1/T_1$  normalized by the concentration of CAs). An alternative involves inducing the formation of aggregates through the complexation of negatively charged Gd complexes with a diblock cationic copolymer bearing simple functional groups.<sup>15</sup> Another option is to use hybrid polyion complexes (HPICs) formed by the complexation of free gadolinium ions with diblock copolymers functionalized with lanthanide-chelate groups that interact<sup>16,17</sup> or more simple function. Hence, poly(ethylene oxide) (PEO) double hydrophilic block copolymer comprising a complexing block based on poly(acrylic acid) (PAA) or poly(vinyl phosphonic acid) (PVPA) exhibit exceptionally high stability upon dilution. These colloids, having a mean radius *ca.* 10 nm, generate high water proton relaxivities *in vitro* and an excellent tolerance *in vivo* after intravenous injection into a rat model, resulting positive signal enhancement.<sup>18–20</sup> Combining different ions within the same HPIC is also a promising strategy for obtaining multifunctional systems with enhanced functions.<sup>21–24</sup> Hence, the insertion of zirconyl ions, reported to be without adverse effects,<sup>25</sup> in addition to gadolinium ions led to the formation of Gd/Zr@HPICs with enhanced stability due to strong affinity of zirconium ions for carboxylate function and improved relaxation properties.<sup>26</sup>

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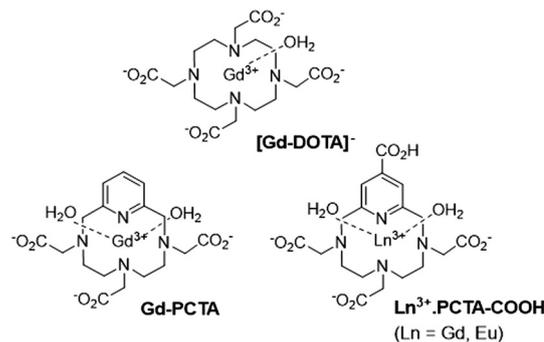
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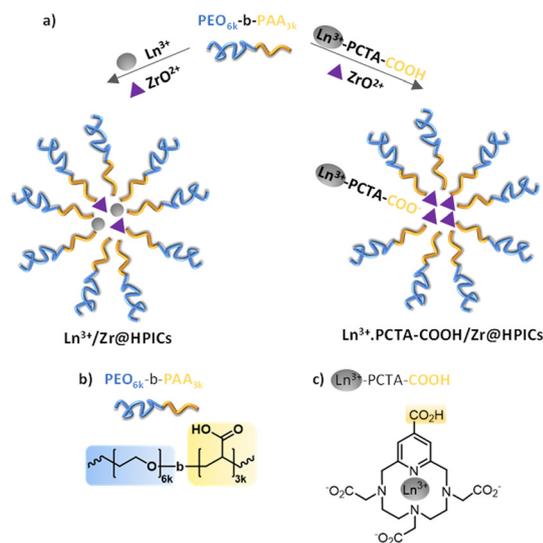
In this article, we will present a strategy that combines the use of macrocyclic complexes and HPICs. This approach avoids the tedious grafting protocol on the polymer structure. The insertion of europium(III) and gadolinium(III), lanthanide chelates within HPICs structures is ensured, as illustrated in Scheme 1 (right), through the simple mixing of a specifically designed chelate, zirconyl ions and PEO<sub>6k</sub>-*b*-PAA<sub>3k</sub> copolymer. This strategy will be compared to the one using lanthanide ions in their free form (Scheme 1, left).

The 12-membered tetraazamacrocyclic chelate PCTA-COOH (PCTA: 3,6,9,15-tetraazabicyclo[9.3.1]pentadeca-1(15),11,13-triene-3,6,9-triacetic acid) investigated in this work for the incorporation of Eu<sup>3+</sup> or Gd<sup>3+</sup> ions is a heptadentate ligand derived from PCTA ligand. PCTA is known as a versatile chelate able of complexing various M<sup>2+</sup> and M<sup>3+</sup> ions for biomedical applications such as diagnostic and radiotherapeutic (Fig. 1). In the field of magnetic resonance imaging (MRI), PCTA forms very stable Gd<sup>3+</sup> complex (log *K*<sub>GdL</sub> = 20.39) with a kinetic inertness favorable for *in vivo* applications.<sup>27</sup> Due to the presence of two water molecules in the first coordination sphere of the metal, the Gd-PCTA complex displays a higher water relaxivity (*r*<sub>1</sub> = 5.4 s<sup>-1</sup> mM<sup>-1</sup> at 20 MHz and 37 °C) than the clinical Gd contrast agent DOTAREM® or the monoqua [Gd-DOTA]<sup>-</sup> complex (*r*<sub>1</sub> = 3.5 s<sup>-1</sup> mM<sup>-1</sup> at 20 MHz and 37 °C) (Fig. 1). This characteristic makes it a promising candidate as an MRI contrast agent.<sup>28–30</sup> The PCTA-COOH chelate contains a pyridine functionalized at the 4-position by a carboxylic acid function,



**Fig. 1** Structures of the corresponding lanthanide complexes of DOTA, PCTA and PCTA-COOH ligands (see text). Ln<sup>3+</sup>.PCTA-COOH are new complexes described in this work.

which, due to geometrical constraints, does not participate in the coordination of the Ln<sup>3+</sup> ion unlike the three pendant acetate arms. The 4-position carboxylic acid function of PCTA-COOH will allow a strong competitive interaction with zirconium ions such as with the double-hydrophilic block copolymer during the formation of the monodisperse nano-objects. Additionally, the pyridine unit of PCTA-COOH is capable of acting as a sensitizer, enhancing the luminescence of Eu(III) ion with a long emission lifetime in the visible region.<sup>31–33</sup> Due to the similar chemical behaviour of Eu(III) and Gd(III) ions, the corresponding Eu(III) chelate of PCTA-COOH ligand is also used to provide a good structural model of Gd<sup>3+</sup>.PCTA-COOH/Zr@HPICs. Luminescence of the europium ion will lead to complementary information on these HPICs architectures.

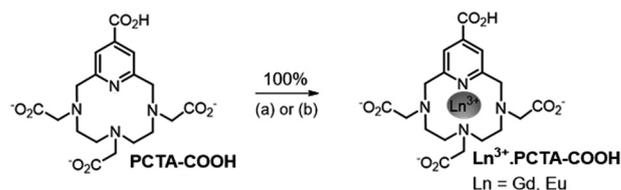


**Scheme 1** Schematic representation of the strategy used in this work. (a) The addition of ZrO<sup>2+</sup> and Ln<sup>3+</sup> in free form and in the form of Ln<sup>3+</sup>.PCTA-COOH complexes to the double hydrophilic block copolymer PEO<sub>6k</sub>-*b*-PAA<sub>3k</sub> leads to polymeric nanoparticles named Ln<sup>3+</sup>.PCTA-COOH/Zr@HPICs or Ln<sup>3+</sup>/Zr@HPICs (Ln = Eu, Gd). (b) Chemical structure of the diblock copolymer used in this work: poly(acrylic acid) and a poly(ethylene oxide) block have average molecular weights of 6000 and 3000 g mol<sup>-1</sup> respectively. The polymer is noted PEO<sub>6k</sub>-*b*-PAA<sub>3k</sub>. (c) Structure of the Ln<sup>3+</sup>.PCTA-COOH complexes used and described in this work. Carboxylic acid function of the isonicotinic moiety has a p*K*<sub>a</sub> around 1.8.

## 2. Results and discussion

### 2.1. Synthesis and characterization of Ln(III) complexes derived from PCTA-COOH

PCTA-COOH ligand was synthesized following an established procedure,<sup>34</sup> in an eight-step with a 50% overall yield using a convergent pathway as shown in ESI Scheme S1.† The lanthanide complexes Ln<sup>3+</sup>.PCTA-COOH (Ln = Eu, Gd) were obtained by mixing a stoichiometric amount of lanthanide chloride hexahydrate in aqueous solution of PCTA-COOH ligand while maintaining the pH at 5 (Scheme 2).



**Scheme 2** Synthesis of Eu<sup>3+</sup> and Gd<sup>3+</sup> complexes derived from PCTA-COOH. Reagents and conditions: (a) GdCl<sub>3</sub>·6H<sub>2</sub>O, H<sub>2</sub>O-NaOH, pH 5–6, rt 16 h; (b) EuCl<sub>3</sub>·6H<sub>2</sub>O, H<sub>2</sub>O-NaOH, pH 5–6, rt 16 h.



After the complexation was completed, the pH was adjusted to 7 with NaOH 1 M. Purification on a C18 chromatography column (1/1: water/methanol) afforded pure complexes characterized by UPLC and high-resolution mass spectrometry (Fig. S1–S4 in ESI†). Identical UPLC retention times for the two complexes confirm the similar chemical properties of the two lanthanide ions complexed. Some UV absorption and time-resolved luminescence properties determined in 0.05 M Tris buffer pH 7.4 at 298 K for the europium complex are gathered in Table 1.

Upon photoexcitation into the ligand absorption band at 281 nm, the  $\text{Eu}^{3+}$ -PCTA-COOH complex emits characteristic red photoluminescence attributed to the  $^5\text{D}_0 \rightarrow ^7\text{F}_J$  ( $J = 0-6$ ) transitions of the europium ion, as shown in Fig. 2. This spectrum is mainly contributed to by the hypersensitive  $^5\text{D}_0 \rightarrow ^7\text{F}_2$  transition and the  $^5\text{D}_0 \rightarrow ^7\text{F}_1$ ,  $^5\text{D}_0 \rightarrow ^7\text{F}_4$  transitions. The sensitized nature of the europium emission is confirmed by the photoluminescence excitation spectrum, which perfectly overlaps the spectral signature of the antenna pyridine in the UV spectrum of the  $\text{Eu}^{3+}$ -PCTA-COOH complex. The metal luminescence lifetime of complex at room temperature is 0.39 ms. Upon solvent deuteration, this lifetime increases by a factor of about five, indicating of strong coupling between the metal ion and O–H oscillators of the solvent, which favors radiationless deactivation of the metal excited state.

Using the well-established empirical relation of Horrocks<sup>35</sup> to estimate the apparent hydration state  $q$  of the complex, these results indicate the presence of two metal-bound water molecules in the  $\text{Eu}^{3+}$ -PCTA-COOH complex. This aligns with the expected seven-coordinating-nature of ligand and the preferred coordination number of 8–9 for  $\text{Eu}^{3+}$ .

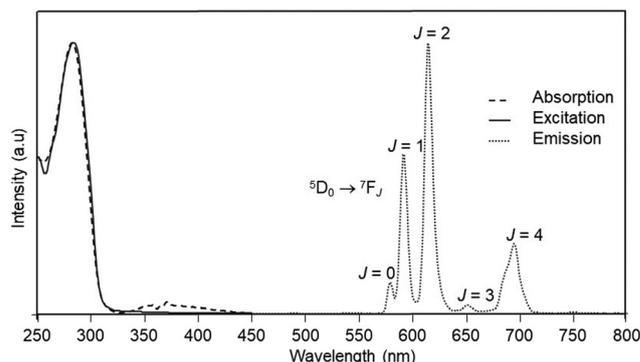
## 2.2. Formation and characterization of HPICs

Zirconyl ions have a high affinity for carboxylic functions<sup>36,37</sup> which have long been used in medical applications without reported adverse effects.<sup>38</sup> Their addition to a solution comprising a mixture of  $\text{Ln}^{3+}$ -PCTA-COOH and the diblock PEO<sub>6k</sub>-*b*-PAA<sub>3k</sub> copolymer induces the formation of HPICs once electroneutrality is reached between the positive charges of  $\text{ZrO}^{2+}$  ions and the potentially available negative charges from the ionized or ionizable carboxylic acid.<sup>26</sup> This interaction enables, as illustrated in Scheme 1, the incorporation of  $\text{Ln}^{3+}$ -PCTA-COOH complexes in HPICs architecture which will be named in the following  $\text{Ln}^{3+}$ -PCTA-COOH/Zr@HPICs. To assess the role of  $\text{Ln}^{3+}$ -PCTA-COOH, model systems with free  $\text{Gd}^{3+}$  and  $\text{Eu}^{3+}$  species were also formed. In this case, a

**Table 1** Key photophysical data (absorption properties, luminescence lifetimes) for  $\text{Eu}^{3+}$ -PCTA-COOH in 0.05 M Tris buffer pH 7.4 at 298 K

$\lambda_{\text{abs}}/\text{nm}$ ( $\epsilon/\text{M}^{-1} \text{cm}^{-1}$ )	$\tau_{\text{H}}^a$ (ms)	$\tau_{\text{D}}^a$ (ms)	$q \pm 0.1^b$
281 (3600)	0.39	2.18	1.99

<sup>a</sup> Tris buffer prepared in  $\text{H}_2\text{O}$  solution (H) or  $\text{D}_2\text{O}$  (D) solution. <sup>b</sup> Number of coordinated  $\text{H}_2\text{O}$  molecules  $q$  calculated using the following equation  $q = 1.11[(\tau_{\text{H}})^{-1} - (\tau_{\text{D}})^{-1} - 0.31]$ .



**Fig. 2** Normalized absorption, corrected excitation ( $\lambda_{\text{em}} = 616$  nm) and emission spectra ( $\lambda_{\text{exc}} = 281$  nm) of  $\text{Eu}^{3+}$ -PCTA-COOH in Tris buffer (pH 7.4) at 298 K. The emission bands arise from  $^5\text{D}_0 \rightarrow ^7\text{F}_J$  transitions; the  $J$  values are shown on the spectrum.

mixture of  $\text{Gd}^{3+}$  or  $\text{Eu}^{3+}$  and  $\text{ZrO}^{2+}$  ions is added to an aqueous solution of the diblock PEO<sub>6k</sub>-*b*-PAA<sub>3k</sub> copolymer (0.1 wt%) respecting electroneutrality (see Experimental section).  $\text{Ln}^{3+}$ /Zr@HPICs complexes are thus obtained. Concerning the respective content of  $\text{Ln}^{3+}$  and  $\text{ZrO}^{2+}$ , previous experiments on  $\text{Gd}^{3+}$ /Zr@HPICs systems have demonstrated that optimal relaxivity properties were obtained for a Gd content equal to 5–10% of the total amount of ions.<sup>26</sup> Therefore a targeted ratio equal to 10% was initially chosen for  $\text{Ln}^{3+}$ -PCTA-COOH/Zr@HPICs. The amount of lanthanide respective to the total amount of ions was estimated from ICP/MS measurements after purification through a dialysis/centrifugation process and are reported in Table 2.

The molecular weight cut-off of the filter was chosen at 3 kDa, enabling the retention of HPICs structures while free  $\text{Ln}^{3+}$ -PCTA-COOH complexes are filtered out. It was found that 60% of the introduced  $\text{Ln}^{3+}$ -PCTA-COOH was retained within the dialysed HPICs, resulting in a final content of  $6 \pm 1\%$  of  $\text{Ln}^{3+}$  (Fig. S5 in ESI†). In the case of  $\text{Ln}^{3+}$ /Zr@HPICs, all introduced  $\text{Ln}^{3+}$  remained within the final HPICs, and the targeted

**Table 2** Studied HPICs nano-objects containing either gadolinium or europium (free or as complexes) mixed with zirconium in various mole fractions

HPICs nano-objets	$\text{Ln}^a$ (%)	$R_{\text{h}}^b$ (nm)	$q \pm 0.1^c$	$r_1^d$ ( $\text{mM}^{-1} \text{s}^{-1}$ )
$\text{Eu}^{3+}$ /Zr@HPICs	6	$7.7 \pm 2.3$	4.3	—
$\text{Eu}^{3+}$ -PCTA-COOH/Zr@HPICs	5	$9.7 \pm 4.0$	1.9	—
$\text{Gd}^{3+}$ /Zr@HPICs	6	$9.8 \pm 3.0$	—	$66.5 \pm 0.7$
$\text{Gd}^{3+}$ -PCTA-COOH/Zr@HPICs	5	$10.1 \pm 5.9$	—	$8.0 \pm 0.2$

<sup>a</sup> Molar amount of lanthanide respective to the total amount of ions estimated from ICP/MS measurements after purification through a dialysis/centrifugation process ( $\pm 1\%$ ). <sup>b</sup> Hydrodynamic radius (and standard deviation)  $R_{\text{h}}$  estimated by cumulant analysis of DLS experiments. <sup>c</sup> Number of coordinated  $\text{H}_2\text{O}$  molecules  $q$  estimated for Eu systems from luminescence measurements and calculated using the following equation  $q = 1.11[(\tau_{\text{H}})^{-1} - (\tau_{\text{D}})^{-1} - 0.31]$ . <sup>d</sup> Estimated for Gd systems from relaxivity measurements in  $\text{H}_2\text{O}$  (pH 6.8–7) at 298 K.



values for Ln content were chosen to be closed to those of  $\text{Ln}^{3+}\cdot\text{PCTA-COOH}/\text{Zr@HPICs}$  (*i.e.* 5%, Table 2).

Obtained colloidal systems were further characterized by DLS measurements (Fig. 3 and Fig. S6†). Well-defined HPICs were formed with a hydrodynamic radius around 10 nm similarly to the size obtained for HPICs based on  $\text{Cu}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Ga}^{3+}$  or  $\text{Gd}^{3+}$  with a similar block copolymer (Table 2).<sup>18,39–41</sup> The number of lanthanide and zirconyl ions within one  $\text{Ln}^{3+}/\text{Zr@HPIC}$  can be roughly estimated from previous studies on  $\text{Gd@HPICs}$  and  $\text{Ga@HPICs}$  based on the same polymer and is around 1000 thousand ions (*i.e.* 50 ions lanthanide per nano-objects).<sup>41</sup>

### 2.3. Luminescence properties of $\text{Eu}^{3+}$ -based HPICs

The study of the luminescence properties of europium-based systems is particularly interesting because these properties are highly sensitive to the europium environment. The encapsulation of  $\text{Eu}^{3+}$  in macrocyclic complexes or in HPICs structures results in the partial substitution of the nine water molecules surrounding the ion by donor atoms from the polymeric or macrocyclic compound. Consequently, non-radiative deactivations associated with the presence of water molecules that are in a first approximation proportional to the number of molecular oscillators of the O–H type in the ion's first coordination sphere are minimized.<sup>42</sup> This results in enhanced luminescence properties in the studied complexes compared to free  $\text{Eu}^{3+}$  ions. Emission spectra ( $\lambda_{\text{ex}} = 287$  nm) of the different studied systems are shown in Fig. 4. In the case of  $\text{Eu}^{3+}\cdot\text{PCTA-COOH}/\text{Zr@HPICs}$ , as for  $\text{Eu}^{3+}\cdot\text{PCTA-COOH}$  free complex, where the pyridine unit of PCTA-COOH acts as an “antenna”, a strong red emission was detected at 590 nm and 615 nm, corresponding respectively to the  ${}^7\text{D}_0 \rightarrow {}^7\text{F}_1$  and  ${}^7\text{D}_0$

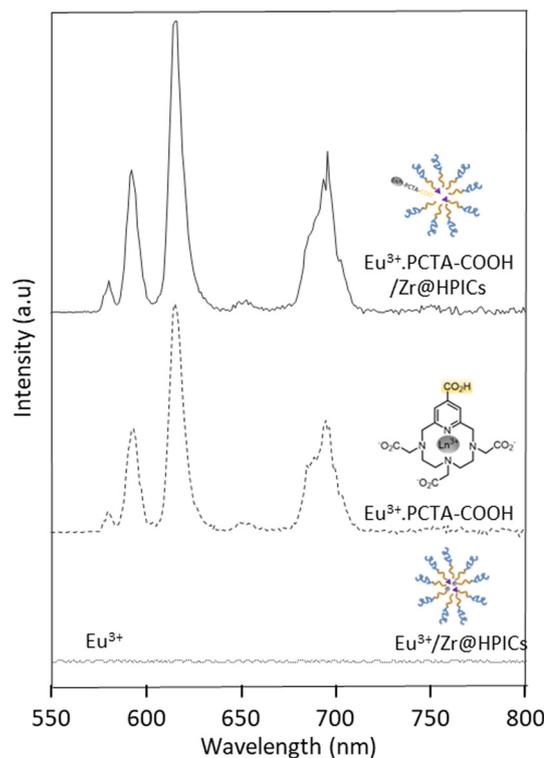


Fig. 4 Corrected emission spectra ( $\lambda_{\text{exc}} = 287$  nm) of  $\text{Eu}^{3+}$ ,  $\text{Eu}^{3+}/\text{Zr@HPICs}$ ,  $\text{Eu}^{3+}\cdot\text{PCTA-COOH}$  and  $\text{Eu}^{3+}\cdot\text{PCTA-COOH}/\text{Zr@HPICs}$  in  $\text{H}_2\text{O}$  (pH 6.8–7) at 298 K ( $[\text{Eu}] = 0.12$  mM).

$\rightarrow {}^7\text{F}_2$  transitions of  $\text{Eu}^{3+}$ ,<sup>43</sup> while no transition was detected in the emission spectrum of an aqueous solution of  $\text{Eu}(\text{NO}_3)_3$  with a similar concentration of  $\text{Eu}^{3+}$  (0.12 mM).

Moreover, the number of water molecules in the first coordination sphere of  $\text{Eu}^{3+}$  ions, estimated using luminescence lifetime measurements, was found to be around  $1.9 \pm 0.1$  water molecules, which is similar to that of  $\text{Eu}^{3+}\cdot\text{PCTA-COOH}$  complex (*i.e.* 1.99, Table 1). The insertion of  $\text{Eu}^{3+}\cdot\text{PCTA-COOH}$  within HPICs did not affect its luminescence properties and did not lead to a decomplexation phenomenon induced by the presence of carboxylic function of the polymer. As expected, for a similar concentration of  $\text{Eu}^{3+}$ , the luminescence measured for  $\text{Eu}^{3+}/\text{Zr@HPICs}$  is barely visible (Fig. 4). Indeed, for this system, the number of water molecules in the first coordination sphere of  $\text{Eu}^{3+}$  ions, estimated using luminescence lifetime measurements, was found to be at a significant higher value,<sup>44</sup> around  $4.3 \pm 0.1$ . Additionally, no antenna effect can promote luminescence properties. In view of the use of  $\text{Gd}^{3+}\cdot\text{PCTA-COOH}/\text{Zr@HPICs}$  as contrast agents, particular attention must be paid to the maintenance of their integrity in the presence of competing ions at physiological pH, due to the high toxicity of the free gadolinium ion. In this context, measurements of luminescence intensities and lifetimes were performed on europium-based analogues in 50 mM Tris buffered saline pH 7.4 ( $[\text{NaCl}] = 0.15$  M) and after addition of phosphate ions or calcium ions (Fig. 5A). The luminescence

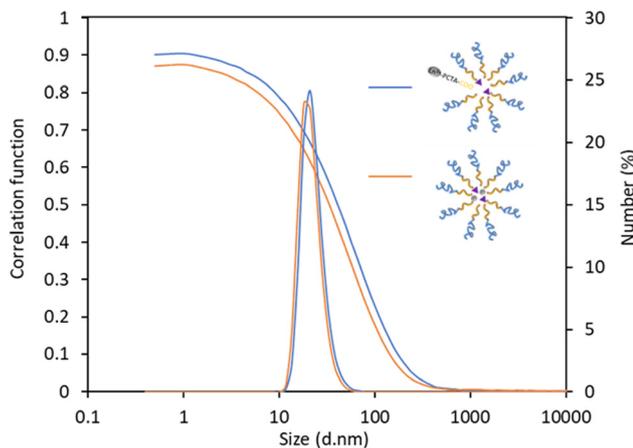
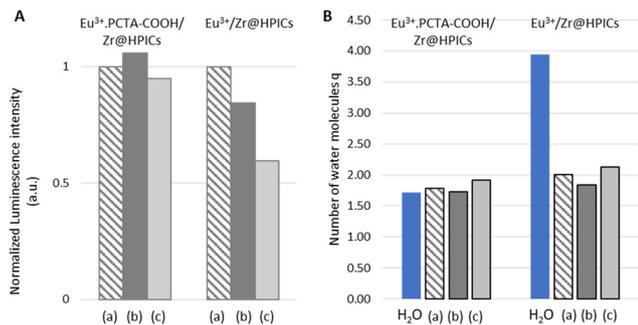


Fig. 3 Number-averaged hydrodynamic diameter distribution obtained on  $\text{Eu}^{3+}/\text{Zr@HPICs}$  (orange) and  $\text{Eu}^{3+}\cdot\text{PCTA-COOH}/\text{Zr@HPICs}$  (blue) from DLS measurements (polymer concentration equal to 0.1 wt%) at pH 7 and corresponding NLS analysis. Correlation functions from which these distributions are issued are superimposed on these distributions and clearly demonstrate the absence of aggregates in studied solutions (NB: for these correlation functions X-axis values corresponding to correlation time is not given, see Fig. S6†).





**Fig. 5** Effects of added ions on  $\text{Eu}^{3+}$ -PCTA-COOH/Zr@HPICs and  $\text{Eu}^{3+}$ /Zr@HPICs ( $[\text{Eu}] = 0.12 \text{ mM}$ ). (A) Normalized luminescence intensity (area-normalized emission spectra,  $\lambda_{\text{exc}} = 287 \text{ nm}$ ) (a) in Tris buffered saline 50 mM pH 7.4 ( $[\text{NaCl}] = 0.15 \text{ M}$ ), and after adding (b) phosphate (0.10 mM) and (c) calcium ions (0.25 mM). (B) Number of coordinated  $\text{H}_2\text{O}$  molecules  $q$  estimated for Eu systems from luminescence lifetime measurements and calculated using the following equation  $q = 1.05 \times 1/\tau_{\text{H}} - 0.70$ , in  $\text{H}_2\text{O}$  at pH 6.8–7, (a) in Tris buffered saline 50 mM pH 7.4 ( $[\text{NaCl}] = 0.15 \text{ M}$ ), and after adding (b) phosphate (0.10 mM) and (c) calcium ions (0.25 mM).

intensities and lifetimes of the  $\text{Eu}^{3+}$ -PCTA-COOH/Zr@HPICs system measured in pure water are not modified in Tris buffer, as well as after the addition of phosphate ions or calcium ions. The hydration parameter  $q = 2$  remains unchanged (Fig. 5B). These observations are thus indicative of good integrity of the entity in the physiological media studied. For the  $\text{Eu}^{3+}$ /Zr@HPICs system, several parameters are affected. On the one hand, compared to pure water, a significant decrease of the hydration parameter  $q$  is observed for the entity in solution in Tris buffer (Fig. 5B). This indicates an interaction between the  $\text{Eu}^{3+}$  ion and the Tris buffer (2-amino-2-(hydroxymethyl) propane-1,3-diol), probably *via* the amino group,<sup>45,46</sup> which induces the partial replacement of 2 of the 4 coordinated water molecules. On the other hand, in Tris buffer, the luminescence intensities of  $\text{Eu}^{3+}$ /Zr@HPICs are decreased by 20% and 40%, respectively, after the addition of phosphate and calcium ions (Fig. 5A), without affecting the luminescence lifetimes (Fig. S7†). This result highlights a partial release of  $\text{Eu}^{3+}$  ions under these conditions and thus indicates a lower stability of the  $\text{Eu}^{3+}$ /Zr@HPICs entity in the physiological media studied.

The stability of europium ions as a function of pH was further studied (Fig. S8†). While the  $\text{Eu}^{3+}$ @HPICs structure shows a decrease of more than 80% in measured intensity as the pH value increases, the insertion of zirconyl ions into the  $\text{Eu}^{3+}$ /Zr@HPICs structure prevents this phenomenon to a large extent. However, to maintain both luminescence properties and the coordination sphere of europium ions, its insertion through PCTA complexes remains the solution of choice.

#### 2.4. Relaxivity properties of $\text{Gd}^{3+}$ -based HPICs

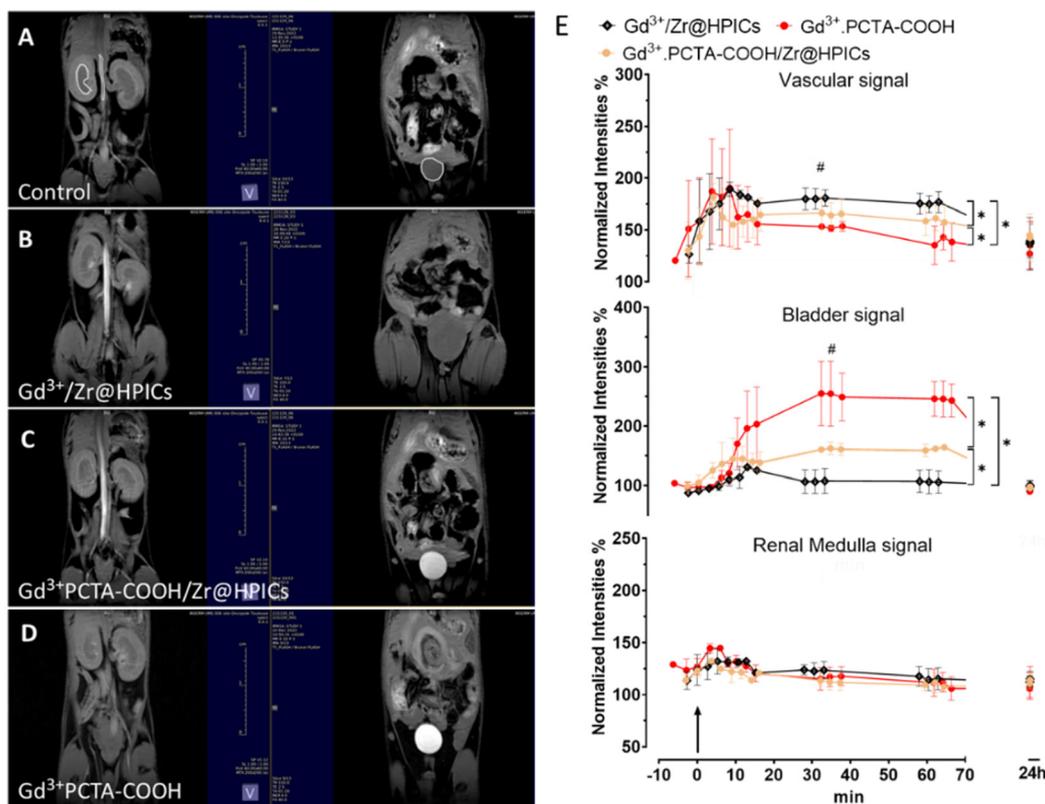
The relaxivity of  $\text{Gd}^{3+}$ /Zr@HPICs and  $\text{Gd}^{3+}$ -PCTA-COOH/Zr@HPICs was further studied in aqueous medium at physiological pH (Fig. S9 in ESI†). In water, the  $r_1$  relaxivity values of

$\text{Gd}^{3+}$ /Zr@HPICs,  $\text{Gd}^{3+}$ -PCTA-COOH/Zr@HPICs, and  $\text{Gd}^{3+}$ -PCTA-COOH were measured to be  $66.5 \pm 0.7 \text{ mM}^{-1} \text{ s}^{-1}$ ,  $8.0 \pm 0.2 \text{ mM}^{-1} \text{ s}^{-1}$  and  $2.8 \pm 0.3 \text{ mM}^{-1} \text{ s}^{-1}$ , respectively (25 °C, 0.47 T). The inclusion of the complexes in the HPICs structure induces, as expected, an increase in the measured relaxivity by a factor of three. However, this relaxivity remains significantly lower than that of the  $\text{Gd}$ /Zr@HPICs. In the latter case, this efficiency might be ascribed to more efficient water diffusion within the polymer matrix.<sup>26</sup> The values measured in the case of macrocyclic complexes encapsulated in HPICs fall within ranges comparable to those measured for gadolinium-based inorganic particles, such as  $\text{GdPO}_4$  and  $\text{NaGdF}_4$ . For these inorganic systems, relaxivity values between 1 and  $30 \text{ mM}^{-1} \text{ s}^{-1}$  have been measured, depending on the particle size and the nature of the stabilizing agent used.<sup>3</sup> Moreover, these values surpass those measured for commercial molecular complexes which are lower than  $6 \text{ mM}^{-1} \text{ s}^{-1}$  in human plasma at 37 °C and 0.47 T.<sup>47</sup> When mixed with Tris buffered saline (pH 7.4, 50 mM), the relaxivity remains roughly constant for  $\text{Gd}^{3+}$ -PCTA-COOH and  $\text{Gd}^{3+}$ -PCTA-COOH/Zr@HPICs, with measured values at  $3.30 \pm 0.5 \text{ mM}^{-1} \text{ s}^{-1}$  and  $6.0 \pm 2.0 \text{ mM}^{-1} \text{ s}^{-1}$ , respectively. Nevertheless, a significant decrease was measured for  $\text{Gd}^{3+}$ /Zr@HPICs at  $23.1 \pm 1.0 \text{ mM}^{-1} \text{ s}^{-1}$ , in agreement with the observed decrease on the hydration parameter  $q$  from 4 to 2, as measured by luminescence for the analog  $\text{Eu}$ /Zr@HPICs in Tris buffered saline medium. As previously described,<sup>26</sup> HPICs based on PEG-PAA present an insignificant cytotoxicity up to 1.3 mM  $\text{Gd}$  (0.1 wt% of polymer). This enables to perform *in vivo* experiments on mice and to obtain preliminary determinations of MR contrast efficacy, pharmacokinetic properties, and tolerance.

#### 2.5. *In vivo* experiments

*In vivo* MRI contrast was assessed after an intravenous (IV) bolus injection of  $\text{Gd}^{3+}$ /Zr@HPICs and  $\text{Gd}^{3+}$ -PCTA-COOH/Zr@HPICs, and it was compared to  $\text{Gd}^{3+}$ -PCTA-COOH at an equivalent  $\text{Gd}$  concentration. Tissue uptake and elimination characteristics were analyzed using a  $T_1$ -weighted dynamic sequence of coronal images centered on the abdominal cavity. Images were taken for 60 minutes post-IV injection at a dose of  $15 \mu\text{mol kg}^{-1}$  equivalent  $\text{Gd}$  concentration, with a control image captured at 24 hours. Signal intensities from the regions of interest *i.e.*, vascular (inferior aorta), renal medulla, and bladder spaces were quantified (see Fig. 6). As anticipated, a rapid increase in signal intensity in the vascular space was observed following the injection. At the 30-minute mark, the contrast enhancements for  $\text{Gd}^{3+}$ /Zr@HPICs,  $\text{Gd}^{3+}$ -PCTA-COOH/Zr@HPICs and  $\text{Gd}^{3+}$ -PCTA-COOH were significantly different, registering at 41%, 20%, and 15%, respectively. Monitoring of bladder signal intensity enables the assessment of urinary excretion of the compounds. The intensities measured for the three compounds differ significantly.  $\text{Gd}^{3+}$ -PCTA-COOH and, to a lesser extent,  $\text{Gd}^{3+}$ -PCTA-COOH/Zr@HPICs induce contrast enhancement in urine, whereas  $\text{Gd}^{3+}$ /Zr@HPICs does not (Fig. 6 – bladder).





**Fig. 6** Dynamics of signal intensities in mouse tissues following administration of  $Gd^{3+}$  complex agents. Typical images of horizontal abdominal sections at the level of the kidneys and lower aorta (left) and the bladder (right) are shown: (A), pre-injection control – regions of interest for the renal medulla, vascular space, and bladder are delineated in white; (B–D) 60 min post-intravenous injection of  $Gd^{3+}/Zr@HPICs$ ,  $Gd^{3+} \cdot PCTA-COOH/Zr@HPICs$  and  $Gd^{3+} \cdot PCTA-COOH$  respectively; (E) evolution of normalized intensities for the vascular space, bladder, and renal medulla is depicted (black arrow indicates the time of injection). Significant differences between the mean normalized intensities (# and \*) were observed ( $p < 0.01$ ,  $n = 3$ ) 30 min and 60 min post-administration, respectively ( $[Gd^{3+}] = 0.12$  mM).

While  $Gd^{3+} \cdot PCTA-COOH$  behaved similarly to DOTAREM,<sup>24</sup> characterized by rapid excretion in tandem with the decline in vascular space signal intensity,  $Gd^{3+}/Zr@HPICs$  shows a behavior similar to the one observed for HPICs based on the complexation of double hydrophilic block copolymers comprising an outer PEG shell, as previously described in the literature.<sup>18,19,23</sup>  $Gd^{3+} \cdot PCTA-COOH/Zr@HPICs$  shows an intermediate behavior. The evolution of the signal suggests that some of the complexes encapsulated in the HPICs structure are rapidly released and contribute to the observed signal enhancement in the bladder, while those interacting more strongly remain in the HPICs structure and extend the lifetime of the signal in the various organs. None of the administered compounds caused alterations in the renal medullary signal in these healthy animals.

### 3. Experimental section/methods

#### 3.1. Materials

$Gd(NO_3)_3 \cdot 6H_2O$ ,  $GdCl_3 \cdot 6H_2O$ ,  $ZrOCl_2 \cdot 8H_2O$ ,  $Eu(NO_3)_3 \cdot 5H_2O$ ,  $EuCl_3 \cdot 6H_2O$  and  $Ga(NO_3)_3 \cdot 6H_2O$  were purchased from Sigma Aldrich Co., Ltd. At highest purity available and used as

received.  $PEO_{6k}-b-PAA_{3k}$  was purchased from Polymer Source™ and used as received. Water was purified through a filter and ion exchange resin using a Purite device (resistivity 18.2  $M\Omega$  cm).  $D_2O$  was obtained from Eurisotop.

#### 3.2. Synthesis

**Synthesis of  $Eu^{3+}$  and  $Gd^{3+}$  complexes:  $Eu^{3+} \cdot PCTA-COOH$  and  $Gd^{3+} \cdot PCTA-COOH$ .** To a solution of ligand  $PCTA-COOH^{34}$  in  $H_2O$  was added  $EuCl_3 \cdot 6H_2O$  or  $GdCl_3 \cdot 6H_2O$  (1.1 equiv.). After stirring at room temperature for 1 h, pH was adjusted to 5–6 with NaOH 0.1 M and the mixture was then stirred for 16 h at room temperature. The pH was then adjusted to 7 with NaOH 0.1 M, the solvent was evaporated to a minimum and the solution was loaded on a Waters Sep-Pak® cartridge (C18, 10 g). Cartridge was rinsed with  $H_2O$  to remove salts and the product was eluted with a  $H_2O/MeOH$  1:1 mixture. The solvents were removed *in vacuo* to give the expected complex with quantitative yield. The absence of free lanthanide ions was verified using a classic test with an arsenazo indicator solution.

**$Eu^{3+} \cdot PCTA-COOH$  complex.** UPLC analysis:  $t_R = 4.11$  min. HRMS (ESI positive ion mode):  $m/z$  calcd for  $C_{18}H_{22}N_4O_8^{151}Eu [M + H]^+$  573.0636, found 573.0643 ( $\Delta m = 1.2$  ppm). UV  $\lambda_{abs}$



(Tris buffer, pH 7.4)/nm 281 ( $\epsilon = 3600 \text{ M}^{-1} \text{ cm}^{-1}$ ). Fluorescence  $\lambda_{\text{em}}$  (Tris buffer, pH 7.4,  $\lambda_{\text{exc}} = 281 \text{ nm}$ )/nm 580 (relative intensity, corrected spectrum 2.4), 592 (17.8), 615 (41.7), 651 (2.2), 695 (35.9).

**Gd<sup>3+</sup>·PCTA-COOH complex.** UPLC analysis:  $t_{\text{R}} = 4.25 \text{ min}$ . HRMS (ESI positive ion mode):  $m/z$  calcd for  $\text{C}_{18}\text{H}_{22}\text{N}_4\text{O}_8^{156}\text{Gd} [\text{M} + \text{H}]^+$  578.0663, found 578.0670 ( $\Delta m = 1.2 \text{ ppm}$ ). UV  $\lambda_{\text{abs}}$  (Tris buffer, pH 7.4)/nm 282 ( $\epsilon = 3900 \text{ M}^{-1} \text{ cm}^{-1}$ ).

**Gd<sup>3+</sup>·PCTA-COOH/Zr@HPICs and Eu<sup>3+</sup>·PCTA-COOH/Zr@HPICs formation.** The formation of  $\text{Ln}^{3+}\cdot\text{PCTA-COOH}/\text{Zr@HPICs}$  was obtained by adding a solution of zirconyl ions to a solution comprising a mixture of  $\text{Ln}^{3+}\cdot\text{PCTA-COOH}$  and diblock  $\text{PEO}_{6k}\text{-}b\text{-PAA}_{3k}$  copolymer. The ratio of charge between the positive charges due to the zirconyl  $\text{ZrO}^{2+}$  ions and the negative ones due to carboxylic functions (coming either from acrylic acid polymer units or from the free carboxylic function of PCTA-COOH) was chosen equal to one. In addition, the molar fraction of lanthanide ions was chosen equal to 10% relatively to the total amount of lanthanide and zirconyl ions. After purification through a dialysis/centrifugation process, this fraction estimated from ICP/MS measurements was found equal to  $6 \pm 1\%$ . Therefore, the final concentrations of acrylic acid unit, zirconyl ions and lanthanide ions *i.e.*  $\text{Ln}^{3+}\cdot\text{PCTA-COOH}$  complexes are equal to  $2.68 \times 10^{-3} \text{ mol L}^{-1}$ ,  $1.40 \times 10^{-3} \text{ mol L}^{-1}$  and  $0.12 \times 10^{-3} \text{ mol L}^{-1}$  respectively.

**Gd<sup>3+</sup>/Zr@HPICs and Eu<sup>3+</sup>/Zr@HPICs formation.** Solutions of HPICs were formed by mixing an aqueous solution of  $\text{PEO}_{6k}\text{-}b\text{-PAA}_{3k}$  with a solution containing  $\text{Gd}(\text{NO}_3)_3\cdot 6\text{H}_2\text{O}$  or  $\text{Eu}(\text{NO}_3)_3\cdot 5\text{H}_2\text{O}$  and  $\text{ZrOCl}_2\cdot 8\text{H}_2\text{O}$ . Gadolinium or europium and zirconium concentrations were adjusted in order to have a molar fraction of gadolinium or europium to zirconyl ions equal to 5% within the HPICs (to have roughly the same value than the one obtained for  $\text{Ln}^{3+}\cdot\text{PCTA-COOH}/\text{Zr@HPICs}$ , *i.e.* 5–6%). The ratio of charge between the charges due to the metallic ions and that due to the polymers was set to be close to unity for all experiments. After mixing, the pH of the solutions was adjusted to 6.8–7. In that case, after purification through a dialysis/centrifugation process, the final concentrations of acrylic acid unit, zirconyl ions and lanthanide ions are equal to  $2.68 \times 10^{-3} \text{ mol L}^{-1}$ ,  $1.16 \times 10^{-3} \text{ mol L}^{-1}$  and  $0.12 \times 10^{-3} \text{ mol L}^{-1}$  respectively.

### 3.3. Methods

**Characterization of  $\text{Ln}^{3+}\cdot\text{PCTA-COOH}$  ( $\text{Ln} = \text{Eu}^{3+}, \text{Gd}^{3+}$ ).** <sup>1</sup>H NMR spectra were recorded using a Bruker Avance 300 spectrometer with D<sub>2</sub>O as solvent. Chemical shifts  $\delta$  are reported in parts per million (ppm) and are referenced to the residual solvent peak (D<sub>2</sub>O : H = 4.79 ppm).

High-Resolution Mass Spectra (HRMS) were obtained on a Xevo G2 Qtof Waters spectrometer. The UPLC analyses were performed on a Waters UPLC Acquity apparatus with PDA (photodiode array) and SQ (simple quadrupole) detectors, and using an Acquity BEH HILIC column (1.7  $\mu\text{m}$ , 100  $\times$  2.1 mm) with a flow rate of 0.4 mL min<sup>-1</sup>. Linear gradient system was H<sub>2</sub>O + 0.1% HCOOH (pH 2)/CH<sub>3</sub>CN + 0.1% HCOOH (pH 2) 5/95 to 50/50 in 7 min, then an isocratic elution 50/50 for

10 min. Absorption measurements were done with a Hewlett Packard 8453 temperature-controlled spectrometer in 10 mm quartz cuvette.

Emission, excitation spectra and luminescence decays of europium complex were measured using a Cary Eclipse spectro fluorimeter equipped with a Xenon flash lamp source and a Hamamatsu R928 photomultiplier. Excitation spectra were corrected for the excitation light intensity, while emission spectra were corrected for the instrument response. Lifetimes  $\tau$  (uncertainty  $\leq 5\%$ ) are made by monitoring the decay at 616 nm, a wavelength corresponding to the maximum intensity of the emission spectrum, following pulsed excitation. They are the average values from at least five separate measurements covering two or more lifetimes. The luminescence decay curves were fitted by an equation of the form  $I(t) = I(0) \exp(-t/\tau)$  by using a curve-fitting program. The average number of coordinated water molecules on europium ions in complex (free or in HPICs) were determined as follow: solutions of  $\text{PEO}_{6k}\text{-}b\text{-PAA}_{3k}$  polymers (0.1 wt%) with various amounts of  $\text{Eu}^{3+}$  and  $\text{ZrO}^{2+}$  were prepared to get HPICs solutions with  $\rho_{\text{charge}} = 1$  and  $\rho_{\text{Eu}}$  equal to 5%. After adjusting of the pH of the solutions to *ca.* 6.8–7, luminescence of the solutions was measured. The solutions were freeze-dried the redispersed in D<sub>2</sub>O with final concentrations equivalent to that in water. DLS experiments on such redispersed solution suggest that the HPICs are maintained during this process. Luminescence of the D<sub>2</sub>O solutions was then recorded. Using the equation proposed by R.M. Supkowski *et al.*,<sup>35</sup> the number ( $q$ ) of water molecules coordinated to the europium ions within the HPICs was estimated.<sup>48</sup>

**Characterization of  $\text{Ln}^{3+}/\text{Zr@HPICs}$  and  $\text{Ln}^{3+}\cdot\text{PCTA-COOH}/\text{Zr@HPICs}$  ( $\text{Ln} = \text{Eu}^{3+}, \text{Gd}^{3+}$ ) properties**

**Colloidal stability.** Dynamic light scattering measurements were conducted using a Zetasizer Nano-ZS (Malvern Instruments, Ltd, UK) with an integrated 4 mW He-Ne laser,  $\lambda = 633 \text{ nm}$ . Light scattering intensity (at 173°) was measured with instrumental parameters set to constant values for all the samples. The correlation function was analyzed *via* the cumulant method to get the Z-average size of the colloids and by the general-purpose method (NNLS) to obtain their distribution in size. The apparent equivalent hydrodynamic radius  $R_{\text{h}}$  were then determined using the Stokes–Einstein equation  $D = (k_{\text{B}}T)/(6\pi\eta R_{\text{h}})$  where  $T$  is the temperature and  $\eta$  the viscosity of the solution. Mean radius values were obtained from five different runs of the number plot.

**Composition.** Inductively coupled plasma – atomic emission spectroscopy (ICP-AES) analysis was performed by Antellis company (<https://www.antellis.com>). Measurements were performed on an ULTIMA 2 inductively coupled plasma atomic emission spectrometer from Horiba Jobin Yvon Technology. To enable analyses, a specific nebulizer (PTFE Mira Mist Nebulizer, supplied by Horiba Jobin Yvon Technology) was used to introduce the solution into the ICP-AES. The nebulizer was inserted into a glass cyclonic chamber and operated at a maximum sample flow rate of 1 mL min<sup>-1</sup> and with a maximum total dissolved solute of 300 g L<sup>-1</sup>. The optical wave-



length for each element was determined to optimize the limits of quantification through calibration curves with 0–10 ppm concentrations (5 points). The sample was introduced into the ICP-AES instrument with a peristaltic pump.

**Relaxivity.** Magnetic relaxation time measurements in solution were carried out at 1.4 T on a Minispec mq60 TD-NMR contrast agent analyser (Bruker Optics, Billerica, MA, USA) at a constant temperature of 25 °C.  $T_1$  relaxation times were measured using an inversion recovery pulse sequence;  $T_2$  relaxation times were measured using a Carr–Purcell–Meiboom–Gill pulse sequence. Experiments were performed on solutions with 0.1 wt% of polymers.

### 3.4. *In vivo* experiments

Nine BALB/cOlaHsd mice (Envigo) aged 10–12 weeks were used for MRI experiments. All *in vivo* experimental procedures were approved by our institutional animal care and use committee CEEA122 (APAFIS 5192-2016041911336422 and 34703-2022011811542488) and conducted in compliance with the Ethics Committee pursuant to European legislation translated into French Law as Decret 2013-118 dated 1st of February 2013.

**Small animal MRI.** Animals were anesthetized with isoflurane (induction 3%–4%, maintenance 1.5% (isoflurane/ $O_2$ )) to insert a catheter in the tail vein. Then, the mice is placed in a specific MRI imaging cell (Minerve, Esternay, France) to preserve the health status (SPF), ensure the temperature regulation and the breathing monitoring. Animals received a dose of 15  $\mu\text{mol kg}^{-1}$  of Gd equivalent followed by a 200  $\mu\text{l}$  flush of saline. MR image acquisitions were performed on a Biospec 7T dedicated to small animals (Bruker, Wissenbourg, France). Acquisitions of the abdominal images were carried out with a 40 mm transmit-receive volume coil and triggered on breathing to reduce motion artifacts.  $T_1$  weighted images were acquired using Flash sequence with the following parameters: TR = 150 ms; TE = 2.5 ms; flip angle: 40°; number of average: 4; FOV: 40 × 40 mm; resolution 200 × 200  $\mu\text{m}$ ; 13 slices of 1 mm thickness; fat suppression; acquisition time: 1 min 20 s. Intensity values were normalized against muscle intensity and given in percentage. Mean Intensity data are shown as mean  $\pm$  SD ( $n = 3$  per contrast agent). An unpaired *t*-test was used to assess differences between normalized intensities recorded at 30 min  $\pm$  5 min and 60  $\pm$  5 min (3 values per contrast agent). A *p*-value less than 0.01 was considered significant.

## 4. Conclusions

Lanthanide-based macrocycles  $\text{Ln}^{3+}$ ·PCTA-COOH are successfully inserted in hybrid polyionic complexes colloidal structures thanks to the interaction of the 4-position carboxylic acid function of PCTA-COOH with zirconium ions during the formation of the monodisperse nano-objects. These obtained nanoobjects, with an average radius of *ca.* 10–15 nm, present good colloidal and chemical stability in physiological medium. Moreover, the lanthanide incorporated as  $\text{Ln}^{3+}$ ·PCTA-COOH

complex in HPICs avoid the partial release of lanthanide ions even in the presence a significant excess of phosphate or calcium ions, endogenous ions potentially interacting with lanthanide ions. Preliminary determinations of MRI contrast efficacy, pharmacokinetic and optical properties and tolerance performed *in vivo* in mice show that these colloids including  $\text{Ln}^{3+}$ ·PCTA-COOH complexes benefit from both their colloidal nature and the specific properties of the lanthanide complexes: while they retain the optical properties and chemical stability of initial  $\text{Ln}^{3+}$ ·PCTA-COOH complexes, the magnetic properties and *in vivo* distribution benefit from the colloidal nature of the nanoobjects formed. Therefore, the strategy proposed in this article opens up new opportunities to pave the way for new applications for metal complexes based on the use of cryptants, whether in biology or catalysis.

## Conflicts of interest

There are no conflicts to declare.

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