Monophosphonic versus Multiphosphonic Acid Based PEGylated Polymers for Functionalization and Stabilization of Metal (Ce, Fe, Ti, Al) Oxide Nanoparticles in Biological Media

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1. Introduction

Over the last decade, engineered nanoparticles have been developed as therapeutic, diagnostic, and theranostic agents, leading to the development of nanomedicine.[1–5] Recent studies have shown however that nanomedicine has not met the initial expectations regarding translation to the clinics. In a literature survey, Wilhelm et al. have found that with regard to solid tumor targeting, around 99% of engineered particles administered intravenously to rodents are cleared from the blood circulation and miss their targets.[6] Others reviews on translational nanomedicine were reported and similar conclusions were reached.[4,7] One reason brought forward to explain these results is related to the hurdles encountered to control nanomaterial interfaces with biological fluids, cells, and tissues. Although many progresses have been made in nanoparticle functionalization, innovative solutions are still to be investigated.

An efficient way to coat particles makes use of polymers[1,3,5] and coassembly methods, avoiding hence the difficulties posed by grafting-to techniques and surface-initiated living radical polymerization.[8,9] With coassembly, the chains adsorb spontaneously at the particle surfaces by single or multiple point attachments and form a diffuse layer.[10–15] This layer is of a few nanometers and represents a barrier against particle aggregation and protein adsorption.[16–19] The affinity toward the surface can be enhanced by the addition of specific chemical groups that can react with the surface. For metal and metal oxide nanoparticles, the most commonly used linkers are alcohol, acid, amine, silane, and thiol compounds.[14,15,17,20–30] Within a few exceptions,[20,31–35] functional polymers are generally synthesized for a single type of particles and for a predetermined application. Nowadays, there is an urgent need for coating agents that can be tailored according to a wide range of surfaces and produced on a large scale. To our knowledge, such a multipurpose and multisubstrate coating has not been yet examined in details.

Herein we explore the possibility to use phosphonic acid groups as efficient linkers to different metal oxide nanocrystals. Previous reports on functionalization have shown that poly(ethylene glycol) (PEG) polymers terminated with a monophosphonic or biphosphonic acid functional groups[36,37] can adsorb on particles of different composition and nature, such as calcium carbonate,[38] iron,[14,17,23,24,26–28,39,40] cerium,[41,42] and titanium[43,44] oxides. In the previous examples, the functional polymers were obtained from different...
synthesis and had different structures. In the context of nanomedicine, special attention was paid to iron oxide that was assessed in vivo as imaging and therapeutic agent. Sandiford et al. exploited PEG conjugates containing a terminal bisphosphonic acid group to overcome the rapid sequestration of the magnetic resonance imaging (MRI) probes and to increase their circulation time in vivo. More recently, our group proposed an alternative strategy to increase the number of polymer attachment points. This strategy resulted in the synthesis of copolymers where phosphonic acid groups and PEG chains are covalently grafted to a poly(methyl methacrylate) backbone. Proof of concept studies performed on cells and on small animals confirmed that this technology has the potential to improve the colloidal stability in biofluids, prevent protein adsorption, and increase the circulation time in vivo.

Here we aim to demonstrate that multiphosphonic acid PEG copolymers are susceptible to coat and stabilize a broad range of metal oxide particles in protein rich culture media. The particles are made of cerium, titanium, iron, and aluminum oxides, which have different morphologies (spheres, platelets, nanoclusters) and their sizes are comprised between 7 and 40 nm. In parallel, we synthesize an ensemble of six phosphonic acid based PEG polymers; three of them carry a unique phosphonic acid group, while the remaining three are statistical copolymers with multiple anchors. It is found that the particles coated with monofunctionalized polymers exhibit a mitigated stability over time (<1 week), whereas the multifunctionalized copolymers provide resilient coatings and long-term stability (> months).

2. Results and Discussion

2.1. Polymer Synthesis and Characterization

In this work, an ensemble of six polymers was synthesized for the coating and functionalization of metal oxide nanoparticles.

Three polymers are linear poly(ethylene glycol) chains of molecular weight 1000, 2000, and 5000 g mol\(^{-1}\) terminated by a single phosphonic acid group, –PO(OH)\(_2\). In the following, these monofunctionalized chains are abbreviated PEG\(_{1K}\)-Ph, PEG\(_{2K}\)-Ph, and PEG\(_{5K}\)-Ph, respectively. The remaining three polymers are statistical copolymers obtained by free radical polymerization following a synthesis pathway described in previous publications. Two of these copolymers consist in a poly(methyl methacrylate) backbone with multiple phosphonic acid groups and methyl terminated PEG lateral chains in the molar proportions (0.50:0.50). The PEGs have molecular weights of 2000 and 5000 g mol\(^{-1}\), leading to the acronyms MPEG\(_{2K}\)-MPh and MPEG\(_{5K}\)-MPh (here “M” refers to the methyl methacrylate end-group of each comonomer). The sixth polymer contains an equimolar amount of methyl and amine terminated PEG chains in addition to the phosphonic acid groups. The molar proportions of PEGs, amine modified PEGs, and phosphonic acids are thus (0.25:0.25:0.50) for this terpolymer, later abbreviated as MPEG\(_{1K}\)-MPEG\(_{5K}\)-MPh (where “a” refers to the amine PEG-terminal group). Details on the synthesis and \(^1\)H NMR characterization can be found in the Experimental section and in Section S1 (Supporting Information).

The weight-averaged molecular weights \(M_w\) are determined from static light scattering using Zimm plots. For Zimm plots, the Rayleigh ratio \(R(c)\) of the dispersions is measured as a function of the polymer concentration and the intercept of \(K_c/R(c)\) versus \(c\) gives the inverse molar weight (Section S2, Supporting Information). Here \(K_c\) is the scattering contrast determined from refractometry. The copolymers MPEG\(_{2K}\)-MPh, MPEG\(_{5K}\)-MPh, and MPEG\(_{2K}\)-MPEG\(_{5K}\)-MPh were found to have molecular weights \(M_w\) of 20 300, 22 000, and 29 200 g mol\(^{-1}\), respectively. Assuming a molar mass dispersity \(D = 1.8\), the number-averaged molecular weights \(M_n\) were determined at 11 300, 12 200, and 16 200 g mol\(^{-1}\). From these values, the average numbers of

![Figure 1. Molecular structures of phosphonic acid based polymers and copolymers synthesized in this work. a) Poly(ethylene glycol) containing a terminal phosphonic acid group and PEG chains of 2000 g mol\(^{-1}\) (PEG\(_{2K}\)-Ph). b) Poly(poly(ethylene glycol) methacrylate-co-dimethyl(methacryloyloxy) methyl phosphonic acid) is a statistical copolymer where the repeating units have lateral methyl terminated PEG\(_{2K}\) chains and lateral phosphonic acids in the molar proportions (0.50:0.50) (MPEG\(_{2K}\)-MPh). c) MPEG\(_{2K}\)-MPEG\(_{5K}\)-MPh is a statistical terpolymer where the repeating units have lateral methyl terminated PEG\(_{2K}\) chains, lateral amine terminated PEG\(_{2K}\) chains, and lateral phosphonic acids in the molar proportions (0.25:0.25:0.50). Monofunctionalized PEGylated chains PEG\(_{1K}\)-Ph and PEG\(_{5K}\)-Ph as well as the statistical copolymer MPEG\(_{5K}\)-MPh were also synthesized and studied as coats.](image)
phosphonic acid were estimated at 5.1, 2.3, and 6.7. These later results are summarized in Table 1.

### 2.2. Nanoparticles

The metal oxide nanoparticles investigated herein are nanocrystals of cerium (CeO₂), titanium (TiO₂), iron (γ-Fe₂O₃), and aluminum (Al₂O₃). Figure 2a–d shows transmission electronic microscopy (TEM) micrographs of the particles together with their size distributions. Cerium oxide nanoparticles (nanoceria) were synthesized by thermo-hydrolysis of cerium nitrate salt under hydrothermal conditions as a 200 g L⁻¹ dispersion. The particles consist in small agglomerates of 3 nm crystallites showing a median TEM size of 7.8 nm. TiO₂ nanoparticles were obtained from Nano-structured & Amorphous Material Inc (Houston, TX, USA) as a 150 g L⁻¹ dispersion. The particles have the shape elongated platelets of median length 9.7 nm. Some small size aggregates are also observed in the TEM image. Iron oxide nanoparticles (maghemite) were synthesized by alkaline coprecipitation of iron(II) and iron(III) salts and further oxidation. The γFe₂O₃ particles are super-paramagnetic and display a slight shape anisotropy and a median size of 13.2 nm. The Al₂O₃ nanoparticles are from Disperal (SASOL, Hamburg, Germany) and provided in the form of a white powder, that is dispersed by sonication and pH adjustment. Particles have the shape of irregular platelets of sizes 41.5 nm in length and 10 nm in thickness. The CeO₂, TiO₂, γ-Fe₂O₃, and Al₂O₃ nanoparticles were also studied by dynamic light scattering, revealing hydrodynamic diameters \( D_H \) of 9.6, 46.2, 29.8, and 55.3 nm, respectively. For cerium, iron, and aluminum oxide nanoparticles, the differences found between the geometric and hydrodynamic diameters are attributed to the particle size and shape dispersity. For titanium oxide, it is ascribed to the presence of sub-100 nm aggregates in the dispersion. All dispersions were prepared in diluted nitric acid at pH 1.5, where these nanoparticles are positively charged and have zeta potentials \( \zeta \) around +30 mV.

### 2.3. Polymer Coated Metal Oxide Nanoparticles

#### 2.3.1. Polymer Coated Cerium Oxide Nanoparticles

We first describe the polymer coating protocol focusing on CeO₂ and study the pH-stability diagrams. In a first step, polymer and particle stock solutions are prepared in the same conditions of pH and concentration. The dispersions are then mixed

| Polymers       | \( M_w^{\text{poly}} [\text{g mol}^{-1}] \) | \( M_n^{\text{poly}} [\text{g mol}^{-1}] \) | Comonomer proportions | Phosphonic acids/polymer |
|----------------|--------------------------------------------|------------------------------------------|------------------------|--------------------------|
| PEG₁₆-Ph       | 1200                                       | 1200                                     | –                      | 1.0                      |
| PEG₂₄-Ph       | 2000                                       | 2000                                     | –                      | 1.0                      |
| PEG₄₄-Ph       | 5000                                       | 5000                                     | –                      | 1.0                      |
| MPEG₂₅-MPh     | 20 300                                     | 11 300                                   | (0.50:0.50)            | 5.1                      |
| MPEG₁₉-MPh     | 22 000                                     | 12 200                                   | (0.50:0.50)            | 2.3                      |
| MPEG₂₅-MPEG₂₅-MPh | 29 200                                     | 16 200                                   | (0.25:0.25:0.50)      | 6.7                      |

Table 1. Molecular characteristics of the phosphonic acid PEGylated polymers and copolymers synthesized in this work.
at different ratios $X = c_{NP}/c_{Pol}$, where $c_{NP}$ and $c_{Pol}$ are the nanoparticle and polymer concentrations and $c = c_{NP} + c_{Pol}$ remains constant. In practice, $c_{NP}$ is held in the range 0.1–10 g L$^{-1}$ and $X$ between $10^{-3}$ and $10^3$. For cerium oxide, the pH is set at 1.5 for the mixing and later increased to pH 8. The total concentration is fixed at $c = 2$ g L$^{-1}$.

Figure 3a–f shows the pH-stability diagrams obtained by plotting the hydrodynamic diameter $D_H$ as a function of $X$. For the three PEG$_{nK}$-Ph polymers (with $n = 1, 2$, and 5), the stability diagrams exhibit similar features (Figure 3a–c). At pH 1.5, $D_H(X)$ decreases continuously from a value around 20 nm to the diameter of the bare particles, $D_H = 9.6$ nm. At pH 8 in contrast, the diagrams show two regions: on the left-hand side the particle size remains stable (the $D_H$’s are identical to those of pH 1.5), whereas on the right-hand side the particles aggregate (shaded area). The limit between the two domains defines the critical ratio $X_C$. For the copolymers MPEG$_{2K}$-MPh, MPEG$_{5K}$-MPh, and MPEG$_{2K}$-MPEG$_{2K}$-MPh (Figure 3d–f), we find that in the range $X = 1$–10, the nanoceria are subjected to a partial aggregation. This aggregation arises from polymer bridging, in which phosphonic acid groups coming from a single chain adsorb on different particles.[16] The critical ratios are found around 1, except for MPEG$_{2K}$-MPh and MPEG$_{5K}$-MPEG$_{2K}$-MPh where it is $1.5 \pm 0.2$ and $0.6 \pm 0.1$, respectively (Table 2).

The interpretation of the data of Figure 3 relies on the non-stoichiometric adsorption model developed by us in the context of polymer coating.[41] This model assumes that the polymers adsorb spontaneously on cerium oxide thanks to the phosphonic acid groups anchoring at the surface. This adsorption results in the stretching of the PEG chains, leading to the formation of a brush. The association is described as non-stoichiometric because the number of polymers adsorbed per particle depends on $X$. It is maximum below $X_C$ and decreases above. In case of partial coverage ($X > X_C$), the particles behave as uncoated CeO$_2$ and precipitate upon pH change.

According to the model, $X_C$ is linked to the number of polymers per particle $n_{Pol/NP}$ through the relationship $n_{Pol/NP} = (1/X_C) M_n^{NP}/M_n^{Ph}$, where $M_n^{NP}$ and $M_n^{Ph}$ are the number-averaged molecular weights of nanoceria and polymers, respectively. For the monofunctionalized polymers, the PEG density decreases from 0.85 to 0.38 and 0.20 nm$^{-2}$ with increasing molecular weight (Table 2). This result is consistent with the

![Figure 3](https://www.advancedsciencenews.com/)  
**Figure 3.** Stability diagram of cerium oxide nanoparticles in presence of a–c) phosphonic acid PEG polymers and d–f) copolymers at pH 1.5 and 8. The hydrodynamic diameter $D_H$ measured by dynamic light scattering is shown as a function of the mixing ratio $X = c_{NP}/c_{Pol}$. The nanoceria are associated with: a) PEG$_{1K}$-Ph, b) PEG$_{2K}$-Ph, c) PEG$_{5K}$-Ph, d) MPEG$_{2K}$-MPh, e) MPEG$_{5K}$-MPh, and f) MPEG$_{2K}$-MPEG$_{2K}$-MPh. For $X > X_C$, particles aggregate when pH is increased from 1.5 to 8. For micrometer-sized aggregates, $D_H$ is set at 1000 nm (shaded area). In the different figures, the bare nanoparticle solutions are set at $X = 10^3$ for convenience.

| Particles                  | $X_C$   | Polymers per particle | PEG chain density [nm$^{-2}$] |
|----------------------------|---------|-----------------------|------------------------------|
| CeO$_2$@PEG$_{1K}$-Ph     | 0.9 ± 0.1| 230                   | 0.85                         |
| CeO$_2$@PEG$_{2K}$-Ph     | 1.2 ± 0.2| 103                   | 0.38                         |
| CeO$_2$@PEG$_{3K}$-Ph     | 0.9 ± 0.1| 55                    | 0.20                         |
| CeO$_2$@MPEG$_{2K}$-Ph    | 1.5 ± 0.2| 15                    | 0.28                         |
| CeO$_2$@MPEG$_{5K}$-Ph    | 0.9 ± 0.1| 23                    | 0.20                         |
| CeO$_2$@MPEG$_{5K}$-MPh   | 0.6 ± 0.1| 26                    | 0.62                         |

**Table 2.** Critical mixing ratio $X_C$, average number of polymers per particle and PEG densities on polymer coated cerium oxide nanoparticles.
Figure 4. Normalized Rayleigh intensity $R(X)/R_{app}$ as a function of $X$ for CeO$_2$ nanoparticles and phosphonic acid PEG polymers at pH 1.5: a) PEG$_{1K}$-Ph, PEG$_{2K}$-Ph, and PEG$_{5K}$-Ph; b) MPEG$_{2K}$-MPh, MPEG$_{5K}$-MPh, and MPEG$_{2K}$-MPEG$_{a2K}$-MPh. The concentration is set at 2 g L$^{-1}$. The continuous lines are best fit calculations using the nonstoichiometric interaction model developed in Section S4 (Supporting Information). [41]

Nanoparticles densities determined by quartz crystal microbalance with dissipation monitoring (QCM-D) on iron oxide flat substrates.[40] From QCM-D, it was concluded that the difference in PEG densities was arising from excluded volume effects and steric repulsion. During the film formation, the already adsorbed chains act as a barrier for the incoming ones, a mechanism that is more effective for longer chains. For the copolymers, the PEG densities are in the range 0.2–0.3 PEG nm$^{-2}$, in agreement with those of literature. [1,20,35,54,55] The value for MPEG$_{2K}$-MPEG$_{a2K}$-MPh is slightly larger (0.67 nm$^{-2}$), probably due to an underestimation of the critical ratio because of the bridging effects discussed previously. Thermogravimetric analysis was performed on nanoceria powder samples coated with MPEG$_{2K}$-MPh and MPEG$_{2K}$-MPEG$_{a2K}$-MPh and revealed PEG densities of 0.12 and 0.18 nm$^{-2}$, respectively (Section S3, Supporting Information). These values are slightly lower than those derived from $X_C$, indicating that the stability diagram determination probably overestimates the amount of adsorbed polymers. The average number of polymers per CeO$_2$ and the PEG densities obtained are listed in Table 2.

Another approach for testing the nonstoichiometric model consists in examining the $X$-dependence of the scattered intensity. This intensity is transposed into the Rayleigh ratio $R(X)$ normalized with that of the nanoceria dispersion $R_{app}$ at $c = 2$ g L$^{-1}$. Figure shows the quantity $R(X)/R_{app}$ as a function of $X$ for the six polymers investigated. For the PEG$_{nk}$-Ph in Figure 4a, the normalized Rayleigh ratio first increases with increasing $X$, passes through a maximum around $X_C$, and then decreases to 1. The continuous lines are best fit calculations using the model equations,[41] as described in Section S4 (Supporting Information). The agreement with the model is excellent for the 3 polymers. The principal fitting parameter is the number of polymers per particle $n_{Pol}/NP$ that determines the maximum position. The $n_{Pol}/NP$ retrieved from the fitting confirms those obtained from the $X_C$ determination in Table 2. With the copolymers, the model fails to account for the scattering intensity, as illustrated in Figure 4b. A good agreement is achieved at low and high $X$-values, but not in the region where the dispersions show aggregation. For these polymers, we rely on the densities determined from the $X_C$. In the upcoming section, coated CeO$_2$ particles are prepared with a large excess of polymers ($X = X_C/5$) and later dialyzed against deionized (DI) water to remove this excess. The dispersions were concentrated to 20 g L$^{-1}$ and stored in the fridge, where they display long-term stability (> months).

2.3.2. Polymer Coated Maghemite, Titania, and Alumina Nanoparticles

The previous strategy was implemented with the titanium, iron, and aluminum oxide particles. Table 3 shows the hydrodynamic diameter $D_H$ for the four polymer coated metal oxide nanoparticles, together with the brush thickness $h = \frac{1}{3} (D_H^\text{meas} - D_H^\text{th})$ derived for the twenty-two polymer-particle configurations tested, where $D_H^\text{meas}$ and $D_H^\text{th}$ stand for the hydrodynamic diameters of the bare and coated particles. It is found that whatever the particle size, the layer thickness remains the same for a given polymer. Such an outcome suggests that the adsorption mechanism and the brush conformation are similar and independent on the substrate. A closer look at Table 3 reveals that for the monofunctionalized polymers, $h$ increases with the PEG molecular weight, from 2.7 nm for PEG$_{1K}$-Ph to 4.5 nm for PEG$_{2K}$-Ph and 8.7 nm for PEG$_{5K}$-Ph. These values are close to those found for films obtained through QCM-D on flat iron surfaces.[40] For the block copolymers with multiphosphonic acids, the film thickness is in the range 9–11 nm and only slightly molecular weight dependent. Figure 5a,b depicts the conformation of
the phosphonic acid end-groups regarding the surface for the monofunctionalized and multifunctionalized polymers, respectively. The inset shows the MPEG2K-MPh bound to a nanoparticle together with the PEG brush. It has been known that phosphonic acids strongly bind to the surface of metal oxides through condensation of their acidic hydroxyls P\(\cdot\)OH with surface metal hydroxyls metal-OH and/or through the coordination of the phosphoryl oxygen to Lewis acid surface sites.\(^{[28,36,37]}\)

Monodentate, bidentate, or tridentate anchoring modes have been proposed in the literature and are illustrated Figure 5b.

### 2.4. Colloidal Stability of Bare and Polymer Coated Oxide Nanoparticles

#### 2.4.1. Bare Oxide Nanoparticles

We now turn to the issue of the colloidal stability as a function of pH, ionic strength, and protein content. Figure 6a,b displays the pH-dependences of the hydrodynamic diameter \(D_H\) and zeta potential \(\zeta\) for the bare cerium, titanium, iron, and aluminum oxide nanoparticles. At low pH, the dispersions are stable and the particle \(D_H\)'s are those of Table 3. The particles are stabilized by electrostatic repulsion mediated by the metal-OH\(^2+\) surface groups. As a result, the zeta potential is positive and around +30 mV. With increasing pH, the charges present at the crystalline planes in contact with the solvent are gradually neutralized, leading to a decrease in density and electrostatic screening. The decrease of the zeta potential in Figure 6b is concomitant to the particle aggregation, which is revealed by the steep \(D_H\)-increase (Figure 6a).

At physiological pH, the dispersions are turbid and precipitation is observed, in agreement with earlier studies.\(^{[50,56–60]}\) The nanoparticle redispersion due to charge inversion at high pH is not observed, indicating the irreversible character of the aggregation process.

Figure 6c–e displays images of the metal oxide dispersions in nitric acid at pH 1.5, in phosphate buffer saline (PBS) and in phenol red free Dulbecco’s Modified Eagle’s Medium (DMEM) complemented with 10% fetal bovine serum (FBS), respectively. At physiological pH, precipitates are observed at the bottom of the PBS and DMEM vials for the four dispersions. The precipitation is the result of a number of interacting factors. In PBS, it is due to pH and ionic strength effects related to the solvent change and to the modification of the interparticle repulsion. In DMEM, proteins and other biological molecules also come into play and cause aggregation. Two movies in the Supporting Information illustrate the process kinetics and show that the phenomenon is rapid (<1 s). There, 20 \(\mu\)L of a concentrated CeO\(_2\) dispersion are added to PBS (Movie S1, Supporting Information) and to protein enriched cell culture medium (Movie S2, Supporting Information). As the drop reaches the solvent, particles aggregate immediately, as indicated by the growth of large scattering flakes within the actuated solution.

#### 2.4.2. Monophosphonic versus Multiphosphonic Acid PEG Polymer Coating

To assess the coating performances of the PEGylated polymers in physiological solvents, light scattering was performed to test the dispersion state over time. In the experiments performed, 20 \(\mu\)L of a 20 g L\(^{-1}\) nanoparticle dispersion is diluted ten times in PBS or in complete cell culture medium. At the concentration of 2 g L\(^{-1}\), it was verified that the scattering arising

### Table 3. Hydrodynamic diameters of polymer coated nanoparticles and respective polymer layer thicknesses obtained in HNO\(_3\), pH 1.5.

| Particles | Polymer coatings |
|-----------|-----------------|
| Bare PEG\(_{1K}\)-Ph | PEG\(_{2K}\)-Ph | PEG\(_{5K}\)-Ph | MPEG\(_{1K}\)-Ph | MPEG\(_{2K}\)-MPh | MPEG\(_{5K}\)-MPh |
| CeO\(_2\)@ | 9.6 | 14.8 | 19.0 | 27.0 | 27.2 | 31.7 | 31.5 |
| TiO\(_2\)@ | 46.2 | – | 57.0 | 65.8 | 62.9 | 68.8 | 65.6 |
| γ-Fe\(_2\)O\(_3\)@ | 29.8 | 35.2 | 40.0 | 48.8 | 49.5 | 55.2 | – |
| Al\(_2\)O\(_3\)@ | 55.3 | 59.1 | 61.0 | 70.0 | 70.5 | 79.5 | 81.8 |
| Shell thickness | – | 2.7 ± 0.6 | 4.5 ± 1.0 | 8.7 ± 1.0 | 8.9 ± 1.0 | 11.8 ± 0.7 | 11.3 ± 1.8 |

Figure 5. a,b) Schematic representation of a nanoparticle coated with phosphonic acid based poly(ethylene glycol) polymers using monofunctionalized and multifunctionalized polymers, respectively. Inset: Possible monodentate, bidentate, or tridentate anchoring modes for phosphonic acid at metal oxide surfaces.
from the particles is much larger than that from the solvent, and that in the cell culture medium the protein contribution was negligible (see Section S5, Supporting Information). The dispersions are then studied as a function of time at days 1, 2, and 7. A final assessment is realized at 60 days after mixing.

Figure 7a–c displays the second-order autocorrelation function of the scattered light, $g^{(2)}(t)$, obtained in cell culture medium for CeO$_2$ coated with the monofunctionalized polymers. At day 1, the data exhibit a quasi-exponential decay associated with a unique relaxation mode. The hydrodynamic diameters are 14.8, 19.0, and 27.0 nm, corresponding to polymer brush thicknesses of 2.6, 4.7, and 8.7 nm (Table 3). At days 2 and 7, CeO$_2$@PEG1K-Ph, CeO$_2$@PEG2K-Ph and CeO$_2$@PEG5K-Ph show signs of aggregation, with autocorrelation function $g^{(2)}(t)$ shifting to the right-hand side and corresponding to the decrease of the diffusion constant. The intensity distributions in the insets also illustrate this augmentation. Note that the shorter the PEGs chains, the faster the kinetics. For the PEG5K-Ph coat, the aggregation is seen only after two months (Section S6, Supporting Information). By contrast, nanoceria coated with the multifunctionalized copolymers have $g^{(2)}(t)$ that remain unchanged over time (Figure 7d–f). The autocorrelation functions exhibit again a unique relaxation mode at days 1, 2, and 7 associated with hydrodynamic diameters of 27.2, 31.7, and 31.5 nm. For these samples, the brush thickness is not altered by the presence of proteins and remains at the values found in DI-water, 8.9, 11.8, and 11.3 nm, respectively. These outcomes suggest that the coated nanoceria are devoid of a protein corona. Experiments performed using PBS under the same conditions show also a mitigated stability for the monofunctionalized polymer coatings and a resilient stability for the multifunctionalized copolymers.

The above results suggest that the colloidal behaviors observed in Figure 7 result from the interplay between different parameters. For the PEG$_{nk}$-Ph coating in PBS, the particle aggregation is attributed to the progressive removal of the PEGylated polymers from the surface. Due to this exchange, the effective ratio $X$ at the particle level increases and beyond the critical value $X_C$ the particles start to destabilize and aggregate (as in Figure 3). In cell medium, the displacement of the PEG$_{nk}$-Ph away from the surface also favors the protein adsorption, which again accelerates the destabilization kinetics. For CeO$_2$@PEG$_{1K}$-Ph, it is also possible that the coating thickness (2.7 nm) is not sufficient to offset the attractive van der Waals forces. By contrast, CeO$_2$ coated with the multiphosphonic acid copolymers is stable both in PBS and complete DMEM for longer times. These results suggest that a multiple anchoring of phosphonic acid groups is more favorable for a resilient copolymer adsorption. We also show that the PEG functionalization by an amino group terminus does not modify this stability property. In conclusion, we have shown that uncoated nanoceria destabilize rapidly in physiological conditions (within less than 1 s), whereas multiphosphonic acid PEG copolymers provide a resilient coating for months. In terms of layer structure, results show that PEG densities in the range $0.2$–$0.5$ nm$^{-2}$ and PEG thickness about 10 nm provide excellent performances.

### 2.4.3. Stabilizing Titanium, Iron, and Aluminum Oxide Dispersions in Biological Environments

The previous stability assays were replicated with the titanium, iron, and aluminum oxide dispersions and with the MPEG$_{2K}$-MPh copolymer. Concentrated dispersions of polymer coated...
metal oxide nanoparticles (20 g L$^{-1}$) were prepared at the ratio $X_C/5$ and pH 1.5, followed by a pH increase and ultracentrifugation. The $X_C$-values determined for each polymer-oxide pair are found at 1.5, 1.5, 1.5, and 3.5 for cerium, titanium, iron, and aluminum nanoparticles. Figure 8a–d compares the time evolution of the autocorrelation functions $g^{(2)}(t)$ for the four metal oxide dispersions in the protein rich cell culture medium, CeO$_2$@MPEG$_{2K}$-MPh, TiO$_2$@MPEG$_{2K}$-MPh, γ-Fe$_2$O$_3$@MPEG$_{2K}$-MPh, and Al$_2$O$_3$@MPEG$_{2K}$-MPh, respectively. The data for PBS can be found in Section S7 (Supporting Information). In each panel, the insets display the corresponding intensity size distributions. Either in DMEM or in PBS, the data show an overall excellent colloidal stability and demonstrate that the phosphonic acid PEG copolymers are efficient coats for nanoparticle substrates of different sizes (7–40 nm) and chemical compositions. An excellent colloidal stability is also obtained with the amine containing terpolymer MPEG$_{2K}$-MPEG$_{a2K}$-MPh (Section S8, Supporting Information), paving the way to further chemical modification. The strategy used for the preparation of polymer coated nanoparticles works well for all particles investigated and is based on mixing bare particle dispersions and polymer solution at acidic pH and mixing volume ratio smaller than a critical value $X_C$, allowing the production of large amounts of dispersions. It is found that the particles coated with monofunctionalized polymers exhibit a mitigated stability over time (<1 week), whereas the multifunctionalized copolymers provide resilient coatings and long-term stability (> months). This multipurpose and multisubstrate coating represents a step toward the understanding and control of nanomaterial interfacial phenomena with biological fluids, cells, and tissues.

3. Conclusion

Cerium, iron, titanium, and aluminum oxide nanoparticles of different morphologies and sizes ranging from 7 to 40 nm are dispersed in a protein enriched cell culture medium and their colloidal stability is investigated by static and dynamic light scattering over time. These particles are coated with six polymers containing poly(ethylene glycol) chains and one or several phosphonic acids as anchoring moieties, among them a terpolymer containing amine functionalized PEG chains suitable for further chemical modification. The strategy used for the preparation of polymer coated nanoparticles works well for all particles investigated and is based on mixing bare particle dispersions and polymer solution at acidic pH and mixing volume ratio smaller than a critical value $X_C$, allowing the production of large amounts of dispersions. It is found that the particles coated with monofunctionalized polymers exhibit a mitigated stability over time (<1 week), whereas the multifunctionalized copolymers provide resilient coatings and long-term stability (> months). This multipurpose and multisubstrate coating represents a step toward the understanding and control of nanomaterial interfacial phenomena with biological fluids, cells, and tissues.

4. Experimental Section

Chemicals: PBS1X, trypsin–EDTA, DMEM, and DMEM without phenol red (called phenol red free DMEM in the following), FBS, and penicillin–streptomycin were purchased from Gibco, Life Technologies. The DMEM composition is shown in Section S9 (Supporting Information). Water was deionized with a Millipore Milli-Q Water system. All products were used without purification.
**Nanoparticles:** Cerium oxide nanoparticles with a nominal diameter of 7.8 nm were synthesized and kindly given by Rhodia (Centre de Recherche d’Aubervilliers, Aubervilliers, France) as a 200 g L⁻¹ aqueous dispersion (pH 1.5). Iron oxide nanoparticles were synthesized according to the Massart method by alkaline coprecipitation of iron(II) and iron(III) salts and oxidation of the magnetite (Fe₃O₄) into maghemite (γ-Fe₂O₃) giving a 20 g L⁻¹ aqueous dispersions at pH 2. Aluminum oxide nanoparticles (Disperal, SASOL) were kindly given by Florent Carn (Laboratoire Matière et Systèmes Complexes, Paris). The powder was dissolved in HNO₃ pH 1.5 and sonicated for 30 min to give a 10 g L⁻¹ aqueous dispersion. Titanium oxide nanoparticles (anatase) with a nominal particle diameter of 15 nm were purchased as a 170 g L⁻¹ TiO₂ suspension in water from Nanostructured & Amorphous Material Inc. (Houston, TX, USA). The dispersion was provided by Serge Stoll from Geneva University.

**Polymers:** The monophosphonic and multiphosphonic acid PEG polymers were synthesized by Specific Polymers, France (http://www.specifypolymers.fr/). Synthesis details can be found in previous reports.[14,39] For the copolymerization, a molar mass dispersity of 1.8 was obtained by size exclusion chromatography on PolyPore column using tetrahydrofuran as eluent and polystyrene standards. The synthesis of the terpolymer MPEG2K-MPEG2K-MPh is described in details in Section S1 (Supporting Information). It was characterized from ¹H NMR and ³¹P NMR using a Bruker Advance 300 spectrometer operating at 300 MHz.

From the molar equivalent of acid groups obtained from NMR and potential determination, the number of phosphonic acids and their pH was adjusted to 8 by addition of ammonium hydroxide. The Rayleigh ratio was measured as a function of the concentration and the polymer molecular masses M_w were determined through the Zimm representation, as detailed in Section S2 (Supporting Information). The M_W^-v_values were 20 300, 22 000, and 29 200 g mol⁻¹ for MPEG 2K-MPh, MPEG2K-MPh, and MPEG2K-MPEG2K-MPh, respectively.

**TEM:** Micrographs were taken with a Tecnai 12 TEM operating at 80 kV equipped with a 1K × 1K Keen View camera. Nanoparticle dispersions were deposited on ultrathin carbon type-A 400 mesh copper grids (Ted Pella, Inc.). Micrographs were analyzed using ImageJ software for 200 particles. The particle size distributions are adjusted using a log-normal function of the form (Figure 2): \[ p(d, D) = \frac{1}{2 \beta \pi (\exp(\frac{\ln^2(D)/\sqrt{2\beta\pi})}{2\beta})} \]

In the previous equation, D is the median diameter and \(\beta\) is related to the size dispersity \(s\) through the relationship \(β(s) = \sqrt{(1+s^2)}\). \(s\) is defined as the ratio between the standard deviation and the average diameter.

For \(β < 0.4\), one has \(β = s\).[14,41]

**Static and Dynamic Light Scattering:** Light scattering measurements were carried out using a NanoZS Zetasizer (Malvern Instruments) at detection angle at 173°. The hydrodynamic diameter \(D_h\) and the zeta potential \(ζ\) were measured. The second-order autocorrelation function was analyzed using the cumulant and CONTIN algorithms to determine the average diffusion coefficient \(D\) of the scatterers. Hydrodynamic diameter \(D_h\) was then calculated according to the Stokes–Einstein relation, \(D_h = k_B T/3πηD\) where \(k_B\) is Boltzmann’s constant, \(T\) the

![Figure 8](image-url)
temperature (298 K), and η_S the solvent viscosity. Measurements were performed in triplicate at 25 °C after an equilibration time of 120 s. Viscosities of the solvents used can be found in Table 4.

Polymer Coated Nanoparticles: Dispersions of CeO_2, γ-Fe_2O_3, TiO_2, and Al_2O_3 nanoparticles were diluted to a concentration of 2 g L^{-1} in HNO_3 (pH 1.5). Polymers solutions of PEG_1K-Ph, PEG_2K-Ph, PEG_5K-Ph, and PEG_3K-Ph were prepared to a weight percent concentration of 2 g L^{-1} in HNO_3 (pH 1.5). All nanoparticle dispersions and polymer solutions were filtered with Millipore filter 0.22 µm. The dispersions were added dropwise to the polymer solutions under magnetic stirring keeping the mixing volume ratio at 1:2. After increasing their pHs to 8 by addition of NH_4OH, the dispersions were centrifuged at 4000 rpm inside Merck centrifuge filters (pore 100 000 g mol^{-1}) and concentrated to 20 g L^{-1}.

Table 4. Parameters used for static and dynamic light scattering measurements.

| Solvent                    | Viscosity η_S [mPa s] | Refractive index |
|----------------------------|-----------------------|-----------------|
| H_2O                       | 0.8872                | 1.333           |
| Phosphate buffer saline (PBS) | 0.9103               | 1.332           |
| Cell culture medium (DMEM + 10% FBS) | 0.9400               | 1.345           |

Nanoparticle Stability: A volume of 100 µL of a 20 g L^{-1} dispersion of polymer coated nanoparticles was poured and homogenized rapidly in 900 µL of PBS or cell culture medium (DMEM) containing 10 vol% fetal bovine serum. Scattered intensity and diameter were measured by light scattering. After mixing, the measurements were monitored at days 1, 2, 7, and 60. Nanoparticles are considered to be stable if their hydrodynamic diameter in a given solvent remains constant as a function of the time and equal to its initial value.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

colloidal stability, functionalization, metal oxide nanoparticles, phosphonic acids, surface coating

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