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Separately doped upconversion-C₆₀ nanoplatform for NIR imaging-guided photodynamic therapy of cancer cells†

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A highly efficient upconversion-C₆₀ nanoplatform was demonstrated for NIR imaging-guided photodynamic therapy of cancer.

Lanthanide ion (Ln³⁺, such as Er³⁺, Tm³⁺, Ho³⁺)-doped upconversion nanoparticles (UCNPs) are emerging as a new generation of multimodal bioprobes, and have attracted a large interest for a variety of biological applications.1,2 The developed luminescent UCNP based photosensitizing nanoplatforms,3 which can be excited with NIR light (~980 nm) falling in the biological window of tissues and generating multicolour emission in the visible spectral region,4 have made image-guided photodynamic therapy (PDT) possible. O₂ is generated in these cases through photosensitizers (PSs) that are activated by energy transfer from UCNPs upon NIR excitation. However, most UCNP-based PDT applications have been limited by the relatively low O₂ production yield. Several strategies have been employed to improve the performance of such nanoplatforms, e.g. developing a covalent strategy to shorten the energy transfer distance,5 using a combination of two PSs for optimally utilizing the upconversion luminescence.6 However, the majority of the currently used PSs are aromatic molecules that have negative side effects and do not have a very high O₂ yield. Searching for more efficient therapeutic agents has led numerous groups to investigate the potential of fullerene derivatives as novel PDT drugs.7 Such molecules are particularly attractive because of their broad absorption spectra,8 lack of dark toxicity and high quantum yield to form reactive species (100% based on generation of O₂).9,10

In this work, we present a NIR-triggered NIR imaging-guided PDT nanoplatform based on multiplexed Förster resonance energy transfer (FRET) in which multicolour UCNPs are used as donors and monomalonic fullerene (C₆₀MA) as an acceptor. They are an ideal donor–acceptor pair. Upon 980 nm CW light excitation, upconversion luminescence (UCL) of a NaYF₄:Yb³⁺, Er³⁺/NaYF₄:Yb³⁺, Tm³⁺ separately doped nanostructure appears simultaneously around 450, 475, 540, 650 and 808 nm. All of these bands, except the 808 nm band, contribute to the transfer of excitation energy to C₆₀MA due to the broad absorption band of the latter and thus trigger PDT. At the same time, the 808 nm emission can be used for high-contrast NIR luminescence imaging as illustrated in Fig. 1. In vitro experiments on cancer cells verify the efficient photodynamic effects of the nanoplatform. As the first demonstration of a multifunctional UCNP–fullerene nanoplatform, this result offers a new possibility in exploring highly stable and efficient nanoplatforms suitable for NIR imaging-guided therapy of cancers.

In order to generate strong multicolour upconversion luminescence, oleylamine-coated NaYF₄:Yb³⁺, Er³⁺/NaYF₄:Yb³⁺, Tm³⁺ separately doped UCNPs were synthesized following a previously reported protocol (see ESI†). The composition, phase purity and morphology of these nanoparticles were examined by TEM and XRD as shown in Fig. 2a (see also Fig. S1–S3, ESI†). From the TEM images it could be concluded that the UCNPs have a good monodispersity with an average diameter of about 45 nm. We employed a strategy of separately doping core and shell with Er³⁺ and Tm³⁺ instead of homogeneous co-doping to achieve strong multicolour upconversion luminescence (Fig. S4, ESI†).11 Hydrophilic NH₂-functionalized UCNPs were prepared following a ligand exchange process using poly(allylamine) as a surface-coating agent. Phase transfer caused negligible effect on the UCL spectrum (Fig. S5, ESI†). To optimize the energy transfer distance and ensure that the majority of C₆₀MA

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molecules were firmly linked to UCNPs, a covalent conjugation strategy was followed that involved a crosslinking reaction between the amino group of the UCNPs and the carboxyl group of C60MA. For the sake of solving the low dispersity of fullerenes in biologically relevant media, PEG-succinimidyl carbonate (PEG-SC), which has a good compatibility with biological systems and can reduce the undesired toxicity of nanoparticles, was used to stabilize the nanocomposites in various biological solvents (Fig. 2c). The conjugation with C60MA did not alter the size and morphology of the UCNPs (Fig. 2b). Fig. 2d shows that the effective hydrodynamic diameter distributions of the UCNPs before and after conjugation were centered at 46 nm and 64 nm, respectively, indicating successful functionalization. Covalent coupling between UCNPs and C60MA was confirmed from FTIR absorption spectra shown in Fig. S6 (ESI†). After conjugation with UCNPs, the peak at 1717 cm⁻¹ (C═O stretching mode of the carboxyl group on C60MA) disappeared and two new peaks associated with the C═O stretching and N-H bending modes of a secondary amide appeared at 1648 and 1556 cm⁻¹, respectively. The observation of a dark brown precipitate and a nearly colourless supernatant after centrifugation—while no precipitate or colour change was noticed in the bare C60MA sample—further confirmed the bonding of C60MA (Fig. S7, ESI†). The C60MA loading capacity was characterized using UV-VIS spectroscopy. The absorption of UCNPs–C60MA composites became larger with increasing amounts of C60MA and saturated at 10.5% (w/w) at C60MA concentrations above 300 μL (0.25 mg mL⁻¹) (Fig. S8, ESI†).

The present multifunctional nanoplatform was constructed guided by the fact that the broad absorption spectrum of C60MA overlaps well with the multicolour upconversion luminescence bands (450, 475, 540, 650 nm) of NaYF₄:Yb⁺⁺,Er⁺⁺/NaYF₄:Yb⁺⁺,Tm⁺⁺ UCNP–C60MA nanocomposites dispersed in various biological media (SPSS: stroke-physiological saline solution). (d) Hydrodynamic diameter distributions of the UCNPs before and after surface functionalization.

45% at 650 nm. We attribute the high energy transfer efficiency partly to the robust covalent binding between C60MA and UCNPs. The energy transfer process was further verified by the temporal behavior of UCL of both UCNPs and UCNP–C60MA composites recorded at 450, 475, 540 and 650 nm (Fig. S9, ESI†). The significant shortening of the upconversion luminescence kinetics that was observed in these experiments is in line with the strong energy transfer concluded from the analysis of the steady-state UC luminescence quenching.

Another aspect entering the design of our UCNP–C60MA nanoplatform is the high ¹O₂ production yield of C60 derivatives, which is even higher than those of traditional photosensitizers such as rose bengal, methylene blue and eosin yellowish. In order to assess the capability of our UCNP–C60MA nanoplatform to generate ¹O₂, we employed the chemiluminescence of a fluoresceinyl Cypridina luciferin analogue (FCLA). FCLA can be oxidized by ¹O₂, resulting in an increase of its fluorescence at around 524 nm, and can thus be used as a ¹O₂ detector. Fig. S11a (ESI†) illustrates the FCLA fluorescence intensity variation in the presence of UCNP–C60MA nanocomposites. Without the nanocomposites or 980 nm light illumination, the FCLA luminescence showed a negligible change with time (Fig. S10, ESI†). When illuminated with 980 nm light, the fluorescence of FCLA in UCNP–C60MA solutions was boosted, indicating efficient generation of ¹O₂. To further illustrate that our nanoplatform is indeed superior, three other energy transfer models, i.e., (i) UCNPs (Yb, Er)–C60MA, (ii) UCNPs (Yb, Tm)–C60MA and (iii) UCNPs (Yb, Er, Tm)–rose bengal were constructed. Fluorescence spectra of FCLA, recorded as a function of exposure time under 980 nm irradiation are shown in Fig. S11 (ESI†) for these three samples and the UCNP (Yb, Er, Tm)–C60MA samples. The corresponding fluorescence intensity changes are depicted in Fig. 3b. Since the slopes of the curves represent the efficiency of singlet oxygen generation, it is clear that the designed UCNP (Yb, Er, Tm)–C60MA nanocomposites are indeed a highly efficient nanoplatform for ¹O₂ generation and potentially for NIR light triggered photodynamic therapy of cancer.

We studied the cellular uptake of UCNP–C60MA by HeLa cells. To this purpose, the targeting molecule, folic acid (FA), was covalently linked to UCNP–C60MA. Fig. 4a shows the target staining of the UCNP–C60MA/FA nanoplatform in HeLa cells and the control result using human alveolar adenocarcinoma (A549) cells. The upconversion luminescence was collected at...
808 nm, a wavelength that lies in the biological window (700–1100 nm) and enables high-contrast optical imaging. The nanocomposites were mainly located within the cells (Fig. 4a, left), illustrating the specific targeting of the nanoplatform. The absence of autofluorescence confirmed that the UCNP- C$_{60}$MA/FA platform can be used for high-contrast luminescence imaging of cells in vitro. When the folate receptors on the cancer cell membranes were saturated by free folic acid before incubating with the nanoplatform, just a few UCNP- C$_{60}$MA/FA nanoconjugates were stained in the cancer cells (Fig. 4a, middle), which might be due to the nonspecific adsorption of UCNPs. Furthermore, there was no significant morphology change of the cancer cells in the bright field image (Fig. 4a, top), suggesting a good biocompatibility of the nanoplatform. To further verify the specificity of the UCNP–C$_{60}$MA/FA composites, A549 cells, which are poor in expressing the folate receptor, were used for a negative control (Fig. 4a, right). Scale bar, 50 µm.

(a) Specificity of the UCNP–C$_{60}$MA nanoconjugates. HeLa cells were cultured in folate-free medium (left, positive) and in folate-supplemented medium (middle, negative). A negative control was also performed with A549 cells (right). Scale bar, 50 µm. (b) Cell viability of HeLa cells treated with UCNP–C$_{60}$MA of different concentration with or without 980 nm exposure. (c and d) Photographs of purple formazan dissolved in DMSO, indicating the viability of cells treated with nanoconjugates without (c) and with (d) 980 nm exposure.

Notes and references