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# Recent Advances in Near Infrared Upconverting Nanomaterials for Targeted Photodynamic Therapy of Cancer

Carla Arnau del Valle,<sup>a</sup> Thomas Hirsch<sup>b</sup> and María J. Marín<sup>\*a</sup>

<sup>a</sup>School of Chemistry, University of East Anglia, Norwich Research Park, Norwich, NR4 7TJ, UK

<sup>b</sup>Institute of Analytical Chemistry, Chemo- and Biosensors, University of Regensburg, 93040 Regensburg, Germany.

\*Corresponding author, please direct correspondence to [m.marin-altaba@uea.ac.uk](mailto:m.marin-altaba@uea.ac.uk).

## Abstract

Photodynamic therapy (PDT) is a well-established treatment of cancer that uses the toxic reactive oxygen species, including singlet oxygen ( $^1\text{O}_2$ ), generated by photosensitiser drugs following irradiation of a specific wavelength to destroy the cancerous cells and tumours. Visible light is commonly used as the excitation source in PDT which are not ideal for cancer treatment due to their reduced tissue penetration, and thus inefficiency to treat deep-lying tumours. Additionally, these wavelengths exhibit elevated autofluorescence background from the biological tissues which hinders optical biomedical imaging. An alternative to UV-Vis irradiation is the use of near infrared (NIR) excitation for PDT. This can be achieved using upconverting nanoparticles (UCNPs) functionalised with photosensitiser drugs where UCNPs can be used as an indirect excitation source for the activation of PS drugs yielding to the production of singlet  $^1\text{O}_2$  following NIR excitation. The use of nanoparticles for PDT is also beneficial due to their tumour targeting capability, either passively *via* the enhanced permeability and retention (EPR) effect or actively *via* stimuli-responsive targeting and ligand-mediated targeting (*ie.* using recognition units that can bind specific receptors only present or overexpressed on tumour cells). Here, we review recent advances in near infrared upconverting nanomaterials for PDT of cancer with a clear distinction between those reported nanoparticles that could potentially target the tumour due to accumulation *via* the EPR effect (passive targeting) and nanoparticle-based systems that contain targeting agents with the aim of actively target the tumour *via* a molecular recognition process.

**Keywords:** photodynamic therapy; cancer; upconverting nanoparticles; targeting agents; near infrared

## 1. Introduction

Photodynamic therapy (PDT) is a minimally invasive treatment that combines the use of light, oxygen and photosensitiser (PS) drugs to generate reactive oxygen species (ROS),<sup>1,2</sup> being singlet oxygen ( $^1\text{O}_2$ ) the most common cytotoxic oxygen-based molecular species.<sup>3</sup> These cytotoxic species are then able to destroy tumours by oxidising biological substrates.<sup>3</sup> PS drugs are photoactive molecules able to produce  $^1\text{O}_2$  or other ROS after being excited with light of a specific wavelength, most commonly visible or ultraviolet light.<sup>2</sup> Excited PS can lose their energy *via* fluorescence emission and/or heat;<sup>4</sup> or following a non-radiative pathway, intersystem crossing, forming a long-lived excited triplet state. From the PS excited triplet state, the energy may decay emitting light or can undergo two different types of reactions yielding radicals and ROS.<sup>5</sup> Type I reaction is based on an electron or hydrogen transfer and produce radical molecules such as hydroxyl radical ( $\text{HO}^\bullet$ ). In contrast, type II reaction involves an energy transfer from the PS excited triplet state to the ground triplet state of molecular oxygen ( $\text{O}_2$ ) leading the formation of  $^1\text{O}_2$ .<sup>4,5</sup>

Apoptosis, necrosis and autophagy are the main cell death pathways that occur by immediate consequence of PDT.<sup>6,7</sup> Factors such as cell type, light dosage, photosensitiser intracellular localisation and concentration define the mechanism of cell death induced by PDT.<sup>8</sup> For example, if the PS accumulates in the mitochondria or the endoplasmic reticulum (ER), apoptosis is the main path for cell death.<sup>7,8</sup> If, by contrast, the PS is targeted either in the plasma membrane or lysosomes, the cells will die *via* necrosis.<sup>5</sup> An elevated concentration of PS drug or light dose has also been related to a necrotic cell death.<sup>7</sup> Mitochondrial damage yielding to cytochrome c release and formation of the protein apoptosome has been reported due to the acute stress response produced by PDT.<sup>9</sup>

PDT is currently used to treat different types of early-stage cancers including skin,<sup>10</sup> oesophageal,<sup>11</sup> mouth<sup>12</sup> and lung<sup>13</sup> cancer. One of the major advantages of PDT compared to conventional cancer treatments, such as chemotherapy and radiotherapy, is that it is a non-invasive, localised treatment and thus, its side effects are considerably reduced. The combination of PDT with other anticancer therapies has shown synergistic effects.<sup>14-16</sup> For example, PDT has been combined with low doses of X-ray radiation for the treatment of breast cancer cells (MCF-7) in *in vitro* experiments resulting more effective than each treatment alone.<sup>16</sup> The combination of PDT with chemotherapy has been studied in, for example, metastatic melanoma resulting in a higher decrease of metastatic melanoma tumorigenic cells than the decrease observed for the individual treatments.<sup>17</sup>

Phthalocyanines, porphyrins, naphthalocyanines, chlorins, bacteriochlorins, texaphyrins, among others, are examples of organic PS drugs commonly reported in the literature for PDT of cancer.<sup>3,18</sup> Inorganic PS, based on nanoparticles of semiconductor metal oxides (TiO<sub>2</sub> and ZnO) have also been successfully employed for PDT of cancer.<sup>19,20</sup> The effectiveness of PDT is dependent on the chemical properties, photostability, physiological stability, absorption coefficient and efficiency of <sup>1</sup>O<sub>2</sub> production of the PS drugs.<sup>1</sup> Despite the large number of examples of PS drugs reported in the literature, only a few of these are currently approved by the Food and Drug Administration (FDA) and the European Medicines Agency (EMA) for clinical use,<sup>21,22</sup> most likely due to the limitations of the reported PS drugs. The majority of them are hydrophobic molecules, thus easily internalised by cells but with restricted transportation through the body.<sup>1,23</sup> Furthermore, most PS exhibit non-specific biodistribution,<sup>24</sup> leading to severe side effects; and their activation to produce <sup>1</sup>O<sub>2</sub> requires of UV-Vis light,<sup>25</sup> which are not ideal for cancer treatment due to their reduced tissue penetration, and thus inefficiency to treat deep-lying tumours.<sup>26</sup> It is important to mention that PDT is more effectively achieved when the PSs are close enough to the tumour sites due to the short half-time (0.04 μs) and the high reactivity of <sup>1</sup>O<sub>2</sub> after being formed, thus resulting in a ratio of action of *ca.* 0.02 μm.<sup>18</sup> Additionally, in the UV-Vis range, there is an elevated autofluorescence background from the biological tissues which hinders optical biomedical imaging. With the aim of overcoming the limitations of UV-Vis excitation, and as it will be detailed later in this review, the use of near infrared (NIR) excitation for PDT has attracted extensive interest in the past decades since it shows minimal light absorption and scattering by biological tissue, thus reducing the photodamage and enabling deeper tissue penetration.<sup>26,27</sup>

The use of nanoparticles as delivery systems of PS drugs for PDT has been extensively investigated offering many advantages over molecular PS and overcoming some of the listed drawbacks.<sup>28</sup> Incorporation of PS onto nanoparticles can increase the water-solubility of the drugs, elongating their blood circulation time and thus improving their cellular/tumour uptake, pharmacokinetics and biodistribution; and can protect the PS against, for example, enzymatic degradation.<sup>29</sup> Additionally, nanoparticles can pass through the leaky blood vessels of tumour sites and accumulate in the malign tissues in a process known as the enhanced permeability and retention (EPR) effect; yielding a passive tumour-targeting.<sup>30-32</sup> The small size, tailored surface and multi-functionality characteristics of nanoparticles lead furthermore to high drug-loading capacity improving the photostability of the PS and reducing the photobleaching effect normally observed in molecular PS.<sup>32</sup> Examples of the most commonly used carrier nanoparticles for PDT include polymeric nanoparticles,<sup>33</sup> liposomes,<sup>34</sup> silica nanoparticles<sup>35</sup> and metallic nanoparticles

(such as gold,<sup>36-39</sup> silver<sup>40</sup> and iron oxide<sup>41,42</sup>). For example, Wang *et al.* functionalised gold nanostars with Chlorin e6 (Ce6) and reported higher PDT efficiency both in *in vitro* and *in vivo* when using the nanostars compared to free Ce6.<sup>43</sup> The incorporation of PS drugs onto a nanoplatform has been shown to improve the biocompatibility of hydrophobic drugs.<sup>37,44</sup> For instance, Lee *et al.* developed chitosan nanoparticles loaded with Ce6 for tumour treatment via PDT.<sup>44</sup> Although the  $^1\text{O}_2$  generation was slower for the Ce6 loaded nanoparticles than for the free drug, the Ce6 loaded chitosan nanoparticles were biocompatible showing prolonged blood circulation times and enhanced tumour targeting compared to the free drug.<sup>44</sup> Nanoparticles have also been reported to increase the PDT effect of some hydrophobic and hydrophilic photosensitiser drugs. For example, Penon *et al.* reported two different functionalised iron oxide nanoparticles containing either hydrophobic or hydrophilic porphyrin derivative ligands.<sup>41</sup> Upon irradiation using a blue light source (400 – 500 nm) both functionalised nanoparticles showed higher levels of  $^1\text{O}_2$  production than the corresponding free porphyrin-based ligands.<sup>41</sup> Alea-Reyes *et al.* studied different types of gold-based vehicles including nanoparticles, nanorods and microparticles, as carriers of porphyrin derivatives for PDT.<sup>45</sup> The authors reported higher  $^1\text{O}_2$  production when using gold nanoparticles and, when used for PDT in HeLa cervical cancer cells, the functionalised gold nanoparticles proved to be more efficient than the corresponding free porphyrin.<sup>45</sup> An example of polymeric nanoparticles for encapsulation of PS drugs was published by Brandhonneur *et al.* in which poly(D,L-lactide-co-glycolide) (PLGA) nanoparticles were used for the loading of a molybdenum cluster as PS drug leading to encapsulation efficiency higher than 80%.<sup>46</sup> The loaded PLGA nanoparticles were used for the PDT treatment of ovarian cancer cells (A2780 cell line). Upon irradiation at 365 nm, the molybdenum cluster loaded nanoparticles showed a higher cellular viability decrease (*ca.* 20% higher) compared to the free cluster.<sup>46</sup> All of these examples prove that nanoparticles are promising carriers of PS drugs for PDT of cancer, overcoming some of the limitations of the free PS drugs and enhancing the efficiency of the treatment. However, one of the persistent problems when using nanoparticles as drug delivery systems is their clearance by the reticuloendothelial system (RES)<sup>47</sup> which can be overcome by covering them with biocompatible ligands such as proteins, liposomes or polyethylene glycol (PEG); being the incorporation of PEG the most common approach to enhance the water dispersibility of the nanosystems, elongating their circulation time in blood and reducing their RES uptake.<sup>47</sup> Camerin *et al.* reported PEGylated gold nanoparticles containing a hydrophobic Zn(II)-phthalocyanine derivative as PS for *in vivo* PDT of amelanotic melanoma that resulted in 40% of the mice completely recovered following treatment and no tumour regrowth following PDT.<sup>36</sup>

Another advantage of using nanoparticles for the delivery of PS drugs is that they can be further functionalised with specific targeting molecules to ensure the targeted delivery to the tumour side and thus, the targeted treatment of cancer *via* PDT. Targeting agents such as antibodies, folic acid, transferrin, peptides, aptamers, and carbohydrates, amongst others, are frequently used. For example, Penon *et al.* reported a water-soluble gold nanosystem functionalised with a hydrophobic porphyrin derivative and the antibody anti-erbB2 conjugated to PEG ligands to specifically target the erbB2 receptors expressed in SK-BR-3 breast cancer cells.<sup>48</sup> High cellular uptake of the antibody-porphyrin-functionalised nanoparticles was observed confirming the antibody-antigen interactions; and PDT induced cell death was achieved following irradiation using a blue light source.<sup>48</sup>

In all the aforementioned examples, the nanoparticles are not directly involved in the photosensitisation process but act as passive carriers of the PS drugs. By contrast, nanoparticles such as quantum dots (QDs)<sup>49,50</sup> and upconverting nanoparticles (UCNPs)<sup>51-53</sup> have been used not only as carriers of PS drugs but as active participants in the PS excitation for PDT of cancer.<sup>27,49,54,55</sup> Although QDs are excellent candidates in PDT of cancer, this review paper will focus its attention on the use of UCNPs for PDT due to the advantages that indirect NIR excitation of PS drugs through UCNPs present.

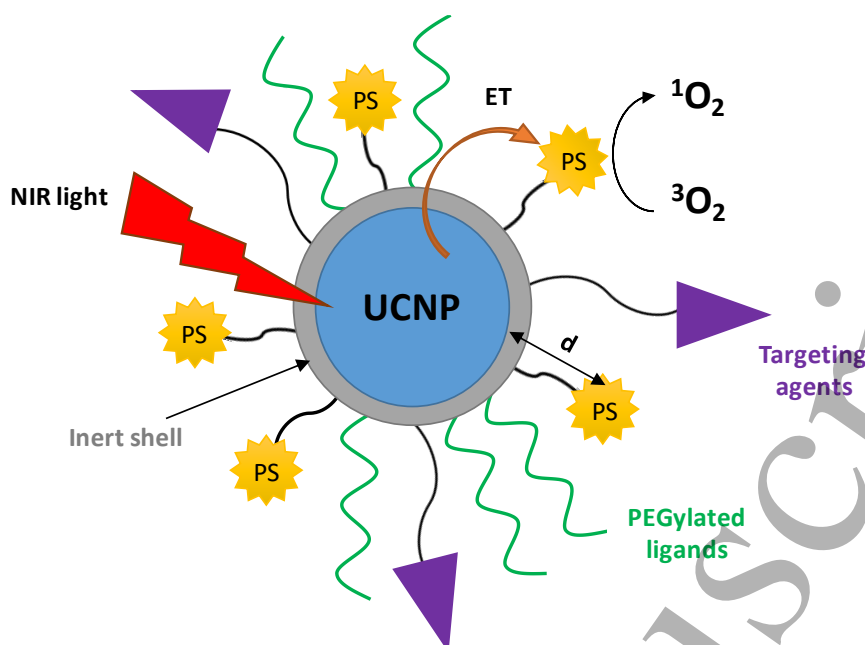
**2. UCNPs and their role in PDT**

UCNPs are nanomaterials capable of converting low energy excitation (NIR) light into high energy emitting photons through an anti-Stokes process which can be separated from other scattered light.<sup>56,57</sup> UCNPs consist of a crystalline host lattice (hexagonal NaYF<sub>4</sub> being the most efficient to date for green and blue upconversion<sup>56</sup>) containing trivalent lanthanide dopants that act as sensitisers and emitters of energy yielding the upconversion energy transfer process to occur.<sup>56,58</sup> The sensitiser lanthanide ions (ytterbium ions (Yb<sup>3+</sup>) typically used for 980 nm excitation) can absorb NIR light and transfer two or more photons to the emitting lanthanide ions (the most common are erbium (Er<sup>3+</sup>), holmium (Ho<sup>3+</sup>) and thulium (Tm<sup>3+</sup>)).<sup>56,59</sup> Cubic or hexagonal NaYF<sub>4</sub> nanoparticles doped with Yb<sup>3+</sup> and Er<sup>3+</sup> (NaYF<sub>4</sub> (20%Yb, 2%Er)) result in green or red emissions (522, 541 and 655 nm peaks),<sup>60</sup> whereas the emission peaks for NaYF<sub>4</sub> (25%Yb<sup>3+</sup>, 0.3%Tm<sup>3+</sup>) nanocrystal are in the blue spectral region (450 nm and 475 nm).<sup>60</sup> Lanthanide-doped upconverting NaYF<sub>4</sub>:Yb<sup>3+</sup>,Er<sup>3+</sup> nanoparticles are commonly synthesised *via* thermal decomposition of trifluoroacetates in solvent mixtures of oleic acid and octadecene.<sup>56,61</sup> UCNPs can be also synthesised following other procedures including co-precipitation and hydrothermal

methods.<sup>62</sup> Importantly, the size, shape, crystal phase and morphology of the nanoparticles can be controlled during the synthesis taking into account parameters such as temperature, dopant concentrations and reaction time resulting in narrow particle size distribution and high reproducibility.<sup>61,62</sup>

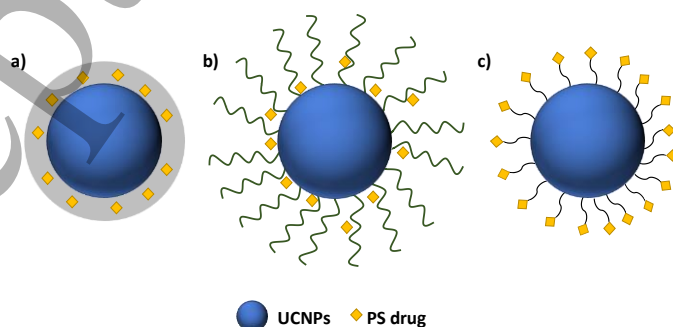
The interest in using UCNPs is increasing in fields such as material science, bioimaging and biomedicine due to their intrinsic upconversion luminescent properties.<sup>63-69</sup> They present advantages compared to downconversion systems (quantum dots and fluorescent organic dyes) such as high signal-to-noise ratio, large anti-stokes shifts, non-autofluorescent background, narrow absorption and emission peaks, long lifetimes, high quantum yields and superior photostability, and they have shown to have low toxicity.<sup>70,71</sup> These lanthanide-doped nanoparticles are chemically stable and in general, less toxic than QDs.<sup>71</sup> In PDT, UCNPs have attracted considerable attention since the first proof-of-concept studies were reported by Zhang *et al.* in 2007.<sup>72,73</sup> UCNPs overcome the drawback of visible excitation and other limitations of molecular PS including hydrophobicity and non-specificity. In systems consisting of UCNPs functionalised with PS drugs, UCNPs have been used as an indirect excitation source for the activation of PS drugs yielding to the production of singlet  $^1\text{O}_2$ . The energy transfer between the UCNPs and the PS can take place by radiative (*i.e.* direct absorption of the emitted luminescence photons by the PS drugs) or non-radiative (*i.e.* Förster resonance energy transfer (FRET) mechanism) transitions.<sup>74</sup>

When designing UCNPs functionalised with PS drugs for PDT of cancer, there are several features to be considered (**Figure 1**): (1) the spectral overlap between the light emitted by the UCNPs and the maximum absorption wavelength of the PS; (2) the distance between the inner core of the UCNP and the PS – which is key for an efficient energy transfer; (3) the loading of the PS – which plays an important role in the efficiency of PDT (an excess of PS could inversely affect the PDT effect);<sup>55</sup> (4) the thickness of the shell, when a core-shell strategy is chosen, since the distance between the PS drug and the luminescence core affects the energy transfer process that activates the PS and thus, the PDT efficiency; (5) the biocompatibility of the nanosystem – which may be increased by introducing ligands such as PEG derivatives; and (6) the targeted PDT strategies – which can be introduced by further functionalisation of PS-loaded UCNPs with targeting agents, thus increasing the specificity and the selectivity of the treatment.



**Figure 1.** Schematic representation of a core-shell UCNP functionalised with PS drugs, PEGylated ligands and targeting agents. NIR irradiation of UCNP generates upconversion luminescence emission which activates the PS drug *via* energy transfer (ET) to produce singlet oxygen ( $^1\text{O}_2$ ) from molecular oxygen ( $^3\text{O}_2$ ).

The surface of UCNP can be modified with ligand relevant for bioimaging, diagnostics or/and therapeutics *via* ligand exchange, ligand oxidation reaction, host-guest interactions, layer-by-layer self-assembly method, silica encapsulation or coating with amphiphilic polymers.<sup>75</sup> Loading of PS on the surface of the nanoparticles to obtain an effective electronic excitation energy transfer between the UCNP and the drug can be achieved following: 1) a non-covalent loading of the PS on the surface of the UCNP using a silica shell coating (**Figure 2a**) or a physical adsorption which is achieved by using for example amphiphilic polymers (**Figure 2b**);<sup>55,72,76,77</sup> or 2) a covalent chemical linkage where PS drugs are anchored to the surface of the nanoparticle (**Figure 2c**).<sup>51,78,79</sup>

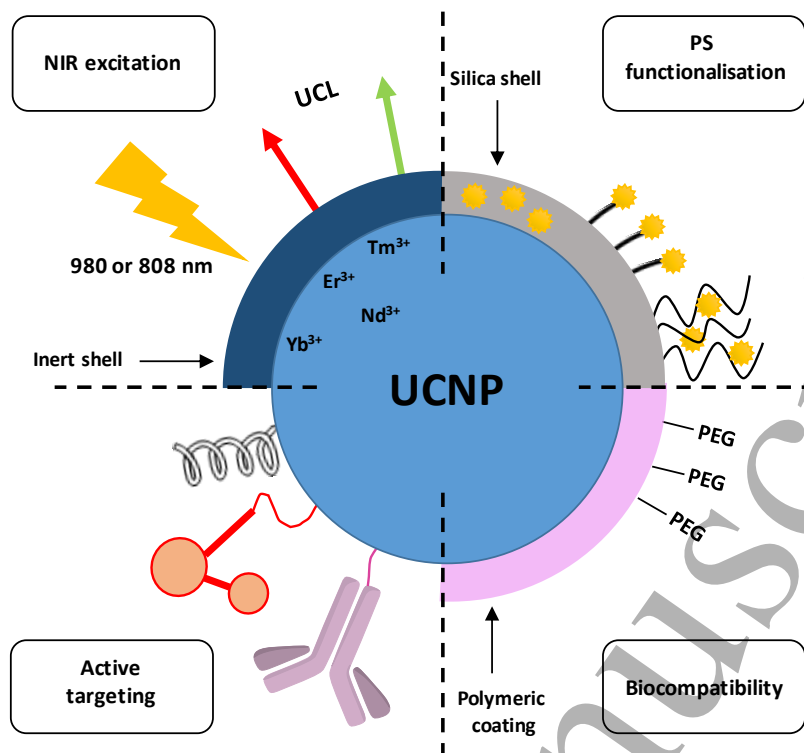


**Figure 2.** Schematic representation of functionalised UCNP with PS through **a)** silica encapsulation, **b)** physical adsorption and **c)** covalent chemical bonding strategies.



Ce6 ( $A_{\max}$  at *ca.* 400 nm), zinc phthalocyanine (ZnPc) ( $A_{\max}$  at *ca.* 660 nm), merocyanine 540 (MC540) ( $A_{\max}$  at *ca.* 540 nm), Rose Bengal (RB) ( $A_{\max}$  at *ca.* 550 nm) and methylene blue (MB) ( $A_{\max}$  at *ca.* 650 nm) are PS drugs commonly used for the functionalisation of UCNPs since their absorption spectrum overlaps with the luminescence emission intensities of commonly used UCNPs. For instance, NaYF<sub>4</sub>:Yb,Er nanoparticles exhibit two main luminescence emission wavelengths in the green (522 and 541 nm) and the red (655 nm) regions. This can lead to an effective energy transfer between the NaYF<sub>4</sub>:Yb,Er UCNPs and the aforementioned PS drugs and to successful NIR-induced PDT of cancer. Although NaYF<sub>4</sub>:Yb,Er are the most commonly used UCNPs for PDT due to their high upconversion efficiency, UCNPs doped with Tm<sup>3+</sup> have also been reported resulting in luminescence emissions in the blue region (450 and 475 nm) that overlap with PS such as riboflavin, fullerenes, ZnO or TiO<sub>2</sub>.

The first example of PS-loaded UCNPs for PDT of cancer was reported by Zhang *et al.* in 2007.<sup>72</sup> In this work, the PS M-540 was encapsulated onto silica coated NaYF<sub>4</sub>:Yb<sup>3+</sup>,Er<sup>3+</sup> nanoparticles.<sup>72</sup> Upon irradiation at 974 nm, the UCNPs emitted light at two wavelengths, 537 and 635 nm, with the former effectively overlapping the absorption spectrum of M-540. The M-540-UCNPs were further functionalised with a mouse monoclonal antibody (anti-MUC1/episialin) to specifically target the MUC1 receptors overexpressed in MCF-7/AZ breast cancer cells. Phototoxicity studies performed for MCF-7/AZ cells incubated with the antibody-M-540-UCNPs and irradiated at 974 nm confirmed the effective PDT induced cell death.<sup>72</sup> Taking this first reported example of targeted agent-PS-UCNPs system as inspiration, a large number of articles can be found in the literature describing the use of PS-UCNPs for the targeted delivery of photosensitiser drugs for PDT of cancer. This review paper provides an in-depth analysis of the most relevant articles reporting the use of UCNPs for targeted-PDT. The review will differentiate between those reported nanoparticles that could potentially target the tumour due to accumulation *via* the EPR effect (passive targeting) and nanoparticle-based systems that contain targeting agents with the aim of actively target the tumour *via* a molecular recognition processes<sup>80</sup> (active targeting). An schematic representation of the engineering possibilities when designing UCNPs for PDT is given in **Figure 3** and examples of the different approaches will be given in the forthcoming sections of this review paper.



**Figure 3.** Schematic representation of an UCNP and its engineering possibilities: NIR excitable nanoparticle ( $\lambda_{exc} = 980$  or 808 nm) capped with an inert shell, different functionalisation strategies for the incorporation of the PS on the surface of the UCNP, functionalisation with active targeting agents and further coating to enhance the biocompatibility of the nanosystem.

### 3. Targeted photodynamic therapy using UCNPs

#### 3.1. Passive targeting

The passive targeting of tumour sites using nanoparticles has been extensively exploited for bioimaging and therapeutic applications, including PDT.<sup>29,54,81,82</sup> The accumulation of the nanoparticles in the solid tumour enhances the specificity of the drug and reduces the side effects on the healthy tissue.<sup>37,43,44</sup>

A vast number of nanosystems based on PS-UCNPs have been reported to induce cell death *via* NIR triggered PDT. Since the first reported silica shell encapsulation of M-540 PS drug on the surface of the UCNPs by Zhang *et al.*,<sup>72</sup> a plethora of non-covalent strategies for the incorporation of PS on UCNPs have been described.<sup>68,76,77,83-88</sup> PS drugs can be encapsulated onto silica shells surrounding the UCNPs using a mesoporous silica layer or a dense silica shell. The mesoporous silica layer provides a larger surface area than the dense silica coating allowing for higher PS loading, thus this has become the preferred approach on the preparation of silica

layered-PS-UCNPs. For example, Zhang and co-workers reported core-shell  $\text{NaYF}_4:\text{Yb,Er}@$ silica nanoparticles functionalised with a mesoporous silica layer loaded with zinc (II) phthalocyanine (ZnPc) (0.1 wt%).<sup>76</sup> ZnPc was not released from the silica following soaking of the particles in deionised water, phosphate buffer saline or RPMI 1640 cell culture medium for one hour. Leaching was however observed when the particles were soaked in ethanol for one hour. The nanoparticles presented an average diameter size of *ca.* 35 nm width and 60 nm length; with a *ca.* 10 nm thickness silica shell and a *ca.* 11 nm mesoporous silica layer. Their red emission band (*ca.* 660 nm) overlapped the absorption peak of the ZnPc (670 nm) allowing the activation of ZnPc to generate  $^1\text{O}_2$  upon irradiation at 980 nm as confirmed measuring the photobleaching of the singlet oxygen probe ABDA (9,10-anthracenediyl-bis(methylene) dimalononic acid) following the endoperoxide formation.<sup>76</sup> However, lifetime measurements to confirm the FRET process occurring between the UCNPs and the PS drug were not reported. The cellular uptake of the nanoparticles in MB49 bladder cancer cells following 24 h incubation was confirmed using confocal fluorescence microscopy with excitation at 980 nm ( $\Delta\lambda_{\text{em}} = 525 \pm 50$  nm and  $640 \pm 90$  nm). Cell viability studies (3-(4,5-dimethylthiazol-2-yl)-2, 5-diphenyl tetrazoliumbromide, MTT assay) show lower viability for cells incubated with the ZnPc-UCNPs and irradiated at 980 nm (output power of 500 mW, 5 min) than for cells treated with UCNPs without ZnPc and treated under the same conditions. The cellular uptake of the ZnPc-UCNPs was also investigated measuring the intracellular concentration of yttrium over time using inductively coupled plasma-atomic emission spectroscopy (ICP-AES) (maximum  $\text{Y}^{3+}$  concentration after 6 h of incubation).<sup>77</sup> In this work, the intracellular production of ROS was confirmed in MB49 cells incubated with ZnPc-UCNPs ( $100 \mu\text{g mL}^{-1}$ ) and irradiated at 980 nm (500 mW) using a ROS fluorescent probe (5-(and-6)-carboxy-2',7'-dichlorodihydrofluorescein diacetate) that emits green fluorescence following oxidation in the presence of ROS.<sup>77</sup> The PDT efficiency of the ZnPc-UCNPs was investigated, using MTT assay, 48 h following NIR irradiation. A drop in cell viability was observed for MB49 cells treated with ZnPc-UCNPs and irradiated for 5 min at 980 nm compared to the corresponding controls (without irradiation and without ZnPc on the UCNPs) – although cell death was observed without irradiation at high dose nanoparticle concentration.<sup>77</sup> The photodynamic effect of the ZnPc-UCNPs in MB49 cell following 980 nm irradiation was further confirmed by changes in the nuclear morphology – by DAPI staining; intranucleosomal DNA fragmentation – by DNA-ladder agarose gel electrophoresis; cytochrome *c* release – by fluorescence staining of cytochrome *c*; and inhibition of the expression of prostate specific antigen (PSA) – by ELISA.

With the aim of increasing the loading capacity of the PS drug on to the mesoporous silica layer and to avoid the PS leaching, a new strategy was proposed by Han *et al.* in which the authors designed an electrostatic-driven PS loading.<sup>83,84</sup> NaYF<sub>4</sub>:Yb,Er,Nd nanoparticles were coated with a mesoporous silica shell and further functionalised with NH<sub>2</sub> groups resulting in positively charge silica coated UCNPs. Functionalisation of the positively charged UCNPs with the negatively charged Rose Bengal photosensitiser molecules was achieved *via* electronic interactions. In order to prevent the leaching of the PS and to improve the biocompatibility of the nanoparticles, 1-adamantane carboxylic acid molecules were linked to the surface of the UCNPs as guest unit and hydrophilic  $\beta$ -cyclodextrin was used to coat the surface of the RB-UCNPs acting as host molecules.<sup>83</sup> The resulting RB-UCNPs ( $64 \pm 2$  nm) were stable to RB leaching in a PBS buffer solution for up to 70 h, as confirmed by UV-Vis measurements.<sup>83</sup> Upon irradiation at 808 nm, NaYF<sub>4</sub>:Yb,Er,Nd nanoparticles exhibited a main emission band centred at 540 nm which overlapped the absorption spectrum of the RB. The effective energy transfer between the UCNPs and the RB was evidenced by the intensity decrease of the upconversion luminescence band at 540 nm in the presence of RB. The <sup>1</sup>O<sub>2</sub> production upon 808 nm irradiation (power density of 4 W·cm<sup>-2</sup>) of RB-UCNPs containing different loadings of RB was monitored using ABMA. The optimal RB content was determined to be 1 wt% since lower concentrations showed less <sup>1</sup>O<sub>2</sub> production and increasing RB concentration led to a reduced <sup>1</sup>O<sub>2</sub> generation possibly due to the self-quenching effect of the RB.<sup>83</sup> A comparative study using 808 or 980 nm excitation indicated that the former was superior for penetration and for <sup>1</sup>O<sub>2</sub> generation. The RB-UCNPs were taken up by HeLa cervical cancer cells as confirmed using fluorescence microscopy and recording the intracellular emission of the RB on the UCNPs (whether the RB was excited directly or through the UCNPs was not indicated).<sup>83</sup> Using a CCK-8 assay, a significant induced cell death was observed for HeLa cells treated with RB-UCNPs (250  $\mu$ g·mL<sup>-1</sup>) following PDT treatment (808 nm, 1 W·cm<sup>-2</sup>, 10 min) compared to the corresponding controls, non-irradiated cells treated with RB-UCNPs. Comparative experiments were performed irradiating HeLa cells with 808 nm and 980 nm light for the same period of time and concluded that the latter resulted in lower cell viability due to an overheating effect.<sup>83</sup> This detailed work was preceded by an interesting delivery system reported by the same authors based also on UCNPs nanoparticles coated with a solid silica shell and a mesoporous silica shell containing pore channels.<sup>84</sup> The photosensitiser methylene blue was embedded in the solid silica shell while RB (as model drug) was loaded in the pores. The novelty of this system lied on the further functionalisation of the particles with a “gatekeeper” to avoid the release of RB from the mesoporous shell. The gatekeeper was a strategically placed <sup>1</sup>O<sub>2</sub>-sensitive linker that would only be opened in the presence of <sup>1</sup>O<sub>2</sub> releasing the trapped RB. MB was chosen since its absorption spectrum overlaps the emission

of the UCNPs at 660 nm which undergoes a decrease in intensity, due to the energy transferred to MB, following 980 nm irradiation. The  $^1\text{O}_2$  production by the MB-RB-UCNPs and the subsequent release of the RB was confirmed following 980 nm. Cytotoxicity of the nanosystem was observed in A549 lung cancer cells at concentrations higher than  $64 \mu\text{g mL}^{-1}$ ; however, PDT could be performed at lower concentrations ( $32 \mu\text{g mL}^{-1}$  UCNPs, 980 nm irradiation for 50 s at  $2.0 \text{ W}\cdot\text{cm}^{-2}$ ). The authors reported also the cell imaging capability of this nanosystem following irradiation at 980 nm.<sup>84</sup>

Biocompatible PS drugs like Vitamin B<sub>12</sub> (VB<sub>12</sub>), have also been used with UCNPs for PDT of cancer. Xu *et al.* reported mesoporous-silica-coated NaYF<sub>4</sub>:Yb,Er nanoparticles functionalised with VB<sub>12</sub>.<sup>85</sup> The NaYF<sub>4</sub>:Yb/Er UCNPs emit light at 545 nm ( $\lambda_{\text{exc}} = 980 \text{ nm}$ ) which overlaps the absorption of VB<sub>12</sub>. MDA-MB-231 breast cancer cells loaded with VB<sub>12</sub>-UCNPs exhibited a 40% cell viability decrease (MTT assay) following 10 min irradiation at 980 nm.<sup>85</sup> Control experiments with non-irradiated cells incubated with VB<sub>12</sub>-UCNPs and irradiated cells incubated with non-functionalised UCNPs confirmed that NIR excitation did not damage the cells and that the designed nanosystem exhibits good biocompatibility under the tested conditions. This work would have benefited from stability studies confirming that the VB<sub>12</sub> was still present on the UCNPs when stored overtime.<sup>85</sup>

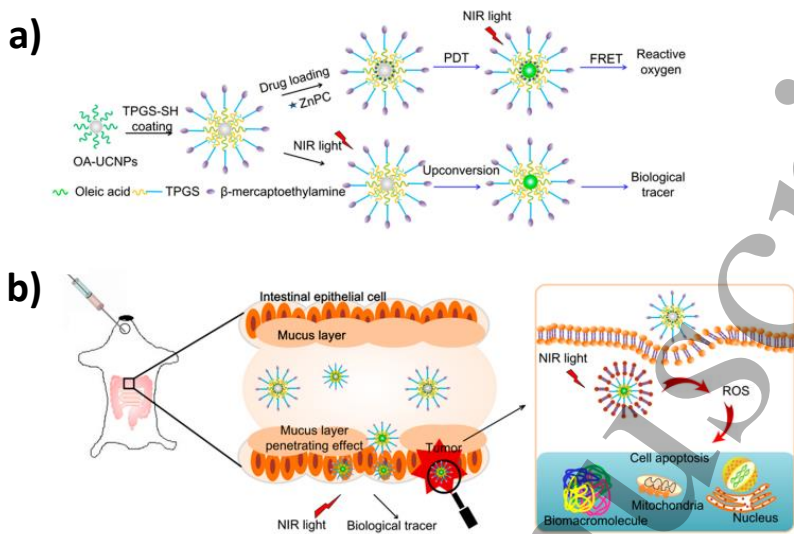
Although mesoporous silica coated UCNPs functionalised with PS drugs have proven to be efficient for the energy transfer from the UCNPs to the loaded-PS drugs, other approaches to link PS drugs non-covalently to the UCNPs have been reported, including physical adsorption, which results in a more straightforward methodology. For example, the addition of biocompatible ligands or polymers, such as PEG, to the surface of the UCNPs could act as a hydrophobic environment for the incorporation of PS and increase the water-dispersibility and stability of the nanosystem. These biocompatible PS-UCNPs are expected to have increased blood circulation times and consequently higher chance to accumulate in the tumour through the EPR effect. These non-covalent physical adsorption strategies include the entrapping of the PS on an amphiphilic polymeric coating. For instance, Wang *et al.* reported water-soluble PEGylated NaYF<sub>4</sub>:Yb,Er nanoparticles functionalised with Ce6 *via* hydrophobic interactions between the PEG chains and the PS with a ca. 8% loading capacity reported.<sup>86</sup> This was the first article published reporting the potential use of UCNPs for *in vivo* PDT. The Ce6-UCNPs were stable under different physiological conditions (PBS, cell culture medium and foetal bovine serum) and only a 10% Ce6 release was observed in PBS (pH 7.4) after 50 h at room temperature. The energy transfer from the UCNPs to the Ce6 was confirmed by the quenching of the red

emission band of the naked UCNPs after the loading of the PS. The efficiency of the Ce6-UCNPs for NIR light-activated PDT was investigated both *in vitro* and *in vivo*. Ce6-UCNPs were incubated in 4T1 murine breast cancer cells and a significant reduction in cell viability (MTT assay) was observed following 980 nm excitation (10 min, 0.5 W·cm<sup>-2</sup>) which was not observed when the cells were irradiated following treatment with naked UCNPs or with free Ce6. *In vivo* experiments were performed by intratumoural injection of Ce6-UCNPs in 4T1 murine breast tumour-bearing Balb/c mice and treatment in 980 nm NIR light exposure (0.5 W·cm<sup>-2</sup>, 30 min). Two weeks after treatment, the disappearance of the tumour was observed in 7 out of 10 mice and the mice remained alive for up to 60 days (when the mice were put down).<sup>86</sup> In addition, the tissue penetration ability of the NIR activated PDT in comparison with the direct excitation of the Ce6 on the nanoparticles using 660 nm irradiation was investigated. Although the direct activation of the Ce6 showed higher <sup>1</sup>O<sub>2</sub> generation in solution, a greater tumour reduction was observed following 980 nm irradiation when an 8 mm pork tissue was placed between the laser source and the tumour – simulating deep lying tumours. These results confirmed the higher tissue penetration of NIR light over wavelengths at the visible range and thus the superiority of using PS-UCNPs than the PS drug alone for PDT.<sup>86</sup> Quantitative biodistribution studies were performed showing that although 1 day following treatment of the tumour with the Ce6-UCNPs, the nanoparticles were found mostly on and close to the skin where they had been injected, their concentration was higher in the liver and spleen 15 days following injection and barely detectable in organs and tissues 60 days following injection. Ce-6 was also used as the PS drug by the same authors to report an improved UCNPs-based drug delivery system for PDT.<sup>89</sup> In the new approach, the UCNPs were doped with Mn<sup>2+</sup> to increase the luminescence intensity at 660 nm. Ce6 was loaded following a layer-by-layer self-assembly approach yielding 2xCe6-UCNPs which exhibited higher <sup>1</sup>O<sub>2</sub> generation than Ce6-UCNPs. 2xCe6-UCNPs and 980 nm irradiation (0.5 W·cm<sup>-2</sup>, 30 min) were used to treat BALB/c mice bearing a 4T1 murine breast cancer tumour inducing, interestingly, a delay in tumour growth when the 2xCe6-UCNPs were injected intratumorally that was not observed when they were administered *via* intravenous injection.<sup>89</sup>

Following a similar non-covalent strategy and using amphiphilic polymer coating, Cui *et al.* reported NaYF<sub>4</sub>:Yb,Er nanoparticles, first coated with *N*-succinyl-*N'*-octyl chitosan *via* aqueous phase transfer, doped with ZnPc for *in vivo* PDT.<sup>68</sup> The loading capacity achieved in this synthesis (10.8%) was higher than those obtained in previous reported example of PS-UCNPs.<sup>86</sup> Using 1,3-diphenylisobenzofuran (DPBF) as the <sup>1</sup>O<sub>2</sub> probe, a 65% decrease in the fluorescence emission of DPBF was observed following 60 min irradiation at 980 nm of the ZnPc-chitosan-

UCNPs, whereas a 3% reduction was obtained for non-irradiated void nanoparticles.  $^1\text{O}_2$  production of non-irradiated samples of ZnPc-chitosan-UCNPs was not reported by the authors in this paper. ZnPc-chitosan-UCNPs became toxic to human embryonic lung fibroblast (HELFI) and human breast adenocarcinoma (MCF-7) cells when used at high doses ( $800\text{ }\mu\text{g mL}^{-1}$ ). A decrease in cell viability was observed in MCF-7 cells loaded with ZnPc-chitosan-UCNPs after irradiation at 980 nm (600 mW, 10 min) compared to the control groups (cells incubated with ZnPc-chitosan-UCNPs and non-irradiated and untreated cells irradiated at 980 nm). Additionally, cell apoptosis in ZnPc-chitosan-UCNPs treated cells exposed to NIR light was confirmed by staining with Annexin V-FITC/PI.<sup>68</sup> In *in vivo* studies, a slower increase of tumour volume and higher survival rates were observed in S180 sarcoma tumour bearing mice treated with ZnPc-chitosan-UCNPs and irradiated with NIR light than for mice treated only with NIR light, only with ZnPc-chitosan-UCNPs or for non-treated mice. Fluorescence imaging of isolated organs and tumour tissues confirmed that, 14 days after the injection of the ZnPc-chitosan-UCNPs, the UCNPs accumulated in the tumour tissue and not in the imaged organs (liver, lung, heart, spleen, intestine and kidney) of the mice.<sup>68</sup> Meng *et al.* developed another amphiphilic conjugate for the surface modification of UCNPs which permits the adsorption of the PS and enhances the cellular permeability by inhibiting the P-glycoprotein (P-gp) which is overexpressed in cancer cells and obstructs the internalisation of therapeutic agents (**Figure 4**).<sup>87</sup> Oleate capped  $\text{NaYF}_4\text{:Yb,Er}$  nanoparticles were modified with D- $\alpha$ -tocopherol (vitamin E) polyethylene glycol 1000 succinate-succinic acid-mercaptoethylamine (TPGS-SH) following sonication. The resulting TPGS-SH-UCNPs were water-dispersible containing an outer hydrophilic shell and a hydrophobic core due to the vitamin E segments and the oleate chains respectively; and exhibited two emission bands at 540 and 654 nm. The functionalisation of the UCNPs with ZnPc (with maximum absorption wavelength at 664 nm) was successfully achieved through hydrophobic interactions with a loading capacity of 3.05%.<sup>87</sup> The ZnPc-TPGS-SH-UCNPs exhibited relatively good stability in simulated gastrointestinal media over a period of 6 h with stability in the particle size and reduction of fluorescence intensity of *ca.* 27% after incubation in simulated gastric fluid containing pepsin. The ability of the ZnPc-TPGS-SH-UCNPs to produce  $^1\text{O}_2$  was confirmed by the decrease in absorbance of DPBF following excitation at 980 nm. The consumption of DPBF was not observed when particles without ZnPc were irradiated; a control experiment measuring the consumption of DPBF in the presence of non-irradiated ZnPc-TPGS-SH-UCNPs was not reported. *In vitro*, a significant decrease in cell viability was observed in Caco-2 human colon carcinoma cells incubated with ZnPc-TPGS-SH-UCNPs ( $100\text{ }\mu\text{g mL}^{-1}$ ) and irradiated at 980 nm (800 mW, 10 min). The control groups, including irradiated unloaded UCNPs and non-irradiated unloaded UCNPs, did not exhibit any cell viability decrease (MTT assay).<sup>87</sup> The mucosal penetration of the ZnPc-

TPGS-SH-UCNPs, attributed to the thiol-based ligands, was investigated in Sprague-Dawley rats measuring the  $Y^{3+}$  concentration and showed the accumulation of the nanoparticles on the enterocytes of duodenum.<sup>87</sup>



**Figure 4.** Schematic representation of **a)** ZnPc-TPGS-SH-UCNPs reported by Meng *et al.* and **b)** intestinal distribution, mucosal penetration and subsequent PDT.<sup>87</sup> Reprinted from Ref. 87 with permission from American Chemical Society.<sup>§</sup>

Although non-covalent strategies for the loading of PS drugs onto the surface of UCNPs present a straightforward approach, the precipitate release of the PS can reduce the efficiency of the treatment and lead to side effects. For instance, Liu *et al.* compared the loading capacity of RB on UCNPs following a non-covalent and a covalent strategy.<sup>90</sup> The authors covalently attached RB hexanoic acid to amino-functionalised UCNPs *via* amide formation reaction and compared the RB desorption with RB-loaded UCNPs *via* electrostatic interactions. The eluted RB characterised by UV-Vis spectroscopy was 1 order of magnitude higher for the non-covalent RB loading strategy confirming the higher stability of the covalently functionalised RB-UCNPs.<sup>90</sup> This demonstrates that the use of robust covalent bonds to bind PS – and other cargo – to UCNPs may improve the loading efficiency and stability of the nanosystems ensuring the higher control of the possible leaching and of the overall structure. Additionally, a covalent approach may lead to a better control of the distance between the UCNPs core and the loaded PS, which is key for an efficient energy transfer and thus for the production of  $^1O_2$  in PDT applications.

An effective upconversion energy transfer between the PS and the UCNPs not only relies on the spectral overlap of the PS absorption and the upconverting luminescence emission but the distance between the core and the drug plays also a key role in the effective activation of the PS drug. Longer distances between the PS and the nanocore have been related to a proportional



decrease of the energy transfer resulting in a decrease in  $^1\text{O}_2$  generation.<sup>91,92</sup> Controlling the relative distance between PSs and UCNPs probes is challenging when using a non-covalent strategy; however, this parameter can be more easily controlled when designing a covalent chemical bond between the PS and the UCNPs. For example, Marín and co-workers covalently bonded RB to UCNPs through a L-lysine unit which results in a controlled short distance between the UCNPs and the PS.<sup>51</sup> Oleate-capped core-shell  $\text{NaYF}_4:\text{Yb,Er,Gd}@ \text{NaYF}_4$  nanoparticles ( $17.2 \pm 1.0$  nm). were modified *via* a ligand exchange method yielding  $\text{BF}_4^-$  capped UCNPs and the L-lysine ligand was then incorporated replacing the  $\text{BF}_4^-$  ions. Finally, the lysine-capped UCNPs were functionalised with RB *via* classical EDC/NHS chemistry resulting in RB-lysine-UCNPs.<sup>51</sup> ABMA was used to confirm the ability of the RB-lysine-UCNPs to generate  $^1\text{O}_2$  upon irradiation at 980 nm. Luminescence lifetime measurements were reported to confirm the efficiency of the FRET from the UCNPs to the RB. RB-lysine-UCNPs were internalised by SK-BR-3 breast cancer cells as evidenced by the emission of the RB and the UCNPs using both, confocal laser scanning microscopy and multi-photon microscopy. Using CellTiter Blue<sup>®</sup> assay, the cell viability of SK-BR-3 cells incubated with the RB-lysine-UCNPs and irradiated at 980 nm (200 mW, 6 min) showed a decrease of 67% whereas non-irradiated cells showed a 5% decrease due to the dark toxicity of the RB-lysine-UCNPs.<sup>51</sup>

With the aim of combining the covalent chemical bonding of PS drugs on the surface of UCNPs and obtaining water-dispersible and more biocompatible NIR excitable nanosystems for PDT, the incorporation of biologically acceptable ligands in combination with PS drugs has been investigated by several groups. For example, Sun *et al.* covalently functionalised PEGylated UCNPs with protoporphyrin IX as PS drug resulting in a water-dispersible nanosystem.<sup>93</sup> The protoporphyrin IX structure was modified with jeffamine molecules, to obtain a hydrophilic porphyrin derivative, and a thiolated terminal group was incorporated. Then, PEGylated UCNPs were prepared from core-shell  $\text{NaGdF}_4:\text{Yb,Er}@ \text{NaGdF}_4$  UCNPs ( $14.2 \pm 1.3$  nm) and a subsequently “click” reaction between the maleimide group on the UCNPs surface and the thiolated porphyrin-jeffamine molecules yielded the porphyrin-UCNPs.<sup>93</sup> The porphyrin functionalisation of the UCNPs was confirmed by UV-Vis spectroscopy (2.0% w/w, porphyrin-jeffamine:UCNP) and the energy transfer from the UCNPs to the PS was demonstrated by the quenching of the luminescence emission of the UCNPs in the range of 400 – 650 nm which matches the absorption band of the PS. In solution, the porphyrin-UCNPs were able to produce  $^1\text{O}_2$  following irradiation at 980 nm ( $0.5 \text{ W}\cdot\text{cm}^{-2}$ ) with rates that were slightly higher than those produced by the same concentrations of free porphyrin-jeffamine and by the clinically used HMME (hematoporphyrin mono-methylether) irradiated directly at 635 nm ( $0.5 \text{ W}\cdot\text{cm}^{-2}$ ). The

efficiency of the porphyrin-UCNPs to generate  $^1\text{O}_2$  was investigated in an intestinal cancer cell line LS180 using MTT assay. A decrease in cell viability of almost 100% was observed after NIR irradiation (980 nm,  $1 \text{ W}\cdot\text{cm}^{-2}$ , 10 min) of LS180 cells treated with  $1.5 \text{ mg}\cdot\text{mL}^{-1}$  of porphyrin-UCNPs ( $36 \text{ }\mu\text{M}$  porphyrin-jeffamine) whereas the non-irradiated cells incubated with the same concentration of nanoparticles showed a cell viability *ca.* 85%.<sup>93</sup>

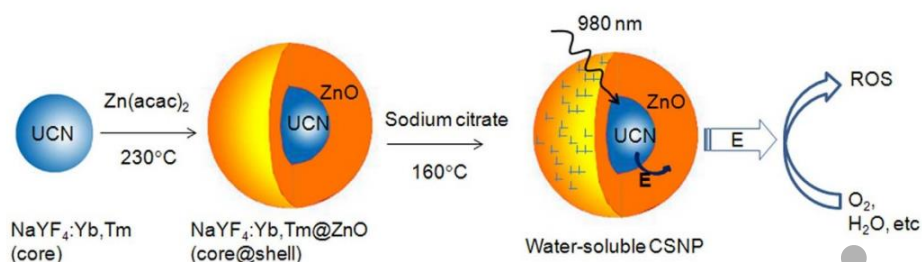
Natural coating strategies including the incorporation of protein layers (*e.g.* bovine serum albumin (BSA)<sup>79</sup> and apolipoproteins<sup>94</sup>) or cell membranes<sup>95</sup> (*e.g.* red blood cells and stem cells) have been also employed for loading PS drugs on the surface of UCNPs. Sabri *et al.* reported the covalent functionalisation of RB on the surface of BSA-UCNPs for PDT of cancer.<sup>79</sup> First, RB hexanoic acid was covalently linked to the free amine groups of the lysine units present the BSA of BSA-modified  $\text{NaGdF}_4\cdot\text{Yb,Er}$  nanoparticles. This work demonstrated the importance that the PS loading concentration has on the effective energy transfer between the UCNPs and the PS. The energy transfer from the UCNPs to the RB was investigated at different RB concentrations, *i.e.* 3, 20 and  $30 \text{ }\mu\text{M}$ ; the maximum energy transfer (68%) was observed for the particles containing  $20 \text{ }\mu\text{M}$  RB. Higher concentrations of RB ( $30 \text{ }\mu\text{M}$ ) led to a decrease on energy transfer due to the self-quenching between the RB molecules. The NIR activated production of  $^1\text{O}_2$  was evidenced using DPBF and monitoring the decrease in absorption intensity at 415 nm following 980 nm irradiation. Interestingly, the number of molecules of  $^1\text{O}_2$  produced was estimated to be  $5.9\times 10^{21}$  molecules which is above the number of molecules required to produce cell damage ( $7\times 10^9$ ).<sup>96</sup> Confocal microscopy was used to study the cellular uptake of the RB-BSA-UCNPs and to compare it with that of the free RB hexanoic acid and of BSA-UCNPs without RB. Interestingly, RB was localised in the cytoplasm of human lung cancer A549 cells, BSA-UCNPs did not penetrate the cellular membrane and RB-BSA-UCNPs were localised in the cytosol. Therefore, the BSA capping of UCNPs was not involved in the cellular uptake but the conjugated BSA-UCNPs with RB acquire the ability to be internalised by A549 cells. MTT assay was used to study the cell viability of the A549 cells treated with the RB-BSA-UCNPs ( $250 \text{ }\mu\text{g mL}^{-1}$ ) following 10 min irradiation at 980 nm ( $13 \text{ mW}\cdot\text{cm}^{-2}$ ). Although a 36% cell death was determined for the irradiated cells incubated with RB-BSA-UCNPs, an intrinsic cellular toxicity of 15% was observed without light irradiation. Even though the authors showed an efficient covalent RB loading on the surface of the UCNPs, the ability of those nanosystems to induce cell death *via* PDT could be further improved.

Stem-cells have been used as biomimetic carriers of UCNPs for PDT resulting in a prolonged blood circulation time and enhanced tumour passive targeting. The first example of stem-cell coated UCNPs was reported by Gao *et al.* in 2016 and presented an exhaustive investigation of

the nanoplatform both *in vivo* and *in vitro*.<sup>97</sup> The authors synthesised NaYF<sub>4</sub>:Yb,Er nanoparticles coated with a mesoporous silica layer that exhibited two main luminescence emission bands, green (*ca.* 540 nm) and red (*ca.* 660 nm). Two PS drugs, MC540 (overlaps green emission) and ZnPc (overlaps red emission), were incorporated into the mesoporous silica shell to enhance the PDT effect. Stem-cell-membranes isolated from human and rat bone-marrow-derived mesenchymal stem cells were used to prepare the stem-cell-membrane vesicles *via* physical extrusion method.<sup>97</sup> Stem-cell-membrane coated UCNPs loaded with MC540 and ZnPc were obtained by an extrusion approach in which the particles were mixed with the previously extruded stem-cell-membranes and passed through 200 nm pore-size polycarbonate membrane 11 times. The stem-MC540-ZnPc-mSiO<sub>2</sub>-UCNPs had a core size of *ca.* 120 nm and were surrounded by a lipid layer of *ca.* 10 nm in thickness. The size of the stem-MC540-ZnPc-mSiO<sub>2</sub>-UCNPs remained stable in solutions containing PBS or foetal bovine serum for up to 2 weeks. The nanocomposites remained stable once taken up by HeLa cells since both the stem-cell-membrane and the UCNPs co-localised in the intracellular environment. The biocompatibility of the designed stem-MC540-ZnPc-mSiO<sub>2</sub>-UCNPs was tested by MTT cell viability studies, haemolysis and blood-smear-test; and the three assays confirmed the suitability of the nanoplatform for biological applications. The target-capability of the stem-MC540-ZnPc-mSiO<sub>2</sub>-UCNPs was confirmed in HeLa cells using confocal microscopy and by comparison with the reduced internalisation of the particles without stem-cell-membrane by the same cell line. These studies were nicely supported by quantitative studies using flow cytometry where an increase in fluorescence intensity was observed for cells treated with a FITC-labelled stem-MC540-ZnPc-mSiO<sub>2</sub>-UCNPs compared to the increase observed for cells treated with FITC-labelled MC540-ZnPc-mSiO<sub>2</sub>-UCNPs. To further the applicability of the nanoplatform, *in vivo* tumour-targeting experiments were performed using fluorescence imaging in mice bearing HeLa tumours and following the labelling of the stem-MC540-ZnPc-mSiO<sub>2</sub>-UCNPs and MC540-ZnPc-mSiO<sub>2</sub>-UCNPs with a NIR excitable dye, Cy7. These studies confirmed the role that the stem-cell-membranes play on the accumulation of the UCNPs in the tumour and on the reduction of the clearance by the RES. The potential of the stem-MC540-ZnPc-mSiO<sub>2</sub>-UCNPs as PDT agents was evaluated both *in vitro* and *in vivo*. *In vitro*, HeLa cells were treated with stem-MC540-ZnPc-mSiO<sub>2</sub>-UCNPs and controls included cells treated with mSiO<sub>2</sub>-UCNPs, MC540-ZnPc-mSiO<sub>2</sub>-UCNPs, stem-mSiO<sub>2</sub>-UCNPs and PBS. Fluorescence cell staining with a living cell fluorophore (calcein AM) and an apoptosis fluorophore (propidium iodide) and quantitative analysis *via* MTT assay confirmed that only the combination of cells treated with nanoparticles containing the photosensitiser drugs and irradiated at 980 nm (0.35 W·cm<sup>-2</sup>, 15 min) yielded to reduce cell viability. Interestingly, stem-MC540-ZnPc-mSiO<sub>2</sub>-UCNPs are twice more effective for PDT than MC540-

ZnPc-mSiO<sub>2</sub>-UCNPs without the stem-cell-membranes thus, confirming the targeting ability of the newly developed platform. This complete study concluded with the *in vivo* validation of the system in HeLa cervical tumour-bearing Balb/c mice. The mice were treated under different conditions including PBS, stem-mSiO<sub>2</sub>-UCNPs (without PS drugs), MC540-ZnPc-mSiO<sub>2</sub>-UCNPs and stem-MC540-ZnPc-mSiO<sub>2</sub>-UCNPs all of them following irradiation with 980 nm laser (0.35 W·cm<sup>-1</sup> for 1 h) or without irradiation. 15 days after the treatment, all the mice were euthanised and the tumour sizes were measured which confirmed that only those mice that had been treated with stem-MC540-ZnPc-mSiO<sub>2</sub>-UCNPs following NIR irradiation showed tumour growth inhibition confirming the excellent potential of this novel nanopatform for *in vivo* PDT.

Although the majority of the UCNP-based NIR light triggered PDT systems are designed using organic molecules as PS, some semiconductor materials (such as ZnO and TiO<sub>2</sub>) have been also employed as inorganic PS. Incorporation of ZnO or TiO<sub>2</sub> shells onto the surface of UCNPs results on an easy PS loading process compared to the surface modifications and PS anchoring approaches when using organic PS drugs. For example, Dou *et al.* reported a core-shell design with UCNPs (NaYF<sub>4</sub>:Yb,Tm) as the core and ZnO as the shell (2 – 3 nm width) structure (**Figure 5**).<sup>98</sup> The ZnO-UCNPs were further modified with anhydrous sodium citrate to yield water-dispersible UCNPs. The energy transfer between the UCNPs and the ZnO occurs upon irradiation at 980 nm yielding to the disappearance of the luminescence emission band that overlaps the absorbance of ZnO. The ROS production was confirmed by fluorescence spectroscopy, using 3'-(*p*-aminophenyl) fluorescein (ARF) as fluorescent ROS probe.<sup>98</sup> The ZnO-UCNPs were incubated in two breast cancer cell lines (4T1 and MDA-MB-231 cells) showing good biocompatibility when low nanoparticles concentration was used (10 µg/mL). The PDT effect of the ZnO-UCNPs was evaluated in MDA-MB-231 breast cancer cells by MTT assay using 980 nm irradiation (5 mW) at different times. The results showed a decrease in the cell viability 72 h after treatment (*ca.* 50%) for cells incubated with ZnO-UCNPs and exposed to NIR light for 30 min. UCNPs have also been functionalised with a TiO<sub>2</sub> following different approaches, including the surface coating with a TiO<sub>2</sub> shell<sup>99</sup> and the conjugation of TiO<sub>2</sub> nanoparticles<sup>100</sup> on the surface of UCNPs. Although the PS-loading of inorganic crystals results in a more straightforward strategy, in most cases, further surface modification is needed to provide the hydrophilicity to the systems.



**Figure 5.** Schematic representation of the ZnO functionalisation of UCNPs and the ROS generation upon irradiation at 980 nm.<sup>98</sup> Reprinted from Ref. 98 with permission from Springer Nature. §§

Other photosensitisers such as transition metal-based complexes (*e.g.* iridium (III) complex<sup>101</sup> and ruthenium (II) complex<sup>102</sup>) have been recently combined with UCNPs for PDT treatment *in vitro* and *in vivo*. For example, Meijer *et al.* reported the first example of UCNPs decorated with a metal-based PS drug for NIR-triggered PDT of cancer.<sup>102</sup> NaYF<sub>4</sub>:Yb,Tm nanoparticles (44.2 ± 2.2 nm) exhibited luminescence at 451, 475, 510, 648, 698, 740 and 803 nm when excited at 969 nm, being 451 and 475 nm the desired wavelengths to activate the PS Ru(II) complex. Functionalisation of the UCNPs with the Ru(II) complex was performed using a mixture of phospholipids (sodium 1,2-dioleoyl-*sn*-glycero-3-phosphate and 1,2-dioleoyl-*sn*-glycero-3-phosphocholine) and cholesterol in chloroform. A lipid film was formed containing the Ru(II) complex (5 mol%) and the UCNPs was hydrated using MES/acetate buffer. A 12% energy transfer between the UCNPs and the Ru(II) complex was calculated by combination of steady-state and time-resolved fluorescence spectroscopies.<sup>102</sup> This low energy transfer could be attributed to the long distance between the UCNPs core and the PS or due to a low concentration of PS on the surface of the UCNPs. Thus, confirming the need of a distance control to enhance the efficiency of the energy transfer which activates the PS to generate the cytotoxic <sup>1</sup>O<sub>2</sub>. The Ru(II) complex-UCNPs were able to generate <sup>1</sup>O<sub>2</sub> following irradiation at 969 nm (2.0 W, 50 W·cm<sup>-2</sup>, 2 h) as indicated by an increase in the absorption intensity of DHFA.<sup>102</sup> Although water-dispersible phospholipid coated Ru(II) complex-UCNPs with an excellent overlap between the absorption of Ru(II) complex and the emission of UCNPs were successfully synthesised, a low energy transfer was observed between the nanoparticles and the Ru(II) complex limiting the <sup>1</sup>O<sub>2</sub> production and thus the potential of this nanosystems for PDT of cancer.

Recently, a porphyrin-based metal-organic framework has been employed by Shi *et al.* as PS drug for the development of PS-UCNPs for PDT of cancer.<sup>103</sup> The authors stressed the ability of the presented nanoplatform to achieve Type I and Type II PDT *via* NIR excitation and the

reported results addressed this shelling point. A layer of meso-tetra(4- carboxyphenyl)porphine (TCPP)-MOF was grown through a solvothermal process on the surface of  $\text{NaYF}_4:\text{Tm,Yb}$  nanoparticles (*ca.* 29 nm) modified with a polyvinylpyrrolidone (PVP) layer.<sup>103</sup> The nanoparticles were then coated with a layer of ultra-small  $\text{TiO}_2$  nanoparticles which was used as a second PS drug yielding UCNPs-MOF- $\text{TiO}_2$  nanoparticles. Upon excitation at 980 nm the naked UCNPs emitted bands at 291, 344, 360, 450, 475 and 648 nm, which strongly decreased upon addition of the MOF and  $\text{TiO}_2$  and thus, confirming the efficient energy transfer between the UCNPs and the other materials. The ability of the UCNPs-MOF- $\text{TiO}_2$  to produce ROS following 980 nm irradiation was determined by monitoring the decrease in the absorbance intensity of DPBF (able to react with several ROS). UCNPs-MOF- $\text{TiO}_2$  were slightly superior in the generation of ROS than UCNPs-MOF. *In vitro* experiments were performed in MCF-7 breast cancer cells. Cells were incubated with UCNPs-MOF- $\text{TiO}_2$  or UCNPs-MOF and further incubated with singlet oxygen sensor green ( $^1\text{O}_2$  probe), dihydroethidium ( $\text{O}_2^{\bullet-}$  probe) and hydroxyphenyl fluorescein ( $\text{HO}^{\bullet}$  probe), irradiated at 980 nm ( $0.72 \text{ W}\cdot\text{cm}^{-2}$ , 5 min) and imaged using the confocal microscope. UCNPs-MOF were able to produce only  $^1\text{O}_2$  while UCNPs-MOF- $\text{TiO}_2$  were able to produce  $^1\text{O}_2$ ,  $\text{O}_2^{\bullet-}$  and  $\text{HO}^{\bullet}$ , thus probing the ability of the UCNPs-MOF- $\text{TiO}_2$  to be used for Type I and Type II PDT. The efficacy of the UCNPs-MOF- $\text{TiO}_2$  for PDT was further confirmed using MTT assays (and confocal microscopy using propidium iodide staining) reporting a 70% decrease in cell viability only when MCF-7 cells were treated with the nanoparticles and irradiated with NIR light. No decrease was observed in cells treated with the UCNPs-MOF- $\text{TiO}_2$  without irradiation confirming the biocompatibility of the developed nanosystem. Furthermore, MTT assays also reported the superiority of UCNPs-MOF- $\text{TiO}_2$  over UCNPs-MOF to induce cell death *via* PDT following irradiation. The UCNPs-MOF- $\text{TiO}_2$  were also evaluated for *in vivo* PDT using MCF-7 tumor-bearing BALB/c mice. The mice were treated under four different conditions: 1) PBS intravenously injected and no irradiation; 2) PBS intravenously injected and tumour irradiated with a 980 nm NIR laser ( $0.72 \text{ W}\cdot\text{cm}^{-2}$ , light dose  $648 \text{ J}\cdot\text{cm}^{-2}$ , 15 min); 3) UCNPs-MOF- $\text{TiO}_2$  (1 mg/mL, 100  $\mu\text{L}$ ) intravenously injected and no irradiation; and 4) UCNPs-MOF- $\text{TiO}_2$  (1 mg/mL, 100  $\mu\text{L}$ ) intravenously injected and tumour irradiated with a 980 nm NIR laser ( $0.72 \text{ W}\cdot\text{cm}^{-2}$ , light dose  $648 \text{ J}\cdot\text{cm}^{-2}$ , 15 min). Only those mice treated with the nanoparticles and irradiated with NIR light showed a considerable tumour volume reduction over time with complete disappearance after 90 days and prolonged survival rates for as long as 100 days (the mice in the control groups survived for less than 50 days); thus, confirming the potential of the newly developed platform for PDT of cancer.

### 3.2 Active targeting

Although a lot of the examples of PDT using UCNPs follow passive targeting strategies taking advantage of the EPR effect,<sup>51,104</sup> the efficiency of the treatment can be significantly enhanced using active targeting strategies. There are mainly two types of active targeting, stimuli-responsive targeting and ligand-mediated targeting. In the stimuli sensitive approach nanoparticles are tuned to respond to specific changes that occur in the cellular environment of cancer cells but not in healthy cells;<sup>80</sup> therefore results in a very specific treatment minimising the side effects. This can be achieved by tailoring the surface of the nanoparticles or modifying the PS structure. Another strategy to develop an active targeted PDT is to further functionalise PS-UCNPs with recognition units such as folic acid, antibodies, peptides, carbohydrates, among others, that can bind specific receptors only present or overexpressed on tumour cells.<sup>80</sup> The use of targeting agents facilitates the uptake of the nanoparticles by cancer cells minimising the undesired side effects.<sup>80</sup> The following sections in this review paper will be devoted to reporting recent papers describing the development of PS-UCNPs that can be used to target cancer in an active manner, *i.e. via* stimuli-responsive targeting or using ligands that can recognise specific receptors on the cancer cell surface.

#### 3.2.1 Stimuli-responsive targeting

Examples of external stimulus only present on tumour sites include differences on the pH,<sup>105,106</sup> H<sub>2</sub>O<sub>2</sub> concentration<sup>107</sup> or the presence of specific enzymes<sup>108</sup> in the intracellular microenvironments. Delivery platforms are designed bearing this in mind and thus, the PS drugs are just activated when they reach environments that exhibit these specific conditions resulting in an “off-on” strategy. For example, Han and co-workers synthesised UCNPs covalently functionalised with a clinically used prodrug, 5-aminolevulinic acid (ALA), that could be released intracellularly and form the PS protoporphyrin IX only under the acidic environments found in cancer cells.<sup>106</sup> The reported UCNPs consist of cubic phase  $\alpha$ -NaYF<sub>4</sub> doped with 80% Yb<sup>3+</sup> and 20% Er<sup>3+</sup> as core and CaF<sub>2</sub> as the shell of the nanoparticles ( $\alpha$ -NaYF<sub>4</sub>:Yb,Er@CaF<sub>2</sub>, *ca.* 26 nm). The functionalisation of the UCNPs with ALA was performed through a covalent pH-sensitive hydrazone linked to poly(acrylic acid)-functionalised UCNPs with the aim of the prodrug being released by the lower pH of the endosomes and the subsequent formation of the PS protoporphyrin IX in the mitochondria where it could generate <sup>1</sup>O<sub>2</sub> upon red light excitation.<sup>109</sup> The formation of protoporphyrin IX and the generation of <sup>1</sup>O<sub>2</sub> was confirmed in HeLa cells incubated with ALA-UCNPs (100  $\mu$ g mL<sup>-1</sup>) following irradiation at 980 nm (0.5 W·cm<sup>-2</sup>, 10 min)

using a  $^1\text{O}_2$  fluorescent probe, 2',7'-dichlorofluorescein diacetate (DCFDA). No  $^1\text{O}_2$  production was evidenced in the control group where cells were treated with UCNPs that did not contain ALA (Hyd-UCNPs).<sup>106</sup> MTT assays showed a cell viability decrease of *ca.* 70% after 20 min irradiation at 980 nm that was not observed when the cells were incubated with Hyd-UCNPs or free ALA and irradiated or only irradiated. One of the aims of this research was to increase the deep-tissue treatment by amplifying the red emission of the nanoparticles. To this aim, the authors optimised the content of  $\text{Yb}^{3+}$  to 80% in solution which was also confirmed in *in vitro* experiments where the PDT effect of ALA-functionalised core-shell cubic nanoparticles  $\alpha\text{-NaYF}_4\text{:Yb(80\%),Er(2\%)}@ \text{CaF}_2$  was compared with that of hexagonal core-shell UCNPs ( $\beta\text{-NaYF}_4\text{:Yb(20\%),Er(2\%)}@ \beta\text{-NaYF}_4$ ) *via* MTT assay.<sup>106</sup> With the purpose of studying the deeper tissue efficacy of the NIR-triggered PDT, a piece of pork (1.2 cm) was placed between the laser and the cell-containing well. The results showed a decrease in the cell viability of the cells treated with ALA-UCNPs irradiated with NIR light during 40 min through the piece of pork.<sup>106</sup> Additionally, *in vivo* experiments were performed in female Balb/c mice treated with ALA-UCNPs comparing the PDT effect following 980 nm irradiation or direct irradiation of the PS. A significant reduction in tumour size was observed for both treatments with no statistically significant differences found between them. However, when a 1.2 cm piece of pork was placed between the tumour side and the laser source, a phototherapeutic effect was observed when 980 nm was used as irradiation source, but no tumour size reduction was evidenced when red light excitation was employed. These results further confirm the superiority of using UCNPs in combination with NIR excitation for deep tissue penetration PDT.<sup>106</sup>

Another example of pH-induced PDT using UCNPs was reported by Feng *et al.*<sup>105</sup> The authors designed RB-UCNPs with a sensitive activation of the  $^1\text{O}_2$  generation into tumour acidic environment. The “off-on” strategy was achieved by the incorporation of a pH-sensitive PEGylated polymer and a fluorescence quencher, black hole quencher (BHQ). It is expected that the photoactivity of the nanoplatfrom will be in the “off” state at pH 7.4 in the blood and it will be “turned on” once the nanosystem is internalised in the tumour side and thus reaches environments with lower pH. Core-shell  $\text{NaYF}_4\text{:Yb,Er}@ \text{NaYF}_4$  nanoparticles (*ca.* 26 nm) were non-covalently functionalised with RB by mixing the oleate-capped UCNPs with RB hexanoic acid. Next, two PEGylated polymeric micelles were prepared containing RB or BHQ, and were used as polymeric shells for the RB-UCNPs. The  $^1\text{O}_2$  generation mediated by pH changes was investigated upon NIR light irradiation using DPBF showing that at pH 5.5 the polymeric shells are released from the particles allowing the recovery of the emission and thus the generation of  $^1\text{O}_2$ . The cleavage of the polymeric shell was also confirmed measuring the hydrodynamic



diameter of the nanoparticles at both pH values and a decrease in size from 102 nm at pH 7.4 to 68 nm at pH 5.5 was observed in agreement with the singlet oxygen production experiments. MCF-7 breast cancer cells were used to evaluate the *in vitro* PDT effect (MTT assay) of three types of nanoparticles: “off-on”-RB-UCNPs which contained PEG polymer ligands with RB and BHQ that were cleaved at acidic pH; “always-off”-RB-UCNPs in which the PEG polymer used contained both RB and BHQ but did not present a pH-cleavable section (negative control); and “always-on”-RB-UCNPs in which the polymer used to build the shell was not modified with the quenchers (positive control). The MCF-7 incubated with “off-on”-RB-UCNPs and irradiated at 980 nm ( $0.7 \text{ W} \cdot \text{cm}^{-2}$ , 15 min) exhibited similar cell viability decrease than those cells incubated with the positive control “always-on”-RB-UCNPs and irradiated. The decrease in cell viability was considerably large compared to the small decrease (*ca.* < 20%) observed when the cells were incubated with “always-off”-RB-UCNPs and irradiated. The paper claims that these results support the theory of activation of the “off-on”-RB-UCNPs when taken up by cancer cells. However, a comparison with the results obtained with healthy cells following the same treatment is essential to support the targeting ability of the particles. The ability of the nanosystem to perform *in vitro* PDT was also confirmed using flow cytometry and staining of apoptotic and necrotic cells which confirms a similar behaviour between “off-on”-RB-UCNPs and “always-on”-RB-UCNPs. The “off-on”-RB-UCNPs were used to image tumour sides in MCF-7 tumour bearing mice 4 h after intravenous injection of the nanoparticles. Furthermore, the “off-on”-RB-UCNPs exhibited good biocompatibility and were able to reduce the relative tumour volume following irradiation with 980 nm NIR laser (15 min at  $0.6 \text{ W cm}^{-2}$ ).<sup>105</sup>

Cancer cells present higher levels of  $\text{H}_2\text{O}_2$  than normal cells and elevated concentrations of  $\text{H}_2\text{O}_2$  have been associated with malignant cell proliferation.<sup>110</sup> Thus  $\text{H}_2\text{O}_2$ -induced PDT has been investigated as a strategy for the active targeting of cancer cells.<sup>107</sup> For example, Ding *et al.* reported a lanthanide-based nanoplatfrom functionalised with MC540 as PS and  $\text{MnFe}_2\text{O}_4$  as a Fenton catalyst to generate  $\text{O}_2$  from the intracellular  $\text{H}_2\text{O}_2$  thus potentially enhancing the efficiency of the PDT in cancer cells by increasing tissue penetration (with UCNPs) and reducing hypoxia levels (increasing  $\text{O}_2$  concentration at the tumour side).<sup>107</sup> Core-shell  $\text{NaYF}_4:\text{Yb},\text{Er}$  nanoparticles coated with a mesoporous silica shell *via* silica sol-gel reaction were functionalised with amine groups using 3-aminopropyltriethoxysilane (ATPES).  $\text{MnFe}_2\text{O}_4$  nanocrystals, prepared following a hydrothermal method and modified with 2-bromo-2-methylpropionic acid (BMPA), were covalently bonded to the amine-functionalised UCNPs *via* nucleophilic substitution reaction. The  $\text{MnFe}_2\text{O}_4$ -UCNPs were further modified with MC540, which absorption band (540 nm) overlaps one of the luminescence wavelengths of the UCNPs (541

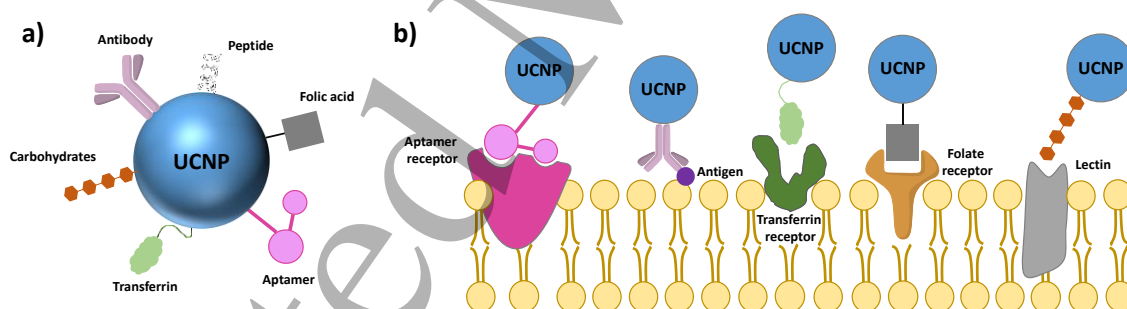
nm). The loading of MC540 on the silica porous was achieved with a 11.52 wt% loading efficiency with no stability studies reported for potential leaching of the PS drug. The MC540-MnFe<sub>2</sub>O<sub>4</sub>-UCNPs were able to generate O<sub>2</sub> from H<sub>2</sub>O<sub>2</sub> in solution. *In vitro* experiments were performed to test the ability of the MC540-MnFe<sub>2</sub>O<sub>4</sub>-UCNPs to induce the production of <sup>1</sup>O<sub>2</sub> in HepG human liver cancer cells under both, normoxic and hypoxic conditions. A ROS probe, DHFA, and fluorescence microscopy were used to detect the intracellular <sup>1</sup>O<sub>2</sub> formation following treatment of the cells with the MC540-MnFe<sub>2</sub>O<sub>4</sub>-UCNPs and irradiation at 980 nm (0.5 W·cm<sup>-2</sup>, 10 min). A comparative study between MC540-MnFe<sub>2</sub>O<sub>4</sub>-UCNPs and MC540-UCNPs in HepG cells confirmed the ability of the former to produce <sup>1</sup>O<sub>2</sub> under hypoxic conditions (1% O<sub>2</sub>, 5% CO<sub>2</sub> and 94% N<sub>2</sub>).<sup>107</sup> MTT assays were performed to quantitatively study the *in vitro* PDT effect of MC540-MnFe<sub>2</sub>O<sub>4</sub>-UCNPs and MC540-UCNPs under normoxic and hypoxic conditions. Both types of nanoparticles (400 µg mL<sup>-1</sup>) yielded to significant cell mortality when incubated in HepG cells and irradiated at 980 nm (5 min) in normoxic conditions. However, when the cells were incubated under hypoxic atmosphere, a notable difference in cell viability was observed, *ca.* 25% for MC540-MnFe<sub>2</sub>O<sub>4</sub>-UCNPs and *ca.* 90% for MC540-UCNPs. These results confirmed the higher PDT efficiency of MC540-MnFe<sub>2</sub>O<sub>4</sub>-UCNPs over MC540-UCNPs in HepG cancer cells due to the ability of MnFe<sub>2</sub>O<sub>4</sub> to generate O<sub>2</sub>.<sup>107</sup> The incorporation of MnFe<sub>2</sub>O<sub>4</sub> onto the UCNPs results not just on a O<sub>2</sub> catalytic generation but also allows the nanoparticles to be magnetically-guided to the tumour sites. The accumulation of the MC540-MnFe<sub>2</sub>O<sub>4</sub>-UCNPs, injected through the tail, into malignant regions was investigated *in vivo* using BALB/c mice to which H22 mouse hepatoma cells had been subcutaneously injected. Magnetic-guided and non-guided accumulation of the nanoparticles in the tumour was determined by measuring the yttrium concentration by ICP-AES resulting in higher levels of Y<sup>3+</sup> when a magnetic guidance was applied.<sup>107</sup> The *in vivo* PDT effect of MC540-MnFe<sub>2</sub>O<sub>4</sub>-UCNPs was then studied in HepG2 tumour bearing nude mice (average tumour volume of 60 mm<sup>3</sup>) irradiated at 980 nm (10 min). Tumour growth was observed in control groups (treated with PBS or treated with particles without irradiation) in comparison to the impressive tumour inhibition observed for mice treated with MC540-MnFe<sub>2</sub>O<sub>4</sub>-UCNPs and irradiated which was superior to the observed for mice treated with MC540-UCNPs and irradiated; and thus, may confirm the role that MnFe<sub>2</sub>O<sub>4</sub> plays in the generation of O<sub>2</sub> to overcome hypoxia. Additionally, a remarkably *in vivo* PDT improvement was evidenced when administrating MC540-MnFe<sub>2</sub>O<sub>4</sub>-UCNPs and using magnetic guidance of the nanoparticles to the tumours furthering the great potential of this platform for *in vivo* PDT, imaging and MR.<sup>107</sup> These ambitious examples have confirmed that stimuli-response strategies could be a potential way to reduce the cytotoxicity effects in normal cells. However, the non-specific distribution of the nanoparticles in the body is still an issue and further efforts are

necessary to deliver the nanoparticles specifically and for them to accumulate in the tumour side. A well-known strategy to achieve this is the incorporation of ligands that can recognise receptors expressed only (or overexpressed) on cancer cells, thus increasing the concentration of PS drugs on the cancer tissue and, therefore, significantly improving the efficiency of the PDT.

### 3.2.2 Ligands or receptor mediated targeting

The multifunctionalisation capability of UCNPs permits the addition of targeting agents onto the surface of nanoparticles resulting in the specific recognition of the cancerogenic tissue/cells.<sup>53,63-65,111</sup> Functionalisation of the nanosystems with targeting agents offers advantages over passive targeting such as high specificity and selectivity reducing any adverse effects due to non-targeted toxicities and enhancing the cellular uptake. In general, the active targeted PDT has shown to maximise the accumulation of the PS drugs into malignant tissue and minimise the potential toxicity on normal tissues.<sup>48</sup>

In order to achieve a targeted application, specific targeting agents can be incorporated into the nanoparticle, including monoclonal antibodies<sup>48,111</sup>, peptides<sup>63</sup>, aptamers<sup>53</sup>, carbohydrates<sup>64,112</sup> and other receptors as folate<sup>65</sup> and transferrin<sup>113</sup> (Figure 6).



**Figure 6.** Schematic representation of targeting agents reported in the literature to induce active targeting of cancer cells when UCNPs have been used for PDT of cancer; **a)** UCNP functionalised with the different targeting agents and **b)** specific recognition of the receptors in the cell membrane in each case.

- **Antibodies**

Antibodies are proteins that recognise, highly specifically, other proteins. Some antibodies, such as trastuzumab and cetuximab, have been approved for therapeutics of some types of cancer;<sup>114</sup> and a large number of reports describe the modification of drugs and nanoparticles for the targeted delivery to cancer cells. Antibodies were the first targeting agents used to deliver PS-UCNPs specifically to the cancer cells to perform PDT.<sup>72</sup> In this pioneering work, Zhang *et al.* covalently functionalised the antibody anti-MUC1/episialin onto the surface of the silica capped UCNPs loaded with M-540 as PS to ensure the targeted PDT of breast cancer cells.<sup>72</sup> Thus, this example was not only the first lanthanide-based nanoparticles designed for PDT but the first active targeted PDT of cancer using UCNPs in combination with a PS drug. Following this initial paper, an large number of papers have reported antibody-PS-UCNPs conjugates for the targeted delivery of the nanoparticles to cancer cells/tissues and thus, with the aim of improving the selectivity of the PDT of cancer.

With the aim of improving the functionalisation of UCNPs with antibodies maintaining the functionality and selectivity of the targeting agent, Liang *et al.* reported a new synthetic strategy in which antibodies were added, in a controlled manner, to the UCNPs through a bifunctional fusion protein.<sup>115</sup> Core-shell NaYF<sub>4</sub>:Yb,Er@NaGdF<sub>4</sub> nanoparticles were synthesised using a solvothermal decomposition method and coated with a silica layer in the presence of RB using a water-in-oil microemulsion method yielding *ca.* 43 ± 2 nm UCNP@SiO<sub>2</sub>(RB). The UCNP@SiO<sub>2</sub>(RB) were further modified with a monoclonal antibody following a novel protocol that would allow the control of the orientation of the antibody and thus, minimise the hindrance of the antigen-binding sides during and after the functionalisation process. First, the UCNPs were modified with a bifunctional fusion protein that contained a silica-specific solid-binding peptide – to bind to the silica on the UCNP@SiO<sub>2</sub>(RB) – fused to an antibody-binding protein to specifically bind the Fc fragment of the antibody. Once this step was performed, a monoclonal antibody for epithelial cell adhesion molecules (EpCAM; also known as CD326) was added to the nanoparticle conjugate yielding anti-EpCAM-UCNP@SiO<sub>2</sub>(RB). Anti-EpCAM functionalisation was confirmed by a negative shift of the zeta-potential values and an increase of the hydrodynamic diameter of the nanoparticles. The energy transfer between the UCNPs and the RB was evidenced by a decrease of the upconversion luminescence emission of the UCNPs at *ca.* 545 nm. The ability of the anti-EpCAM-UCNP@SiO<sub>2</sub>(RB) to produce <sup>1</sup>O<sub>2</sub> was tested under 980 nm (1.5 W·cm<sup>-2</sup>) excitation using the DPBF singlet oxygen probe with a 30% of the DPBF consumed after 30 min irradiation. No <sup>1</sup>O<sub>2</sub> production was observed for non-irradiated anti-EpCAM-UCNP@SiO<sub>2</sub>(RB) or for irradiated anti-EpCAM-UCNP@SiO<sub>2</sub> confirming the importance of having

the three elements together, UCNPs+RB+980 nm excitation, to generate  $^1\text{O}_2$ . The ability of the anti-EpCAM-UCNP@SiO<sub>2</sub>(RB) to specifically target cancer cells was investigated *in vitro* with EpCAM-overexpressing human colon adenocarcinoma HT-29 cells and EpCAM-negative murine microglia BV2 cells. After 1 h incubation, the luminescence emission of the UCNPs was observed in the HT-29 but negligible fluorescence was detected in the BV2 cells indicating the specific cellular uptake of the anti-EpCAM-UCNP@SiO<sub>2</sub>(RB). To further confirm the targeting ability of the anti-EpCAM-UCNP@SiO<sub>2</sub>(RB), UCNPs@SiO<sub>2</sub>(RB) without antibody were tested in HT-29 cells showing less emission intensity compared to the cells incubated with anti-EpCAM-UCNP@SiO<sub>2</sub>(RB). Additionally, a control murine monoclonal antibody CRY104 (non-specific to EpCAM) was conjugated to the UCNPs@SiO<sub>2</sub>(RB) and incubated in HT-29 cells resulting in an insignificant green emission.<sup>115</sup> The intracellular ROS production of the anti-EpCAM-UCNP@SiO<sub>2</sub>(RB) upon 980 nm irradiation was confirmed in HT-29 cells using DCFH-DA (that converts to DCFH intracellularly) as  $^1\text{O}_2$  probe. A greater increase in the green fluorescence emission intensity due to the formation of DCFH was observed for those cells that had been incubated with anti-EpCAM-UCNP@SiO<sub>2</sub>(RB) and exposed to 980 nm irradiation compared to the change observed in the cells treated with anti-EpCAM-UCNP@SiO<sub>2</sub>. The PDT effect was also investigated *in vitro* using MTT assay resulting in *ca.* 20% dark cytotoxicity at 200  $\mu\text{g}\cdot\text{mL}^{-1}$  of anti-EpCAM-UCNP@SiO<sub>2</sub>(RB). Upon irradiation at 980 nm (1.5 W·cm<sup>-2</sup>, 10 min) *ca.* 40% cell viability was obtained indicating the therapeutic effect of the anti-EpCAM-UCNP@SiO<sub>2</sub>(RB) in HT-29 cells. Furthermore, higher PDT effect was evidenced for the anti-EpCAM-UCNP@SiO<sub>2</sub>(RB) than for the corresponding controls, anti-EpCAM-UCNP@SiO<sub>2</sub> and UCNPs@SiO<sub>2</sub>(RB).<sup>115</sup>

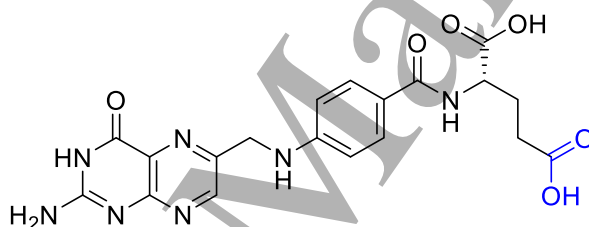
Ramírez-García *et al.* developed ZnPc-NaYF<sub>4</sub>:Yb,Er (60% Yb<sup>3+</sup> and 2% Er<sup>3+</sup>) nanoparticles bioconjugated with trastuzumab for the specific targeted PDT of HER2-positive breast cancer cells.<sup>116</sup> First, a ligand exchange reaction to remove the oleic acid from the oleate capped UCNPs was performed using cysteamine and then ZnPc molecules were covalently functionalised to the UCNPs through carbonamide bond formation between the amine group of the cysteamine (Cys) and the carboxyl group of the ZnPc. The ZnPc-UCNPs were then bioconjugated with trastuzumab (TRAS) *via* EDC/NHS chemistry and the concentration of antibody and reaction time were optimised to avoid aggregation or non-specific orientation. The functionalisation of the UCNPs was confirmed by measuring the FTIR spectra of the nanoparticles. The TRAS-ZnPc-UCNPs showed good colloidal stability and a size of *ca.* 23 nm. The energy transfer between the luminescence at 659 nm and the absorption at 675 nm (ZnPc) upon 975 nm excitation was calculated to be 84.3%.<sup>116</sup> ZnPc-UCNPs and TRAS-ZnPc-UCNPs were able to generate  $^1\text{O}_2$  in solution following irradiation at 972 nm (ABMA monitoring) while no obvious production was

observed for the control nanoparticles (Cys-UCNPs). Subsequently, the targeting ability of the TRAS-ZnPC-UCNPs was studied in MCF-7 (HER2-negative) and SK-BR-3 (HER2-positive) breast cancer cells using confocal microscopy with 980 nm excitation. Cys-UCNPs were internalised in both cells lines whereas the ZnPC-UCNPs were not observed in the cells indicating that the uptake of the nanoparticles is diminished when the ZnPC is present on the surface of the UCNPs. Finally, the TRAS-ZnPC-UCNPs were incubated in both cell lines showing only the upconversion luminescence signal on the SK-BR-3 cells. To evaluate The PDT effect of the TRAS-ZnPC-UCNPs, several concentrations of the nanoparticles (0 – 1000  $\mu\text{g/mL}$ ) were incubated in both cell lines and the cell viability was measured (XTT assay) after 975 nm ( $0.71 \text{ W}\cdot\text{cm}^{-2}$ , 5 min). Similar cytotoxicity results were obtained for both cell lines when the cells were treated either with Cys-UCNPs or ZnPC-UCNPs. However, higher reductions of the cell viability were observed when SK-BR-3 were incubated with TRAS-ZnPC-UCNPs and irradiated at 975 nm.<sup>116</sup> Therefore, the bioconjugation of PS-UCNPs with trastuzumab enable the targeted PDT of cancer cells that overexpress the tyrosine kinase receptor HER2.

Epithelial growth factor receptors (EGFRs) are commonly overexpressed in lung and breast cancers and in glioblastoma, thus different EGFR-based targeting strategies have been developed using antibodies.<sup>117</sup> Zhang and co-workers fabricated UCNPs functionalised with a non-immunoglobulin-derived affinity protein known as Affibody®.<sup>118</sup>  $\text{TiO}_2$ -capped  $\text{NaYF}_4:\text{Yb,Tm}$  nanoparticles were bioconjugated with the anti-EGFR Affibody through a PEG chain. To this aim, dimerised anti-EGFR was first reduced using dithiothreitol (DTT) and then reacted to maleimide-PEG-COOH yielding anti-EGFR-PEG-COOH that was grafted to silane and used for the covalent functionalisation of the  $\text{TiO}_2$ -UCNPs yielding anti-EGFR-PEG- $\text{TiO}_2$ -UCNPs (ca. 50 nm). The antibody functionalisation was confirm using FTIR. The anti-EGFR-PEG- $\text{TiO}_2$ -UCNPs show stability after 6 h stored in water and cell culture medium (10% FBS) but not when stored in PBS. The anti-EGFR-PEG- $\text{TiO}_2$ -UCNPs were evaluated *in vitro* in a range of cell lines including EGFR-positive cells such as human epidermoid A431 and human lung adenosquamous carcinoma H596, EGFR wild type cells such as lung cancer H460 cells and EGFR-negative cells such as MCF-7 and HepG2 cells. The results presented in the paper indicate the selectivity of the designed nanosystem towards EGFR expressing cells. The work was completed with a detailed *in vivo* evaluation of the anti-EGFR-PEG- $\text{TiO}_2$ -UCNPs. The nanoparticles were hemocompatible up to a dose of 50 mg/kg and exhibited 100% survival with no obvious toxic side effects in animals up to 120 days. Furthermore, the *in vivo* PDT effect of the anti-EGFR-PEG- $\text{TiO}_2$ -UCNPs was investigated confirming a delay in tumour growth and improved survival rates compared to conventional Ce6 PDT (655 nm).<sup>118</sup>

- **Folic acid**

Folate receptors (FRs) are overexpressed in many types of cancers including breast, lung, kidney and ovarian. There are 100 – 300 times more FRs in cancer than on healthy cells and they can be divided into three isoforms (FR $\alpha$ , FR $\beta$  and FR $\gamma$ ) being FR $\alpha$  the most extensively expressed in cancer cells.<sup>119,120</sup> Folic acid (FA) presents high binding affinity to FRs (dissociation constant ( $K_D$ ) of 0.1 – 1 nM)<sup>119</sup> and, once bound to the FR, FA can be internalised *via* an endocytic transport and accumulated in the cytosol.<sup>120</sup> Thus, the conjugation of FA with organic molecules and nanoparticles has been used as targeting strategy in cancer diagnosis and therapy. FA (**Figure 7**) has a low molecular weight and high stability; and it contains an acid terminal unit that can be employed to link amino-functionalised molecules or nanoparticles simple and low-cost strategy, *via* an amide formation reaction.<sup>120</sup> Therefore, FA-mediated active targeting using FA-UCNPs for PDT of cancer cells has been explored providing high sensitivity and specificity towards the detection of several cancer cells reducing the systemic side effects to normal cells.<sup>90,121-132</sup>



**Figure 7.** Chemical structure of folic acid; the terminal acid group (**blue**) of the glutamic acid is commonly used to bind other moieties.

The first example of *in vivo* targeted PDT using PS-UCNPs was reported by Idris *et al.* in 2012<sup>125</sup> where mesoporous silica coated NaYF<sub>4</sub>:Yb,Er nanoparticles were functionalised with two PS drugs, MC540 and ZnPc, and FA as targeting agent. The FA-ZnPc-MC540-UCNPs emitted two main upconverting luminescence emissions upon 980 nm irradiation, at 540 and 660 nm, overlapping to the absorption spectrum of MC540 and ZnPC, respectively. Dual-PS-UCNPs exhibited higher <sup>1</sup>O<sub>2</sub> generation than UCNPs singly loaded with either MC540 or ZnPc following 980 nm irradiation (2.5 W·cm<sup>-2</sup>, during intervals of 20 min) as observed using ABMA.<sup>125</sup> The intracellular production of ROS by the dual-PS-UCNPs following 980 nm irradiation (40 min) was confirmed in B16-F0 murine skin cancer cells using DCFDA and confocal microscopy. The control groups, UCNPs functionalised with only one PS and void UCNPs, showed lower ROS production. Only a reduction in cell viability of 55% (MTS assay) was obtained when the B16-F0 cells were

incubated with the dual-PS-UCNPs and irradiated at 980 nm (40 min) whereas a 25% decrease was observed for the void UCNPs showing the cytotoxicity of the UCNPs.<sup>125</sup> The efficacy of the dual-PS-UCNPs for *in vivo* PDT was investigated injecting the nanoparticles under the skin of C57BL/6 mice bearing B16-F0 melanoma cells and then irradiating at 980 nm ( $415 \text{ mW cm}^{-2}$ , 2 h) which induced an inhibition of the tumour growth and an enhancement in the population of apoptotic cells as compared to control experiments. A second approach was used in which the dual-PS-UCNPs were intratumorally injected into C57BL/6 mice bearing melanoma tumours and irradiated at 980 nm for 1 h. This treatment slowed the tumour growth during the 11 day period when the mice were monitored. Dual-PS-UCNPs were further functionalised with FA to target the FR overexpressed on B16-F0 cells and PEG to increase the blood circulation time of the UCNPs. Compared to the UCNPs without FA-PEG, the FA-PEG-dual-PS-UCNPs showed a significantly greater reduction in tumour growth when they were intravenously injected in mice bearing B16-F0 melanoma tumours and following NIR irradiation (4 h).<sup>125</sup> Although better results were obtained after the incorporation of FA and PEG, further optimisation is required since the complete regression of the tumours was not achieved with the reported nanosystem. To this aim, optimisation of the number of encapsulated PS drugs and the porous size of the silica layer can be assessed by determining the maximum energy transfer from the UCNPs to the PSs.

Incorporation of FA in amphiphilic coated UCNPs has also been investigated for active targeted PDT of cancer. Thanasekaran *et al.* reported the encapsulation of PS drugs following a phospholipid coating on the surface of UCNPs.<sup>122</sup> Compared to PEGylated strategies, lipid coating results in biocompatible and colloidal stable nanoparticles that are inert to immunological resistance.<sup>122</sup> Additionally, the fatty chain of the phospholipid layer enables the loading of PS drugs through hydrophobic interactions. In this work, oleate-capped  $\text{NaYF}_4:\text{Yb,Er}$  UCNPs were coated with zwitterionic phospholipids (L- $\alpha$ -phosphatidylcholine (EggPC) and cholesterol, 1:1 molar ratio) resulting in colloidal stable UCNPs with an average diameter of  $40 \pm 2 \text{ nm}$ .<sup>122</sup> In order to study the PS-loading efficiency of the phospholipid-coated UCNPs, a screening of several PS drugs, which absorption overlaps the upconversion luminescence bands, was performed including RB, meso-tetraphenylporphine (TPP), ZnPc, aluminum phthalocyanine chloride (AlPc), fac-(2,2'-bipyridine)-tricarbonylbromorhenium(I) ( $\text{Re}(\text{bpy})(\text{CO})_3\text{Br}$ ), perinaphthenone (PN) and MB. As expected, the most hydrophobic PS, such as the porphyrin-based PS, exhibited higher encapsulation efficiency and slower release rates when loaded onto the phospholipid-coated UCNPs than the less hydrophobic PS.<sup>122</sup> Determination of  $^1\text{O}_2$  generation by the PS-phospholipid-UCNPs irradiated at 980 nm was performed using p-nitrosodimethylaniline (RNO) in the presence of imidazole (RNO + imidazole method). TPP-UCNPs



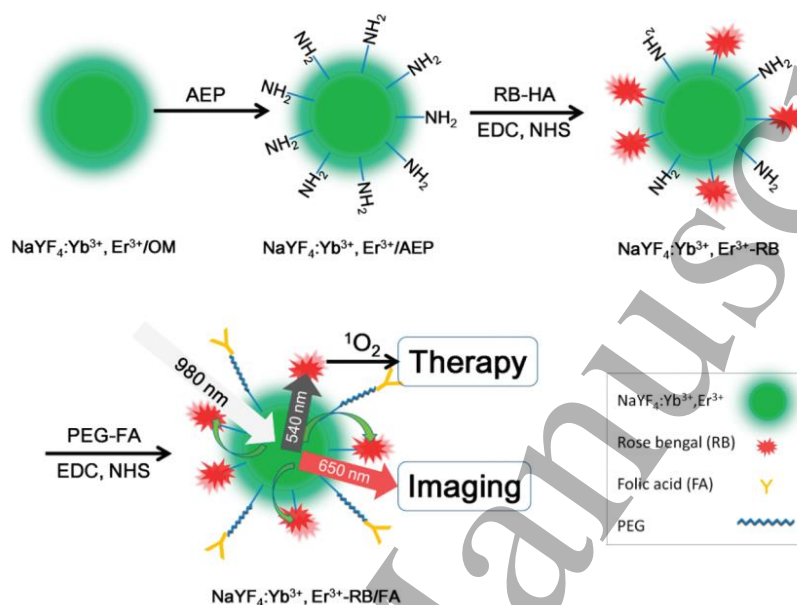
showed the best performance in the  $^1\text{O}_2$  production compared to the rest of PS drugs and were selected for cellular experiments.<sup>122</sup> The TPP-UCNPs were modified with FA (TPP-UCNP-FA) to assess the targeting ability of the nanosystem. TPP-UCNP-FA nanoparticles were separately incubated in FR-positive KB cells (keratin-forming tumour cell line HeLa) and FR-negative REF52 cells (rat embryonic fibroblast) showing higher receptor-mediated cellular uptake in KB cells. PDT studies performed in KB cells and REF52 cells incubated with TPP-UCNP-FA and irradiated at 980 nm (1 h) resulted in greater cell death for FR positive than for FR negative cells (cell viability determined staining the cells with propidium iodide). TPP-UCNP-FA were also investigated for *in vivo* PDT in mice bearing CT-26wt tumours *via* intratumoral injection and following irradiation at 980 nm ( $1\text{ W cm}^{-2}$ , 30 min). The tumour size was monitored over a period of 10 days and the results showed a very similar tumour growth delay for mice injected with TPP-UCNP-FA and TPP-UCNP and irradiated with NIR light.<sup>122</sup>

Another example of FA-modified amphiphilic coated UCNPs loaded with PS drugs was published by Cui *et al.*<sup>127</sup> FA-modified amphiphilic *N*-succinyl-*N'*-octyl chitosan (FA-SOC) was first synthesised by amide formation reaction between the carboxyl groups of the FA and the amino groups of the SOC and used to coat previously synthesised oleate-capped  $\text{NaYF}_4:\text{Yb,Er}$  nanoparticles (*ca.* 50 nm) *via* hydrophobic interactions between the octadecyl groups on the UCNPs and the octyl groups of FA-SOC. ZnPc was trapped into the nanosystem through hydrophobic interactions. The luminescence band at 660 nm (from the excitation for UCNPs at 980 nm) was used to activate the ZnPc to generate  $^1\text{O}_2$  whereas the second luminescence band (540 nm) was used to image the UCNPs. The highest loading capacity of ZnPc into the amphiphilic chitosan shell was 10%; however, the optimal behaviour was obtained with *ca.* 6% loading. Due to the sensitivity of the chitosan towards acidic pH values ( $< 6.5$ ), releasing studies of the ZnPc were performed at different pHs (7.4, 6.5 and 5.7) showing less than 20% leaching after 50 h at  $37^\circ\text{C}$  in all cases.<sup>127</sup> The FA-SOC-ZnPc-UCNPs were incubated in human liver cancer Bel-7402 cells and imaged using confocal microscopy confirming the intracellular co-localisation of the ZnPc and the UCNPs. Cytotoxicity experiments incubating FA-SOC-ZnPc-UCNPs in human embryo lung HELF and human breast MDA-MB-231 cancer cells showed a negligible decrease in cell viability (using MTT assay) under dark conditions. To investigate the targeting ability of FA-SOC-ZnPc-UCNPs in cells, several cancer cell lines with different levels of FR expression (Bel-7402, MDA-MB231 and A549) were cultured with the same concentration of nanoparticles. The results showed a concomitant relation between the increased uptake of the FA-SOC-ZnPc-UCNPs in cells expressing higher levels of FR. The FA-mediated internalisation was further confirmed with an FR blocking experiment in which before the incubation of the nanoparticles,

FR-positive Bel-7402 and MDA-MB-231 cells were treated with free FA. These results demonstrate the uptake of the FA-SOC-ZnPc-UCNPs in FR-positive cancer cells *via* FR-mediated endocytosis.<sup>127</sup> After confirming the cellular uptake of the FA-SOC-ZnPc-UCNPs, the intracellular <sup>1</sup>O<sub>2</sub> generation was investigated under 980 nm and 660 nm irradiation for the indirect and direct activation of ZnPc, respectively. To this end, DPBF and DCFDA ROS probes were separately added to Bel-7402 cells incubated with FA-SOC-ZnPc-UCNPs showing in both cases similar results. Higher ROS production was observed when the cells were excited at 660 nm (*ca.* 70%) than when 980 nm laser was used (*ca.* 55%) using the same power density (0.2 W·cm<sup>-2</sup>). When the cells were covered with pork tissue (1 cm), higher ROS generation was determined for cells irradiated at 980 nm (*ca.* 40%) than at 660 nm (*ca.* 15%). *In vivo* studies, performed with FA-SOC-UCNPs (without ZnPc) showed high toxicity of the nanoconstruct when administered at high doses (> 150 mg/kg) and accumulation in the liver, intestines, lungs and kidneys 24 h post injection. The targeting ability of FA-SOC-UCNPs over SOC-UCNPs was also demonstrated *in vivo*. Finally, the PDT treatment was investigated in S180 tumour-bearing mice using 980 nm or 660 nm irradiation conditions. 660 nm irradiation was superior when the tumours were directly exposed to the irradiation; however better results were obtained with 980 nm irradiation when a 1 cm pork tissue was placed over the tumour.<sup>127</sup>

To avoid the leaching of the PS drug from the nanosystem, Zhang and co-workers described UCNPs covalently functionalised with RB and containing FA as targeting agent.<sup>90</sup> Amine-functionalised NaYF<sub>4</sub>:Yb,Er nanoparticles were obtained by ligand exchange using 2-aminoethyl dihydrogenphosphate (AEP) replacing the oleylamine ligands obtained from the synthesis of the UCNPs. RB hexanoic acid was covalently bound to the amine-functionalised UCNPs *via* EDC/NHS chemistry yielding RB-UCNPs (**Figure 8**).<sup>90</sup> The luminescence spectrum of the UCNPs exhibited a significant decrease of the upconversion luminescence band at 540 nm in the presence of RB on the nanoparticle while the band at 650 nm remained stable; thus, confirming the effective energy transfer from the UCNPs to the RB. The FRET efficiency was estimated to be *ca.* 83%, which is higher than for non-covalent RB encapsulation strategies which reported maximum energy transfer efficiencies of *ca.* 65-68%.<sup>78,79</sup> The energy transfer was further confirmed by measuring the luminescence decay lifetimes, showing a decrease in the average decay value recorded at 540 nm for the RB-UCNPs.<sup>90</sup> The production of <sup>1</sup>O<sub>2</sub> by the RB-UCNPs under 980 nm irradiation was examined using DPBF as <sup>1</sup>O<sub>2</sub> probe, showing a 50% decrease in absorption after 16 min irradiation at 980 nm. For the intracellular studies, FA was covalently attached to the surface of the UCNPs through a PEG ligand (NH<sub>2</sub>-PEG-COOH) to enhance the targeting efficiency of the RB-UCNPs in cancer cells. FA-RB-UCNPs were incubated at different concentrations in JAR

choriocarcinoma and noncancerous NIH 3T3 fibroblast cells and the targeted-PDT treatment following NIR irradiation was investigated using MTT assay.<sup>90</sup> The JAR cells showed a significant decrease in the cell viability with an increase of FA-RB-UCNPs concentration while NIH 3T3 cells did not show changes in cell viability. A negligible decrease in cell viability was also observed for the control of non-irradiated cells incubated with.<sup>90</sup>



**Figure 8.** Schematic representation of the preparation of the FA-RB-UCNPs: NaYF<sub>4</sub>:Yb,Er UCNPs functionalised with RB, PEG and FA.<sup>90</sup> Reprinted from Ref. 90 with permission from American Chemical Society. §§§

Another strategy to enhance the energy transfer between the UCNPs and the PS drug is to enhance the upconversion luminescence of the UCNPs. To this aim, different strategies have been developed including the construction of core-shell nanoparticles to avoid any energy losses due to surface defects and/or to increase the doping concentration of the lanthanide ions to enhance the upconversion emission from the UCNPs. Using their previous work as starting point<sup>90</sup>, Zhang and co-workers, designed NaYF<sub>4</sub>:Yb,Er UCNPs with 5% additional Yb<sup>3+</sup> concentration (25% instead of the initial 20%) to increase the upconversion luminescence at 660 nm.<sup>129</sup> The resulting nanoparticles (*ca.* 30 nm) were coated with poly(allylamine) yielding NH<sub>2</sub>-UCNPs. ZnPc (containing carboxyl groups) was covalently attached to the NH<sub>2</sub>-UCNPs *via* crosslinking reaction. Additionally, PEG succinimidyl carbonate was incorporated onto the surface of the UCNPs enhancing the dispersibility and stability of the nanoparticles in biological media. Different concentrations of ZnPc were loaded onto the UCNPs and a 6% loading was found to be optimal for the generation of <sup>1</sup>O<sub>2</sub> under 980 nm irradiation (as determined using

DPBF). A comparative study between a covalent and a non-covalent (physical absorption) incorporation of ZnPc onto the UCNPs was performed showing higher  $^1\text{O}_2$  production when the PS drug was covalently attached to the nanoparticles.<sup>129</sup> In order to achieve the specific cancer targeting ability of the nanoparticles, FA was covalently linked to the ZnPc-PEG-UCNPs *via* a cross-linking strategy. Subsequently, the energy transfer between the UCNPs and the ZnPc was determined using steady-state upconverting luminescence spectroscopy and decay kinetics resulting in an 80.9%,<sup>129</sup> similar to the value obtained for the covalently functionalised RB-UCNPs (83%).<sup>90</sup> After the confirmation of the outstanding efficiency to generate  $^1\text{O}_2$  upon 980 nm irradiation in non-aqueous solution (74% DPBF consumption after 4 min irradiation), FA-ZnPc-PEG-UCNPs were incubated in HeLa cells (FR-positive) and human alveolar adenocarcinoma A549 cells (FR-negative). The upconversion fluorescence images of the incubated cells under 980 nm excitation ( $0.19 \text{ W}\cdot\text{cm}^{-2}$ ) showed the efficient cellular uptake *via* FR-mediated endocytosis in FR-positive cells whereas negligible upconversion emission was observed for the FR-negative cells. The targeting capability of the FA ligands was further demonstrated with FR blocking experiments in HeLa cells (previous addition of free FA) showing the absence of fluorescence in the incubated cells upon 980 nm excitation.<sup>129</sup> The PDT effect of the FA-ZnPc-PEG-UCNPs in HeLa cells upon NIR irradiation was studied using MTT assay and show a significant decrease (70%) of the HeLa cell viability when cells were treated with  $200 \mu\text{g}\cdot\text{mL}^{-1}$  of FA-ZnPc-PEG-UCNPs and irradiated at 980 nm ( $0.39 \text{ W}\cdot\text{cm}^{-2}$ , 10 min). The cell viability results showed considerable dark cytotoxicity of the nanoparticles at concentrations above  $200 \mu\text{g}\cdot\text{mL}^{-1}$  whereas a negligible decrease was obtained with lower concentrations. The NIR light induced PDT effects were also investigated *in vivo* using epa1-6 tumour-bearing C57/6J mice. Two weeks following intratumoral injection of the FA-ZnPc-PEG-UCNPs and irradiation at 980 nm ( $0.39 \text{ W cm}^{-2}$ , 15 min) a significant reduction in the tumour growth was observed (tumour inhibitory ratio *ca.* 80.1%). This effect was not observed for control groups treated with NIR irradiation or FA-ZnPc-PEG-UCNPs only; thus, confirming the PDT effect of irradiated FA-ZnPc-PEG-UCNPs. The behaviour of ZnPc-PEG-UCNPs without FA to fully confirm the targeting ability of the nanoparticles was not investigated in this work.<sup>129</sup>

Wang *et al.* developed UCNPs ( $\text{NaYF}_4:\text{Yb}(8\%)/\text{Ho}(1\%)@ \text{NaYF}_4:\text{Nd}(20\%)@ \text{NaYF}_4$  core-shell-shell) functionalised with RB through an amide coupling reaction using EDC/NHS chemistry in which is the first example reported in the literature with UCNPs excitable at 808 nm for PDT treatment.<sup>78</sup> The  $^1\text{O}_2$  production of the RB-UCNPs was investigated in solution using DPBF as  $^1\text{O}_2$  probe. A comparative study of PDT performance of RB-UCNPs, depending on the active layer thickness, was performed using 808 nm irradiation showing the larger production of  $^1\text{O}_2$  with a shell

thickness of 1.6 nm (compared to shells of 0.4, 2.5 and 4.2 nm). HeLa cells were used to confirm the efficiency of the PDT effect *in vitro* following 808 nm excitation and minimisation of the overheating effect when using this irradiation wavelength was confirmed following a comparative study with 980 nm irradiation.<sup>78</sup>

Hypericin-loaded NaYF<sub>4</sub>:Yb,Er nanoparticles modified with FA were reported by Yang *et al.*<sup>124</sup> The oleate-capped UCNPs were first coated with a silica layer and the photosensitiser hypericin was covalently bound to the silica shell. The absorption band of hypericin at 550 nm overlapped the green luminescence emission of the UCNPs ensuring the effective energy transfer. FA was then conjugated to the surface of the hypericin-UCNPs for the receptor-mediated delivery of the UCNPs.<sup>124</sup> The production of <sup>1</sup>O<sub>2</sub> by the FA-hypericin-UCNPs under 980 nm irradiation was confirmed using ABMA as a <sup>1</sup>O<sub>2</sub> chemical probe. Two photon laser scanning confocal microscopy was used to study the uptake of the FA-hypericin-UCNPs in FR-overexpressing cancer cells (HeLa cervical cancer cells) and normal cells with lower FR expression (293T embryonic kidney cells), showing higher internalisation of the nanoparticles in HeLa cells. Additionally, the uptake of FA-hypericin-UCNPs and hypericin-UCNPs was compared in HeLa cells resulting in a higher fluorescence emission intensity in the cells when FA-hypericin-UCNPs were incubated, confirming the targeting ability of the FA-hypericin-UCNPs.<sup>124</sup> The PDT effect of the FA-hypericin-UCNPs was qualitatively investigated using apoptosis assays, staining treated HeLa cells with Annexin V-FITC/PI after irradiation at 980 nm. The fluorescence images of HeLa cells treated with FA-hypericin-UCNPs after NIR irradiation showed apoptotic cells whereas control groups of cells treated with the nanoparticle but without irradiation did not exhibit any indication of the apoptotic process. Flow cytometry was used for the quantitative study of the PDT effect in HeLa cells by FA-hypericin-UCNPs, showing 36% of early and late apoptosis after 15 min irradiation at 980 nm of treated HeLa cells.<sup>124</sup>

Zhang and co-workers reported core-shell NaYF<sub>4</sub>:Yb,Er@NaYF<sub>4</sub>:Yb,Tm covalently functionalised with monomaleic fullerene (C<sub>60</sub>MA) as PS drug, PEGylated ligands to enhance the biocompatibility of the nanoparticles and FA as targeting agent.<sup>128</sup> To achieve the covalent chemical bonding between the ligands and the nanoparticles, UCNPs were first coated with poly(allylamine) providing an amine functionalisation. C<sub>60</sub>MA was covalently attached to the surface of the amine functionalised UCNPs *via* amide bond formation and a PEGylation process was then performed using PEG-succinimidyl carbonate to increase the water-dispersibility of the C<sub>60</sub>-UCNPs. The resulting PEG-C<sub>60</sub>-UCNPs presented a hydrodynamic diameter of 64 nm measured using dynamic light scattering (DLS). The UCNPs exhibited several upconverting luminescence emission bands (450, 475, 540, 650 and 808 nm) following 980 nm irradiation

which overlap (except 808 nm) the broad absorption spectrum of the C<sub>60</sub>MA. The effective energy transfer between the UCNPs and the C<sub>60</sub>MA was confirmed using steady state upconversion luminescence measurements and lifetime luminescence decays. Even though the intensities at 450, 475, 540 and 650 nm were all significantly quenched, the maximum energy transfer was calculated to be 79% at 450 nm.<sup>128</sup> The <sup>1</sup>O<sub>2</sub> production of the PEG-C<sub>60</sub>-UCNPs was confirmed using fluoresceinyl cypridina luciferin analogue (FCLA) as chemical probe. PEG-C<sub>60</sub>-UCNPs were further functionalised with FA *via* covalent amine formation between the carboxyl group of the FA and the free amine groups on the surface of the nanoparticles. The resulting FA-PEG-C<sub>60</sub>-UCNPs were incubated in FR-positive HeLa cells both, using a folate-free and a folate-supplemented medium, and in FR-negative A549 cells and the cellular uptake was monitored recording the emission at 808 nm using confocal microscopy. FA-PEG-C<sub>60</sub>-UCNPs were taken up by HeLa cells cultured in folate-free medium; however, fewer nanoparticles were internalised in HeLa cells cultured with folate-supplemented medium and in A549 cells. Unfortunately, cell viability studies (MTT assay) showed that very high irradiation power (limits set for human skin exposure to 980 nm light is 0.72 W cm<sup>-2</sup>) and high nanoparticle concentration were needed to induce only a *ca.* 50% viability decrease in HeLa cells incubated with FA-PEG-C<sub>60</sub>-UCNPs (500 µg·mL<sup>-1</sup>) and irradiated at 980 nm (1.37 W·cm<sup>-2</sup>, 10 min).<sup>128</sup> The authors claimed that the low PDT efficiency obtained was caused by large distances between the C<sub>60</sub> and the core of the UCNPs. To reduce the distance and thus to enhance the energy transfer between the UCNPs and the PS, Zhang and co-workers functionalised core-shell NaYF<sub>4</sub>:Yb,Er@NaYF<sub>4</sub>:Yb,Tm nanoparticles with C<sub>60</sub> following a non-covalent strategy.<sup>130</sup> A ligand exchange method was used to replace the oleylamine groups on the surface of the UCNPs by C<sub>60</sub>MA molecules presenting carboxyl groups. Additionally, PEG-block-poly(caprolactone) was incorporated on the C<sub>60</sub>-UCNPs to enhance the stability of the nanosystems in aqueous solutions. The maximum loading capacity obtained for C<sub>60</sub> was found to be 22.5% which was higher than when the covalent strategy was followed (10.5%).<sup>128</sup> The stability of the PEG-C<sub>60</sub>-UCNPs was investigated showing a C<sub>60</sub> release of 2.5% after 72 h in PBS.<sup>128</sup> An enhanced energy transfer between the UCNPs and the PS was obtained by the ligand exchange strategy compared to the covalent assembly, 98.7% and 79% at 450 nm respectively. The <sup>1</sup>O<sub>2</sub> production efficiency was then confirmed using FCLA as chemical probe following irradiation at 980 nm. The results obtained for the <sup>1</sup>O<sub>2</sub> generation of PEG-C<sub>60</sub>-UCNPs cannot be directly compared to the covalently assembled C<sub>60</sub>-UCNPs since different concentrations of C<sub>60</sub> were loaded in both systems. The PEG-C<sub>60</sub>-UCNPs were incubated in HeLa cells and the production of <sup>1</sup>O<sub>2</sub> was achieved following 980 nm irradiation (0.39 W·cm<sup>-2</sup>, 5 min) as confirmed using DCFDA and fluorescence images.<sup>130</sup> To achieve targeting, the PEG-C<sub>60</sub>-UCNPs were further functionalised with FA, directly attached to the PEG units obtaining a FA loading of

5.1%. The FA-PEG-C<sub>60</sub>-UCNPs were incubated in HeLa (FR-positive) and A549 (FR-negative) cells and a higher cellular uptake was observed for HeLa cells when monitoring the luminescence at 808 nm.<sup>130</sup> Subsequently, the PDT effect of FA-PEG-C<sub>60</sub>-UCNPs was studied in HeLa cells (MTT assay) and a 35% viability decrease was observed for cells incubated with FA-PEG-C<sub>60</sub>-UCNPs (500 µg·mL<sup>-1</sup>) and irradiated at 980 nm (0.39 W·cm<sup>-2</sup>, 10 min). The dark toxicity of the FA-PEG-C<sub>60</sub>-UCNPs in HeLa cells was negligible at 500 µg·mL<sup>-1</sup>.<sup>130</sup> This study concluded that the ligand exchange design of FA-PEG-C<sub>60</sub>-UCNPs exhibits superior *in vitro* therapeutic effect than the covalently conjugated FA-PEG-C<sub>60</sub>-UCNPs at lower laser power density. *In vivo* experiments were performed in mice bearing Hepa1-6 tumours (FR-positive) that showed tumour accumulation of tail vein injected FA-PEG-C<sub>60</sub>-UCNPs 2 h following injection. On the other hand, C<sub>60</sub>-UCNPs needed 24 h to accumulate in the tumour following injection and as a result of the EPR effect.

Ai *et al.* reported core-shell-shell NaYbF<sub>4</sub>:Nd@NaGdF<sub>4</sub>:Yb,Er@NaGdF<sub>4</sub> nanoparticles covalently functionalised with Ce6 as photosensitiser and PEGylated modified FA as targeting agent.<sup>121</sup> These UCNPs are excitable at 808 nm and emit luminescence at 520 – 560 nm and 650 – 690 nm. The absorption spectrum of Ce6 exhibits a maximum at 660 nm which perfectly overlaps the red luminescence emission peak of the UCNPs. The nanoparticles were first modified with AEP *via* ligand exchange to obtain the amino functionalisation used to covalently attach the Ce6. Finally, the Ce6-UCNPs were capped with FA *via* a dual functionalisation PEGylated unit (NH<sub>2</sub>-PEG-COOH).<sup>121</sup> The energy transfer between the UCNPs and the Ce6 was confirmed by steady-state upconversion luminescence measurements showing a 70% efficiency and by luminescence lifetime decays. The production of <sup>1</sup>O<sub>2</sub> by FA-Ce6-UCNPs under 808 nm irradiation increased with increasing Ce6 loading concentrations as observed using DPBF being 10% (w/w) the most effective concentration and thus, the selected for the biological experiments. Experiments of light penetration depth were conducted in solution adding different thicknesses of pork slices between the sample and the laser sources (808 or 976 nm). A decrease in <sup>1</sup>O<sub>2</sub> generation was observed with increasing thickness and deeper tissue penetration was achieved with 808 nm light.<sup>121</sup> *In vitro* experiments using FA-Ce6-UCNPs were performed in KB cells (FR-positive) and A549 cells (FR-negative) and resulted in higher uptake of the nanoparticles by the FR-positive human cancer cells. The intracellular PDT effect of FA-Ce6-UCNPs was investigated and a decrease in cell viability (MTT assay) to 8% was observed for KB cells incubated with the nanoparticles following irradiation at 808 nm. Different concentrations of nanoparticles were tested showing an evident PDT effect after 5 min irradiation when cells were incubated with 100 µg mL<sup>-1</sup> of FA-Ce6-UCNPs (negligible dark toxicities were observed for this nanoparticle concentration).<sup>121</sup>

Zhao *et al.* developed UCNPs with folic acid-polyethylene glycol-poly(aspartic acid-hydrazone)-dihydrolipoic acid (FA-PEAH) polymer chains conjugated to the surface.<sup>133</sup> Further functionalisation with pheophorbide a (Pha) as a PS drug *via* an acid-labile hydrazone linker allowed for pH-responsive release of the Pha within the lysosomal compartments of the cells. The emission band of UCNPs at *ca.* 670 nm overlaps with the main absorption band of Pha (broad band at 690 nm) indicating the potential energy transfer between the UCNPs and the PS drug. The successful activation of the Pha upon excitation of the FA-PEAH-UCNPs-Pha at 980 nm was confirmed in solution by detection of the formation of  $^1\text{O}_2$  using DPBF as a probe. Intracellular experiments in MCF7 cells proved the improved water dispersibility of the Pha when present on the surface of the UCNPs. Furthermore, FA-PEAH-UCNPs-Pha ( $30 \mu\text{g mL}^{-1}$ , 980 nm,  $0.1 \text{ mW cm}^{-2}$ , 5 min) showed higher cytotoxicity than the free Pha confirming the improved PDT treatment when using UCNPs. The FA-PEAH-UCNPs-Pha showed also an enhanced PDT effect compared to the PEAH-UCNPs-Pha confirming the targeting ability of the nanosystem.<sup>133</sup> Another example of UCNPs functionalised with FA for targeted PDT was developed by Lim *et al.* in which TCPP was used as PS drug.<sup>134</sup> Core-shell UCNPs were coated with silica and further functionalised *via* APTED addition with TCPP-NHS, PEG-NHS, and FA/PEG-NHS. The resulting UCNPs@SiO<sub>2</sub>-NH<sub>2</sub>@FA/PEG/TCPP nanoparticles were tested in HeLa cells showing similar toxicity results for the free TCPP irradiated at 660 nm and for the UCNPs@SiO<sub>2</sub>-NH<sub>2</sub>@FA/PEG/TCPP irradiated under 808 nm. The cell viability was compared under normoxic and hypoxic conditions showing a significant reduction of the PDT effect in the absence of O<sub>2</sub>.<sup>134</sup>

#### • Transferrin

The receptor for transferrin (known as TfR1 or CD71) is expressed at low levels in most normal human tissues. However, this receptor is expressed at levels many times higher in malignant cells and thus why it is a popular receptor to target for cancer therapy.<sup>135</sup>

With the aim of targeting these receptors, Liu *et al.* designed transferrin decorated UCNPs for the targeted PDT of cancer cells upon NIR irradiation.<sup>136</sup> The oleate-capped NaYF<sub>4</sub>:Yb,Tm nanoparticles containing 20% Yb and 0.5% Tm were first treated to remove the oleic acid ligands *via* an acid treatment and then functionalised with polyelectrolyte poly[9,9-bis(4'-sulfonatobutyl)fluorine-*alt-co*-(1,4-benzo-{2, 1', 3}-thiadiazole)] sodium salt (PFSBT) as PS and with transferrin (Tf) as targeting agent. The PFSBT-Tf-UCNPs were then further functionalised with a second PS, titanocene (Tc) able to generate free radicals and with high binding affinity toward the iron chelating Tf. Irradiation of the UCNPs at 980 nm resulted in emission peaks at

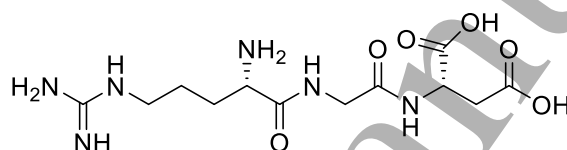


290, 345, 361, 450, 474 and 800 nm, which, apart from 800 nm, overlapped with the absorption of Tc and the PFSBT. An 87% energy transfer from the UCNPs luminescence emission to the PS drugs was estimated at 450 nm and lifetime measurements showed a decrease from 594 to 389  $\mu$ s which also confirmed the energy transfer.<sup>136</sup> The PFSBT-Tf-Tc-UCNPs were incubated in MCF-7 breast cancer cells to examine the PDT effect of the nanostructures upon 980 nm irradiation ( $0.6 \text{ W} \cdot \text{cm}^{-2}$ ). The photo-cytotoxicity of the PFSBT-Tf-Tc-UCNPs was determined by fluorescence microscopy using calcein acetoxymethylester (Calcein-AM) to stain the live cells and PI to stain the dead cells. The results obtained at different concentrations of PFSBT polymer on the nanoparticles showed an evidence number of dead cells when irradiating at 980 nm UCNPs loaded with 10  $\mu$ g of the PFSBT. Experiments with different concentrations of Tf-Tc on the UCNPs were also performed showing an increased cell death when higher amounts were used. *In vivo* PDT experiments using PFSBT-Tf-Tc-UCNPs were performed in a mouse model bearing the H22 tumour and showed a significant inhibition of the tumour growth when the animals received the PFSBT-Tf-Tc-UCNPs and irradiation at 980 nm ( $0.6 \text{ W cm}^{-2}$ , 30 min).<sup>136</sup>

Transferrin has also been used for the targeted delivery of PS-UCNPs containing also the chemotherapeutic drug doxorubicin (DOX) – dual therapy systems.<sup>137,138</sup> Zhang *et al.* reported  $\text{NaYF}_4:\text{Yb, Tm}:\text{NaYF}_4$  nanoparticles containing the PS hypocrellin A (HA) incorporated into a mesoporous silica shell that was further functionalised to incorporate DOX *via* silane coupling reaction and a UV cleavable linker (4-(2-carboxy-ethylsulfanylmethyl)-3-nitro-benzoic acid (CNBA) that functions as a gate to permit the controlled release of the drugs.<sup>137</sup> Finally, transferring was incorporated to the system to achieve targeting delivery of the system. HA-UCNPs were able to produce  $^1\text{O}_2$  in solution under irradiation at 980 nm ( $0.5 \text{ W cm}^{-2}$ ) as monitored using DFBF. The CNBA-DOX-HA-UCNPs showed a photoinduced controlled release of the DOX upon irradiation with NIR light ( $0.5 \text{ W cm}^{-2}$ ) ascribed to the UV cleavable CNBA linkers. The PDT effect of the CNBA-DOX-HA-UCNPs was evaluated (MTT assay) in HeLa and MCF-7 cells observing a synergistic effect of the dual treatment following irradiation at 980 nm ( $0.15 \text{ W cm}^{-2}$ , 20 min). Following these studies, Tf was incorporated into the UCNPs and the targeting ability of the nanosystem was evaluated in HeLa and MCF-7 cancer cells and 293T normal cells were used as controls. Higher accumulation of Tf-CNBA-DOX-HA-UCNPs was observed compared to CNBA-DOX-HA-UCNPs.<sup>137</sup> Similar results were obtained by the same authors when Ce6 was used as the PS drug and the enzyme and pH-sensitive linker succinic acid-glycine-phenylalanine-leucine-glycine was used as the gate to release DOX.<sup>138</sup>

## • Peptides

Peptides have also been used for the targeting of cancer cells since they can enhance the ability to enter the cells (cell penetrating peptides) or they can specifically target tumour epitopes.<sup>139</sup> In addition, peptides are easy to synthesise, present moderate chemical stability and their small molecular weight allows better tumour penetration. *Trans*-activating transcriptional (TAT) activator is an example of cell penetrating peptides that have been successfully used for intracellular delivery of nanoparticles including micelles, liposomes, quantum dots, UCNPs, polymeric, iron oxide, silica and gold nanoparticles.<sup>140-142</sup> The cancer-associated receptors targeted by peptides include integrins, prostate-specific membrane antigen, transferrin receptor, HER2, aminopeptidase N and CXCR4.<sup>143</sup> The tripeptide arginine–glycine–aspartic acid (RGD) (**Figure 9**) is commonly used to target cancer cells and preferentially binds to  $\alpha_v\beta_3$  integrin receptors which are overexpressed on angiogenic endothelial cells.<sup>139</sup>



**Figure 9.** Chemical structure of RGD peptide

Specific peptides with affinity for tumour cells can be combined with PS-nanoparticles to achieve targeted PDT. Peptide-decorated UCNPs have been developed for NIR-activated targeted-PDT of cancer.<sup>141,142,144-147</sup> For example, Wang *et al.* developed polymer coated UCNPs functionalised with MC540 and RGD peptide to achieve targeted PDT.<sup>144</sup> First, PMAO was grafted with L- $\alpha$ -phosphatidylethanolamine, dioleoyl (DOPE) and RGD peptide. Next, NaYF<sub>4</sub>:Yb,Er nanoparticles were coated with the RGD-PMAO-DOPE *via* reverse phase evaporation method resulting in a hydrodynamic diameter of 147 nm. MC540 was trapped into the amphiphilic shell showing a loading efficiency of 9.3%. The <sup>1</sup>O<sub>2</sub> production of MC540-RGD-PMAO-DOPE-UCNPs was confirmed in solution under 980 nm irradiation using ABMA as molecular probe. MC540-RGD-PMAO-DOPE-UCNPs were taken up by MCF-7 breast cancer cells as confirmed by measuring the upconversion luminescence of the UCNPs. The intracellular ROS production was confirmed upon irradiation of cells incubated with MC540-RGD-PMAO-DOPE-UCNPs at 980 nm (ABMA emission measured intracellularly).<sup>144</sup> However, the authors do not report controls of, for example, non-irradiated cells treated with the MC540-RGD-PMAO-DOPE UCNPs to confirm that the observed ROS production was a consequence of the 980 nm irradiation. To investigate the intracellular PDT effect of the nanoparticles, MTS assay of treated MCF-7 breast cancer cells was performed.

A 60% reduction of the cell viability (MTS assay) was obtained after 30 min irradiation of the cells incubated with MC540-RGD-PMAO-DOPE-UCNPs at 980 nm.<sup>144</sup> Although the cell viability decrease obtained for the MC540-RGD-PMAO-DOPE-UCNPs was higher than for the cells treated with MC540-PMAO-DOPE UCNPs without RGD as targeting agent (40%), controls of, for instance, the dark toxicity of the nanoparticles were not performed. Another example, by Hou *et al.*, reports UCNPs decorated with a mesoporous silica shell doped with ZnPc as PS and a cross-linked lipid triple layer formed by PEGylated amphiphilic octadecyl-quaternised polyglutamic acid (OQPGA) which can be further functionalised with cationic RGD peptide.<sup>145</sup> The ZnPc-UCNPs showed an encapsulation efficiency of *ca.* 65%. A 35% ZnPc leached out after 200 min when no crosslinked lipid layer was present and this was reduced to 12.5% in the presence of the lipid layer.<sup>145</sup> The cellular uptake was investigated in HeLa cells substituting the ZnPc by rhodamine to facilitate the fluorescence detection in the microscope. After confirming the co-localisation of the UCNPs and the fluorescence dye by fluorescence microscopy, RGD peptide was incorporated onto the nanoparticles and a slight increase in cellular uptake was observed. The RGD-ZnPc-UCNPs were able to generate  $^1\text{O}_2$  under 980 nm irradiation at higher rates than when free ZnPc was tested (ABMA used as probe). The PDT effect of RGD-ZnPc-UCNPs was evaluated in HeLa cells (MTT assay) showing lower cell viability for cells incubated with RGD-ZnPc-UCNPs and ZnPc-UCNPs and irradiated at 980 nm ( $1.5 \text{ W}\cdot\text{cm}^{-2}$ , 30 min) than when no irradiation was applied. High irradiation power was needed to achieve these results.<sup>145</sup> Although the authors proved the efficiency of the cross-linked lipid layer on the UCNPs reducing the leaching of the PS drug and enhancing the stability of the nanoparticles, additional experiments are required to demonstrate the targeting activity of the nanoparticles decorated with RGD peptide. For instance, tests of the PDT effect *in vivo* will validate the selectivity of the UCNPs to reduce the tumour size *via* PDT.

The aspartyl residue of the linear RGD can suffer a chemical degradation and thus cause the lack of biological activity. The stability against enzymatic degradation of the RGD peptides can be enhanced by using cyclic RGD derivatives.<sup>148</sup> An example of cyclic RGD peptide for targeted PDT using UCNPs was published by Zhou *et al.* and involved  $\text{NaYF}_4:\text{Yb,Er}$  nanoparticles modified with *o*-carboxymethylated chitosan and further functionalised with cyclic Arg-Gly-Asp-(D)-Tyr-Lys (c(RGDyK)) and Ppa as PS drug through the carboxyl groups and the amine groups of the *o*-carboxymethylated chitosan, respectively.<sup>146</sup> Ppa was loaded at 2.8 mg Ppa/mg UCNPs and the RGD-Ppa-UCNPs exhibited high stability at different pH (5, 7.4 and 8) for 24 h. The RGD-Ppa-UCNPs were able to produce higher amount of  $^1\text{O}_2$  when irradiated at 635 nm ( $20 \text{ mW cm}^{-2}$ ) compared to free Ppa (FCLA used as probe).<sup>146</sup> *In vitro* experiments were then performed to

study the  $\alpha_v\beta_3$  integrin targeting capacity of the RGD-Ppa-UCNPs. Integrin positive cells (U87-MG brain cancer cells) and integrin negative cells (MCF-7 breast cancer cells) were incubated with RGD-Ppa-UCNPs and the intracellular production of ROS was measured using DCFA upon irradiation at 980 nm ( $0.5 \text{ W}\cdot\text{cm}^{-2}$ ). Higher production of  $^1\text{O}_2$  was observed for the integrin positive cell line. The  $\alpha_v\beta_3$  integrin-mediated endocytosis of the nanoparticles was confirmed with control experiments where the U87-MG cells were pre-treated with an excess of free c(RGDyK) which showed very low uptake. The PDT effect of RGD-Ppa-UCNPs was also investigated using CCK8 cell viability assay with U87-MG and MCF-7 cells resulting in a significant difference between both cells lines, 60% and 15% reduction, respectively, following irradiation at 980 nm ( $0.5 \text{ W}\cdot\text{cm}^{-2}$ ).<sup>146</sup> The reported nanosystem showed higher  $^1\text{O}_2$  generation than the free PS drug, elevated stability and specific binding to the integrin  $\alpha_v\beta_3$ -positive tumour cells. *In vivo* experiments would be relevant to confirm the benefit of NIR activated PDT for deep-seated tumours and to further confirm the targeting activity of the RGD-Ppa-UCNPs.

Another targeting moiety based on peptides is the TAT protein which is a cell penetrating peptide that can be used as intracellular drug delivery vector. For example, Zhang *et al.* reported core-shell-shell  $\text{NaYbF}_4\text{:Nd@NaGdF}_4\text{:Yb,Er@NaGdF}_4$  nanoparticles functionalised with Ppa as PS drug, PEG and TAT peptide.<sup>142</sup> The oleate-capped UCNPs were first modified with PMAO-PEG- $\text{NH}_2$  allowing the covalent functionalisation of the TAT. Then, Ppa was loaded onto the surface of the PMAO-PEG-TAT-UCNPs *via* hydrophobic interactions resulting in a loading capacity of 0.6 mg Ppa/mg UCNPs. The  $^1\text{O}_2$  generation upon 808 nm irradiation of the Ppa-UCNPs at different loading concentrations (0.025, 0.05, 0.1 and 0.2 ratios) was confirmed using DPBF as chemical probe with the best results obtained when using a loading amount of Ppa of 0.05 mg Ppa/mg UCNPs. The Ppa-UCNPs were stable in a PBS buffer solution (pH 7.4) for a minimum of 4 h.<sup>142</sup> Subsequently, TAT modified UCNPs exhibited a higher cellular uptake in HeLa cells than UCNPs without TAT – as determined by quantification of Gd concentrations using ICP-OES. Intracellular generation of ROS upon irradiation at 808 nm was observed in HeLa cells incubated with the modified UCNPs using DCFDA as fluorescent molecular probe. These results agree with the significant decrease in the cell viability following 808 nm irradiation ( $6 \text{ W}\cdot\text{cm}^{-2}$ , 5 min).<sup>142</sup> Co-localisation studies were performed showing the majority of the Ppa accumulated in the same cytoplasmic region of HeLa cells than the UCNPs verifying the stability of the Ppa-UCNPs after their internalisation into the cells. Ppa was localised in the mitochondria as confirmed by co-localisation studies using MitoTracker green. Additionally, JC-1 assay was used to monitor the damage in the mitochondria upon 808 nm irradiation of cells incubated with Ppa-UCNPs, confirming the potential of the nanosystem for mitochondria-targeted PDT.<sup>142</sup> However,

although the authors demonstrate the phototherapeutic efficiency of the Ppa-UCNPs and the enhanced cellular uptake when TAT peptide was present, it is important to note that the power of laser used in this work is extremely high and not applicable for *in vivo* experiments. Therefore, the efficiency of the system at lower power densities needs to be determined. In order to enhance the cancer-targeting ability of the UCNPs, the same group developed UCNPs decorated with the pH-low insertion peptide (pHLIP) which is a water-soluble membrane peptide able to specifically cross the cell membrane only at slightly acidic pH.<sup>147</sup> The authors synthesised Ppa-core-shell-shell NaYbF<sub>4</sub>:Nd@NaGdF<sub>4</sub>:Yb,Er@NaGdF<sub>4</sub> containing pHLIP covalently attached to the UCNPs. A Ppa release of 10% was observed for pHLIP-Ppa-UCNPs stored under neutral and acidic pH conditions (PBS buffer of pH 7.4 or 6.5) for 40 h.<sup>147</sup> Subsequently, the targeting ability of the pHLIP-Ppa-UCNPs dissolved in PBS at pH 6.5 and 7.4 was investigated in HeLa cervical carcinoma cells. Using confocal laser microscopy, higher emission intensities were observed upon 808 nm excitation when the cells were incubated with pHLIP-Ppa-UCNPs at pH 6.5 indicating the elevated efficiency of the pHLIP-Ppa-UCNPs to penetrate the cell membrane in an acidic environment. Following the same protocol, a comparative study between pHLIP-Ppa-UCNPs and NH<sub>2</sub>-Ppa-UCNPs was performed showing higher UCNPs concentration for the pHLIP-Ppa-UCNPs at pH 6.5. These results indicated that the higher efficiency of the pHLIP-Ppa-UCNPs to enter cancer cells at slightly acidic pH is consequence of the pHLIP peptide functionalisation. Then, the intracellular ROS production of the pHLIP-Ppa-UCNPs at both pH values was evaluated under 808 nm irradiation (6 W·cm<sup>-2</sup>) during 10 min using DCFDA as a probe. The results showed higher ROS generation when HeLa cells were incubated with pHLIP-Ppa-UCNPs at pH 6.5 as expected from the higher uptake at this pH. Measurements of the cell viability were performed to evaluate the photo-cytotoxicity of the pHLIP-Ppa-UCNPs in HeLa cells. A significant decrease of the cell viability was observed when the cells were treated with 50 µg·mL<sup>-1</sup> of pHLIP-Ppa-UCNPs at pH 6.5 and irradiated at 808 nm (6 W·cm<sup>-2</sup>) during 5 min. At this concentration, the cell viability of the non-irradiated cells remained 95.2 ± 11.5%. At neutral pH conditions, a very small reduction of the cell viability was observed even with 200 µg·mL<sup>-1</sup> of pHLIP-Ppa-UCNPs indicating that the PDT efficiency of the pHLIP-Ppa-UCNPs increases at slightly acidic microenvironments. Additionally, 4T1 cells were incubated with pHLIP-Ppa-UCNPs at pH 6.5 showing the same behaviour than for HeLa cells.<sup>147</sup> *In vivo* experiments were then performed, in BALB/c mice bearing 4T1 tumours, confirming the ability of the pHLIP-Ppa-UCNPs to reduce the tumour size *via* PDT treatment (980 nm, 0.5 W cm<sup>-2</sup>, 30 min).

In order to combine the targeted delivery achieved when using RGD peptide and the ability to cross the cell membrane when functionalising nanoparticles with TAT peptide, Wang *et al.*

designed UCNPs modified with RGD/TAT polymeric lipid micelles and functionalised with ZnPc.<sup>141</sup> The authors combined three lipid proteins based on OQPGA including PEG-OQPGA, RGD-OQPGA and TAT-OQPGA. The UCNPs and the ZnPc were encapsulated in the PEG-RGD-TAT-OQPGA lipid micelles prepared using a thin-layer evaporation method obtaining a hydrodynamic size of 82.5 nm. The encapsulation efficiency and the loading efficiency of the ZnPc into the lipid micelles were evaluated showing opposite behaviour, the loading efficiency increased when increasing the volume of solution containing ZnPc whereas the encapsulation efficiency decreased. Additionally, leaking studies were performed showing a 50% ZnPc release after 6h when then loading efficiency was 1.6%. The ability of the nanoparticles to produce  $^1\text{O}_2$  upon 980 nm excitation was confirmed using ABMA as probe.<sup>141</sup> Next, the intracellular  $^1\text{O}_2$  production was investigated in MCF-7 breast cancer cells and using DCFDA as ROS marker. The PEG-RGD-TAT-OQPGA-ZnPc-UCNPs showed higher fluorescent emission intensity indicating the generation of ROS. The PDT effect of PEG-RGD-TAT-OQPGA-ZnPc-UCNPs was investigated in MCF-7 cells using MTS assay showing a decrease in cell viability of 85% after 980 nm excitation. A 60% cell viability decrease was obtained for the nanoparticles without RGD/TAT indicating that the modification of the UCNPs with RGD/TAT targeting agents allows for higher uptake of the nanoparticles. The targeting capability of the nanoparticles was evaluated in B16F1 murine melanoma cells overexpressing  $\alpha_v\beta_3$  integrin. Cells incubated with RGD-TAT-OQPGA-ZnPc-UCNPs showed stronger upconversion luminescence upon 980 nm light irradiation compared to the nanoparticles without RGD peptide.<sup>141</sup> Although an increased uptake of the nanoparticles by cancer cells was observed for the RGD-TAT-OQPGA-ZnPc-UCNPs than for the non-modified nanoparticles with targeting agents, further experiments are required to verify the actual targeting ability. For instance, blocked cells with free RGD peptide previous incubation with the nanoparticles, uptake comparison experiment with a negative- $\alpha_v\beta_3$  integrin cell line and *in vivo* tests would confirm the potential of the RGD-TAT-OQPGA-ZnPc-UCNPs as nanosystems for targeted-PDT of cancer.

Other peptides, such as cMBP, have shown to have targeting properties towards triple-negative breast cancer (TNBC) cells compared to other cancer cells and to normal cells. With the aim of applying the targeted PDT treatment to the TNBC cells, Wang *et al.* designed and synthesised ZnPc@mPEG-PLGA@UCNPs (ZUPEA) using double emulsion coprecipitation method.<sup>149</sup> The resulting ZUPEA nanoparticles were further functionalised with the cMBP-peptide to recognise TNBC cells. Higher loading of the cMBP-ZUPEA was observed in the TNBC cells (MDA-MB-231 cells) compared to the normal cells (MCF-10A cells) and the MCF-7 breast cancer cell and A549 lung cancer cell, indicating the successful targeting of the nanoparticles to the TNBC cells. The

cMBP-ZUPEA exhibited good biocompatibility in normal and cancer cells and showed a great cytotoxicity upon irradiation at 980 nm ( $1.0 \text{ W cm}^{-2}$ , 10 min,). cMBP-ZUPEA were evaluated *in vivo* in 4T1 tumour bearing mice and resulted in higher PDT effect following 980 nm irradiation than when the mice were treated with ZnPc and irradiated at 650 nm. 12 days following PDT treatment with the UCNPs, a significant suppression of the tumour was observed while no abnormalities were observed in the organs of the treated mice.<sup>149</sup>

In a recent work, Li *et al.* developed UCNPs functionalised with an antenna molecule 800CW (for luminescence enhancement), RB as PS drug, Cy3 for diagnosis after treatment and cathepsin B (CaB) substrate peptide labelled with QSY7 quencher for intracellular cathepsin B (CaB)-responsive PDT.<sup>150</sup> The UCNPs were first functionalised with alendronic acid (ADA) to facilitate the further functionalisation. Next, the 800CW dye, RB and Cy3 were immobilised on the surface of the UCNPs and the CaB substrate peptide chain GRRGLGC with terminus-labelled QSY7 (Pep-QSY7) was also incorporated. In the final nanosystem, the presence of the QSY7 quenches the emission of the Cy3 and the RB, thus cancelling the production of  $^1\text{O}_2$  upon irradiation at 808 nm. Upon recognition of the CaB and cleavage of the QSY7 from the UCNPs, the fluorescence emission of the Cy3 is recovered and the RB is activated for the efficient PDT. The PDT effect of the UCNPs in HeLa cells was evaluated by monitoring the formation of ROS with DHR and the cytotoxicity with MTT assay, showing a selective and CaB concentration-dependent phototoxicity. The PDT effect of the multifunctional nanosystem was evaluated *in vivo* using a HeLa tumour xenograft mouse model. Antitumour efficiency was observed for mice intratumorally injected with the nanoparticles ( $300 \mu\text{g mL}^{-1}$ ) and irradiated at 808 nm ( $1.0 \text{ W cm}^{-2}$ , 40 min), which was not observed for control groups (*ie.* without UCNPs but irradiated under the same conditions or injected with UCNPs but non-irradiated).<sup>150</sup>

#### 4. Conclusions

Based on the number of publications that report the use of PS-UCNPs for the effective treatment of cancer via PDT (both *in vivo* and *in vitro*) to date, these nanosystems exhibit the potential to become the next generation of nanodrugs for PDT. Further to their advantage of being NIR excitable and therefore with potential for the treatment of cancers in deep-lying tissue, UCNPs can accumulate in tumour tissues passively *via* the EPR effect and actively by the incorporation of targeting agents to the nanoparticle surface which results in nanodrugs with reduced side effects. However, despite the large body of research that has shown the viability of UCNPs for PDT as an alternative to the currently used photosensitiser drugs, further improvements are

needed to bring this treatment to the clinic. Further efforts are needed to improve their biocompatibility and selectivity which would lead to improvements in therapeutic efficacy.

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