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Near Infra-Red Luminescent Osmium Labelled Gold Nanoparticles for Cellular Imaging and Singlet Oxygen Generation

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Osmium(II) complexes have attractive properties for potential theranostic agents given their anticancer activity, their redox potentials favourable for biological transformations within cancer cells and their luminescence in the near infra red region. To achieve localised detection and delivery, gold nanoparticles (AuNP) provide an attractive scaffold to attach multiple luminescent agents on a single particle and provide a multimodal platform for detection and localised delivery. We have developed 13 nm and 25 nm AuNP decorated with an osmium complex based on 1,10-phenanthroline and surface active bipyridine ligands, OsPhenSS for live cell imaging and singlet oxygen generation, notated as OsPhenSS-AuNP13 and OsPhenSS-AuNP25. The AuNP designs not only allow versatile modalities for localisation of the probe but also water solubility for the osmium metal complex. The osmium decorated nanoparticles OsPhenSS-AuNP13 and OsPhenSS-AuNP25 display characteristic near infra red luminescence from the osmium(II) 1MLCT at 785 nm in aqueous solutions with visible excitation. Upon incubation of the nanoparticles in lung cancer and breast carcinoma the luminescence signature of osmium and the gold reflectance reveal localisation in the cytoplasmic and perinuclear compartments. Excitation of the nanoparticles at 552 nm in the presence of a ROS indicator revealed a marked increase in the green fluorescence from the indicator, consistent with photo-induced ROS generation. The detection of singlet oxygen by time-resolved luminescence studies of the osmium and the nanoparticle probes further demonstrates the dual activity of the osmium-based nanoprobe for imaging and therapy. The introduction of gold nanoparticles for carrying osmium imaging probes allows a novel versatile strategy combining detection and localised therapies at the nanoscale.

1. Introduction

Transition metal polypyridine complexes are attractive luminescence imaging probes for detection based on their photophysical properties arising from the Metal to Ligand Charge Transfer (MLCT) states and their versatility in the ligand functionalisation schemes for adaptation of their biological function.1 Whilst most popular probes rely on rhenium, ruthenium and iridium for cellular imaging, osmium metal complexes offer distinct advantages with detection in the near infra-red (NIR) of the spectrum, away from any interferences and ideal for the biological tissue window.2,3 Few osmium(II) polypyridine complexes have been reported in cellular imaging applications,4,6 and recently pyridyl triazole complexes have been reported as probes with direct excitation of the 1MLCT energy band.7 Dinuclear Os(II) complexes have been reported as a super-resolution NIR Simulated Emission Depletion (STED) probe for nuclear DNA.8 Transition metal complexes are also efficient photosensitisers9-11 due to their appreciable intensity in the ultraviolet and visible range of the spectrum and their long-lived 1MLCT state, which allows susceptibility towards quenching by oxygen in aerated solutions.12

13 The generation of singlet oxygen (O2) which is an extremely reactive oxygen species (ROS) is a critical process in photodynamic therapy.14 The anticancer activity of osmium organometallic and coordination complexes has been well studied with many approaches15,16 adopting in cellulo17 photo-activation18-20 for localised therapeutic activity. It is well known that osmium compounds can exhibit higher oxidation states which may play a key role in biological redox potentials within cancerous cells.21,22 Efficient penetration of the photosensitiser probe into cancer cells is crucial to the effectiveness of the ROS to generate cell death, therefore intracellular tracking and imaging of the probe is

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important in order to evaluate the overall localisation and function. In this study we wish to introduce the employment of gold nanoparticles (AuNP) as a scaffold to deliver Os(II) complexes inside cells, providing water solubility and overcoming cellular uptake of osmium luminescent probes for detection as well as ROS generation.

AuNP offer a versatile platform for the conjugation of lumophores, proteins and antibodies, and a plethora of advantages for imaging applications such as tuneable size, ease of synthesis, chemical inertness and biocompatibility. The high electron density of AuNP allows multimodal detection by Transmission Electron Microscopy (TEM) and light scattering in reflectance-based microscopy to provide imaging capabilities additional to conjugated lumophores. Organic photosensitisers have been conjugated to AuNP for production of ROS but to our knowledge, no osmium complex decorated AuNP has been utilised for its dual capabilities of live cell imaging and ROS generation in cancer cells. There have been couple reports of polypyridine Os(II) complexes on nanoparticles either inside polymers or adsorbed onto 20 nm silver nanoparticles.

The luminescence properties of probes near the AuNP surface can be strongly perturbed by plasmonic interactions that result in luminescence quenching at short distances from the surface and luminescence enhancement at longer distances. The attachment of luminescent metal probes to AuNP has been previously investigated for Ru(II), Ir(III) and Eu(III) metal complexes. In this paper, we report AuNP of different sizes for optimising delivery of a Os(II) complex as theranostic agent in cells for potential synergy of AuNP in plasmon-enhanced 1O2 production. The latter has been demonstrated as the production of 1O2 correlates with maximized scattering yield. The Os(II) complex is designed with a long linker to optimise the position of the luminescent complex from the AuNP surface as previously shown (Figure 1). The decoration of AuNP with osmium(II) complexes is expected to increase the luminescence of the nanoprobe for imaging in cells in the far-red region of the spectrum. The internalisation of the osmium-decorated AuNP in A549 cancer cells has been examined and the ROS production has been evaluated.

![Figure 1. Schematic representation of nanoparticles decorated with OsPhenSS complex: OsPhenSS•AuNP13 and OsPhenSS•AuNP25.](image)

2. Experimental

2.1 Materials

All solvents and chemicals used in synthesis were purchased from Fisher Scientific, VWR Chemicals, Sigma Aldrich and Alfa Aesar without further purification and deuterated NMR solvents were purchased from Goss Scientific. For gold nanoparticle (AuNP) synthesis, Hydrogen tetrachloroaurate (III) (Alfa-Aesar, UK, cat. no. 36400), sodium citrate tribasic dihydrate (Sigma-Aldrich, UK, cat. no. C8532), citric acid (Sigma-Aldrich, UK, cat. No. 251275), ethylenediaminetetraacetic acid (EDTA) (Sigma-Aldrich, UK, cat. No 03620), D2O (Sigma-Aldrich, UK, cat. No. 102494088). Dulbecco’s modified Eagles medium (DMEM) (Sigma-Aldrich, UK, cat. no. D6046), PBS (Sigma-Aldrich, UK, cat. no.P2272). Hydromount mounting medium (National Diagnostics, UK, cat. no. HS-106). Paraformaldehyde solution, 4% in PBS (Thermo Scientific cat. no. 15670799). For ICP-MS: Nitric Acid, Trace Select, Honeywell cat. no. 02650-250 mL. Hydrochloric acid, Trace Select, Fisher cat. no. AS08-P500. Water, Trace Select, Fluka cat. no. 95305-1L. DCF-DA (2′,7′-dichlorodihydrofluorescein diacetate, cat no D6883) and Rose Bengal (cat no 330000) were purchased from Sigma Aldrich, UK for ROS detection experiments.

2.2 Synthesis and Characterisation of OsPhenSS

2.2a Synthesis of 4,4′-di(5-lipoamido-1-pentony)-2,2′-bipyridine. A solution of α-lipoic acid (0.72 g, 3.49 mmol) and 1-hydroxybenzotriazole hydrate (0.52 g, 3.49 mmol) in DMF (7 mL) was cooled to 0−5 °C, upon which 1-ethyl-3-(3-dimethylamino)propyl) carbodiimide (EDC) (0.67 g, 0.7 mL, 3.96 mmol) was added and stirred, maintaining this temperature. The solution was allowed to warm to room temperature and stirred for a further hour. A solution of Et,N (0.29 g, 0.32 mL) and 4,4′-di(5-amino-1-pentony)-2,2′-bipyridine (0.52 g, 1.45 mmol) in DMF (13 mL) was added to the reaction mixture and stirred overnight. The resulting cream precipitate was filtered and dried in the air and washed with DMF (2 x 10 mL) yielding the final product. (0.80g, 76%). 6H (400MHz; CDCl3) 1.35-1.65 (12H, m, H8, 9, 15), 1.61-1.78 (8H, m, H14, 16), 1.79-1.96 (6H, m, H10, 18'), 2.17 (4H, t, 7.4, H13), 2.38-2.50 (2H, dq, 6.2, 12.4, H18), 3.02-3.14 (4H, m, H19), 3.29 (4H, q, 6.4, H11), 3.50-3.60 (2H, p, 6.7, H7), 5.47 (2H, br s, NH), 6.82, 2H, dd, 2.5, 5.7, H5), 7.94 (2H, d, 2.5, H3) and 8.45 (2H, d, 5.7, H6). 8C (400 MHz; CDCl3) 23.40 (C9), 25.4 (C14), 28.6 (C15), 28.9 (C8), 29.4 (C10), 34.6 (C16), 36.5 (C13), 38.5 (C19), 39.3 (C11), 40.2 (C18), 56.4 (C17), 67.7 (C7), 106.8 (C3), 113.3 (C5), 150.2 (C6), 157.8 (C2), 166.1 (C4) and 172.7 (C12). MS [ESI+] m/z 735.3 (M+H)+.

2.2b Synthesis of bis-(1,10-phenanthroline)-osmium dichloride Os(phen)Cl2 was synthesised with modification according to Chao et al. An ethylene glycol solution of OsCl2 0.5H2O (210 mg, 0.57 mmol) and 1, 10-phenanthroline (210 mg, 1.16 mmol) were brought to reflux under N2 atmosphere for 1 h. After cooling to room temperature, the solution was added to an aqueous solution containing Na2SO3 (4.55 g, 25 mL) and kept in a refrigerator overnight. The dark precipitate was collected by vacuum filtration, washed with water and diethyl ether and directly used in the following reaction. MS [ESI+] m/z 622.0 [M]+.
2.2c Synthesis of OsPhenSS Os(phen)$_2$Cl$_2$ (39.5 mg, 0.0635 mmol) and 4,4’-dii(5-lipoamido-1-pentoxy)-2,2’-bipyrindine (46.23 mg, 0.0629 mmol) was suspended in ethylene glycol (20 mL) and heated to 120 °C overnight. The black/ brown solution was cooled to room temperature and 20 mL of deionised water was added. Saturated NH$_4$PF$_6$ in water (1 mL) was added and stirred for 20 min at RT and filtrated to give a black precipitate. The precipitate was washed with copious amounts of ice-cold water and followed by washes of diethyl ether (3 x 20 mL). The solid was dissolved in a minimal volume of MeCN and H$_2$O was added. Saturated NaCl solution (20 mL) was added and the aqueous layer was washed with diethyl ether (3 x 20 mL). The dried MeCN solution was filtrated to give a black precipitate. The precipitate was washed with copious amounts of MeCN to give a black powder. An alumina column in MeCN was performed to remove benzaldehyde (3 x 20 mL). The solid was dissolved in a minimal volume of MeCN with copious amounts of ice-cold water and followed by washes of diethyl ether (3 x 20 mL). The solid was dissolved in a minimal volume of MeCN and brought to reflux. A preheated solution (80 °C) of hydrogen azide (Sigma-Aldrich, Gillingham, UK) and solutions were placed in 1 cm quartz cuvettes. For measurement of singlet oxygen emission from the NPs, solutions were prepared in D$_2$O. Since H$_2$O rapidly quenches singlet oxygen, it was critical to minimise the H$_2$O content when preparing the solution in D$_2$O, as described in section 2.3e. To minimise attenuation of the 532 nm laser excitation beam by the SPR band of the Au NPs, a short pathlength quartz cuvette (2 mm) was employed. The addition of sodium azide (Sigma-Aldrich, Gillingham, UK) dissolved in D$_2$O served as a positive control since azide is an efficient singlet oxygen quencher.

2.2d Photophysical measurements

UV-Vis spectra were collected by a Varian Cary 60 or 5000 spectrometers. Steady-state and time resolved luminescence studies were performed by an Edinburgh Instruments FLS920 spectrometer equipped with 450 W Xe lamp for steady state and an EPL 445 nm pulse diode laser, analysed by FAST software. Detection was performed with a liquid nitrogen cooled Hamamatsu PMT R5509-41. Steady-state and time resolved luminescence studies were performed with a liquid nitrogen cooled Hamamatsu PMT R5509-61. Filters were used to attenuate the laser power. The photon counting detection equipment consisted of a multiscaler board (MSA-300, Becker-Hickl, Berlin, Germany) to extract the singlet oxygen decay lifetime and amplitudes. OsPhenSS was dissolved in deuterated methanol (CH$_3$OD, Sigma-Aldrich, Gillingham, UK) and solutions were placed in 1 cm quartz cuvettes. For measurement of singlet oxygen emission from the NPs, solutions were prepared in D$_2$O. Since H$_2$O rapidly quenches singlet oxygen, it was critical to minimise the H$_2$O content when preparing the solution in D$_2$O, as described in section 2.3e. To minimise attenuation of the 532 nm laser excitation beam by the SPR band of the Au NPs, a short pathlength quartz cuvette (2 mm) was employed. The addition of sodium azide (Sigma-Aldrich, Gillingham, UK) dissolved in D$_2$O served as a positive control since azide is an efficient singlet oxygen quencher.

2.2f Singlet Oxygen Quantum Yield

Determination of the singlet oxygen quantum yield ($\Phi_\Delta$) of OsPhenSS was carried out in deuterated methanol using Rose Bengal ($\Phi_\Delta = 0.79$) as the standard reference compound with optically matched solution absorbances (< 0.1) at the laser wavelength of 532 nm. For matching the absorbance versus the reference compound, spectra were measured using a UV/Vis spectrophotometer (V-630, Jasco (UK) Ltd.) with 1 cm quartz cuvettes. The relative value of $\Phi_\Delta$ for OsPhenSS was calculated vs. Rose Bengal using standard zero-point intercept analysis of the singlet oxygen signal as a function of incident laser power.

2.3 Synthesis and Characterisation of Gold Nanoparticles

2.3a Citrate-capped AuNP13 The synthesis was based on a previously published method which was slightly modified. A solution of trisodium citrate (60.3 mg, 0.21 mmol), citric acid (13.6 mg, 0.07 mmol) and ethylenediaminetetraacetic acid (EDTA) (1.6 mg, 0.004 mmol) in deionised water (100 mL) was stirred vigorously and brought to reflux. A preheated solution (80 °C) of hydrogen tetrachloroaurate (HAuCl$_4$) (8.5 mg, 0.022 mmol) in deionised water (25 mL) was rapidly added to the centre of the vortex. After a 30-minute reflux, the heat was turned off and the solution was allowed to slowly cool to room temperature to form a 1.6 mM solution. $\lambda_{max}$ (H$_2$O) 517 nm (SPR). Diameter/nm: 14 ± 3 (DLS number distribution). PDI = 0.06, $\zeta$-potential / mV = -35 ± 4.

2.3b Citrate-capped AuNP13 in D$_2$O The protocol for synthesizing AuNP13 was based on the published method by Turkevich et al. The glassware used was washed with aqua regia (HCl: HNO$_3$, 3:1) and dried in the oven before use. A solution of trisodium citrate dihydrate (30.3 mg, 0.11 mmol), citric acid (6.8 mg, 0.035 mmol) and ethylenediaminetetraacetic acid (EDTA) (0.8 mg, 0.002 mmol) in 50 mL D$_2$O was vigorously stirred and brought to reflux under a nitrogen atmosphere. This was left to reflux for 15 min, before the rapid addition of a solution of gold(III)chloride trihydrate (HAuCl$_3$·3H$_2$O) (4.3 mg, 0.010 mmol) in 12.5 mL of D$_2$O. The solution was heated at reflux for a further 15 min, the heat was then turned off and the solution was left to cool to room temperature, forming
1.6 nM AuNP13. $\lambda_{\text{max}}$(D:O): 517 nm (SPR). Diameter 13 ± 3 nm (DLS number distribution), PDI = 0.07, $\zeta$-potential/mV = -33 ± 8. The final solution was concentrated by centrifugation at 10,000 g for 30 min. The supernatant was decanted, and the pel let was redispersed in D:O to form a 4.5 nM solution of AuNP13.

2.3c Citrate-capped AuNP25 The protocol was modified using a previously published method by Ziegler et al.44 Three stock solutions were prepared: a solution of 5 mM HAuCl₃·3H₂O, 57 mM ascorbic acid, and 34 mM trisodium citrate dihydrate in MILLI-Q®. AuNP13 (36 mL, 2 nM) were diluted to 40 mL with MILLI-Q® water and vigorously stirred. The solutions in the addition were diluted to 1 mL, 3 mM and 0.75 mM in MILLI-Q® water to 40 mL for HAuCl₃·3H₂O, ascorbic acid and trisodium citrate dihydrate respectively. The two solutions (HAuCl₃·3H₂O and ascorbic acid/trisodium citrate dihydrate) were simultaneously added dropwise over 10 min. The resultant solution was heated to reflux for 30 min forming a solution of 0.7 nM AuNP25. The reaction vessel was allowed to cool to RT and stored in the dark. UV Vis (H₂O) $\lambda_{\text{max}}$ / nm = 519 (SPR). Diameter/nm = 21 ± 5 (DLS number distribution), PDI = 0.07, $\zeta$-potential/mV = -36 ± 4.

2.3d OsPhenSS•AuNP13 A suspension of AuNP13 (2 mL, 2 nM) was centrifuged at 13000 g for 25 min, the supernatant was decanted, and the pel let was re-suspended in filtered MILLI-Q®-water (1 mL) to form 4 nM AuNP13. Zonyl FSA solution (2.5 % w/v) in deionised water (10 µL, 0.05 M) was added to 4 nM AuNP13 (1 mL), stirred for 20 min and centrifuged at 13000 g for 20 min. The supernatant was discarded, and the pel let was re-suspended in filtered MILLI-Q®-water (350 µL) and combined to form Z•AuNP13 (1 mL, 9 nM). From this, a 1 in 1 dilution was performed in Milli-Q H₂O yielding 4.5 nM and 2.5 nM respectively. From this, a 1 in 5 dilution was carried out on all nanoparticle samples in Milli-Q H₂O and a 20 µL aliquot was dropped onto a 200 mesh formvar coated TEM grid and left to dry in the dark overnight. Imaging took place on a JEOL1400 transmission electron microscope (Electron Microscopy service, University of Birmingham). Dynamic Light Scattering (DLS) measurements were carried out on a Malvern Zetasizer nano ZSP in 1 ml quartz cuvettes with a 1:1 dilution factor. Measurements were recorded at pH 7 in MILLI-Q® H₂O.

2.4 Transmission Electron Microscopy (TEM) and Dynamic Light Scattering (DLS) TEM analysis was carried out for citrate-capped AuNP, OsPhen•AuNP13 and OsPhen•AuNP25 from 4 nM, 9 nM and 5 nM stock solutions respectively. For all metal-coated nanoparticle samples, a 1 in 1 dilution was performed in Milli-Q H₂O yielding 4.5 nM and 2.5 nM respectively. From this, a 1 in 5 dilution was carried out on all nanoparticle samples in Milli-Q H₂O and a 20 µL aliquot was dropped onto a 200 mesh formvar coated TEM grid and left to dry in the dark overnight. Imaging took place on a JEOL1400 transmission electron microscope (Electron Microscopy service, University of Birmingham). Dynamic Light Scattering (DLS) measurements were carried out on a Malvern Zetasizer nano ZSP in 1 ml quartz cuvettes with a 1:1 dilution factor. Measurements were recorded at pH 7 in MILLI-Q® H₂O.

2.5 Inductively Coupled Mass Spectrometry Nanoparticle samples were analysed either an ICP-MS Agilent LC-ICP-MS (7500cx) at University of Warwick or a Perkin elmer 300X Nexion at University of Birmingham. To prepare the samples, the coated samples were diluted to 4.5 nM. A 20 µL aliquot was added to 80 µL Milli-Q H₂O yielding a concentration of ~ 1 nM. Samples were digested with ultrapure aqua regia (300 µL). The samples were then diluted to 5 ml to reduce the aqua regia content to < 4% with a 4 % HNO₃ solution containing ascorbic acid (50 mM), EDTA (50 mM) and thiourea (50 mM) to stop the production of the volatile osmium tetraoxide species. A series of gold and osmium standards were used for calibration.

2.6 Cell Culture The human lung cancer A549 was obtained from the European Collection of Authenticated Cell Cultures (ECACC catalogue number 86012804) cell line was maintained in Dulbecco’s Modified Eagle’s Medium (DMEM) supplemented with 10 % w/v fetal bovine serum (FBS), L-glutamine (2 mM) and 1 % penicillin(100 units per mL) (streptomycin (100µg per ml) hereafter called complete media. Cells were cultured in 20 ml of complete media in vented T75 flasks at 37 °C in a humidified 95% air: 5 % CO₂ atmosphere. Cells were routinely sub cultured from high confluency using a standard trypLE protocol. The human breast carcinoma cell line (MCF-7) was obtained from ECACC, (catalogue number 86012803). Cells were cultured in Dulbecco’s Modified Eagle’s Medium/Nutrient Mixture F12 Ham (Sigma Aldrich, Dorset, UK), supplemented with 10% w/v Foetal bovine serum (Gibco, UK) and 1% penicillin (100 units/mL) and streptomycin (100 µg/mL) (Gibco, UK). Dosing of A549 cells was performed in 35
mm dishes with a 10 mm glass insert. Cells were seeded at 100,000 cells per dish in 1 mL complete media. Before dosing with AuNP cells were washed in warm PBS and cell media was replaced with 900 µL fresh media. Samples of OsPhenSS•AuNP13 (100 µL, 9 nM) and OsPhenSS•AuNP25 (100 µL, 5 nM) were diluted upon addition to cell media to final concentrations as indicated in the specific experiments. For confocal microscopy of cells, cell media was removed and cells were washed twice in warm PBS. For Hoechst nuclear staining 20 µM of a 20 mM stock solution of Hoechst 3328 in PBS was added for 10 min in the dark. The cells were washed and phenol red-free cell media was added (1 mL per well). To provide additional validation of cellular uptake and for carrying out ROS generation imaging, we used the human breast carcinoma MCF-7 cell line, which was obtained from the European Collection of Authenticated Cell Cultures (ECACC). Cells were cultured in Dulbecco's Modified Eagle's Medium/Nutrient Mixture F12 Ham (Sigma Aldrich, Dorset, UK), supplemented with 10% fetal bovine serum (Gibco, UK), and 1% penicillin (5000 units/mL) and streptomycin (5000 µg/mL) (Gibco, UK).

2.7 Cell Viability Assay via MTT
Cells were seeded at a density of 5000 cells per well in a 96-well plate. Nanoparticle concentrations were varied across the plate by serial dilution factor in six technical replicates containing a positive (1% v/v triton) and negative control (cell media). Cells were dosed for 24 h with varying concentrations of OsPhen•AuNP (9 nM – 0.14 nM) and washed with phenol red-free media. The cells were then further incubated with (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT, final concentration 0.5mg per mL) reagent in Dulbecco's Modified Eagle Medium (DMEM) for 4 h and then removed completely. DMSO was added to each well to dissolve the purple precipitate and absorption at 590 ± 30 nm using a plate reader (Tecan Infinite 200).

2.8 Confocal Microscopy
Confocal microscopy of fixed A549 cells was performed using a Leica TCS SP8 upright confocal laser scanning system using a 64x oil immersion objective lens. 405 nm, 458 nm, 488 nm, 633 nm solid-state laser lines were used. Confocal microscopy of live A549 cells was performed using the same system with a 40x ceramic H2O immersion dip objective lens. Cells were fixed by the addition of 4% paraformaldehyde (PFA) to each well (1 mL per well) for 15 min in the dark. PFA was removed and cells were washed twice in PBS (0.1 M, pH 7.4). Coverslips were removed and mounted on a droplet of hydromount medium (National Diagnostics, UK) on glass slides, and stored flat in the dark for at least 24 h at 4 °C before imaging. Live cells were imaged immediately after the washing. Fluorescence imaging of live MCF-7 cells was carried out using an upright Leica SP8 confocal microscope. Cells were plated into 35mm diameter Petri dishes equipped with a glass coverslip base (Fluorodish, WPI, Herts, UK) 24 h before the addition of the nanoparticles. The nanoparticles were incubated with the cells for up to 24 h, following by washing and addition of phenol-red free medium added, and imaging was carried out using an immersion objective with excitation at 552 nm and detection in the red/NIR from 680 – 700 nm. For fluorescence of imaging photo-induced generation of reactive oxygen species (ROS), MCF-7 cells were incubated with the ROS probe 2',7-dichlorodihydrofluorescein (DCF-DA, Sigma Aldrich, Dorset, UK). DCF-DA at 10 µM was added to the incubation medium 2 h before imaging. Confocal luminescence imaging was carried out using excitation at 488 nm and emission detection of green fluorescence from 510 – 550 nm. For on-stage photoexcitation to induce intracellular ROS generation, illumination was carried out at 552 nm for 300 s with an incident power < 1 mW to selectively excite the osmium(II) complex but not the DCF-DA probe dye, thereby minimising autooxidation of DCF-DA. Cells were re-imaged within 5 min of the on-stage illumination.

3. Results and discussion
Firstly, the photophysical properties of OsPhenSS in solution were evaluated for further comparisons with the decoated AuNP. UV-Vis spectroscopy studies (Figure 2, Table 1) show an intense ligand-centred (LC) (π → π*) band at 266 nm arising from the phenantholine character, a weak intraligand charge transfer (ILCT) band at 340 nm with 1MLCT (d → π*) band arising between 400 – 500 nm with an estimated λmax at 485 nm (Figure 2, Table 1). This is in accordance with other osmium bis-phenantholine derivatives.45,48 Additionally, the spin forbidden absorption for 3MLCT is also observed at 550 – 750 nm due to Os(II) high spin orbit coupling.49,51 OsPhenSS displays luminescence from the 3MLCT centred at 770 nm in aerated water. The broad emission is significantly red-shifted by 62 nm in comparison to [Os(phen)]2+ suggesting that the bulky ligand moieties may have a stabilising effect on the exited state which is in agreement with other similar osmium(II) complexes.52,53 To examine the effect of fluorosurfactant Zonyl FSA, which stabelises nanoparticle formation, to OsPhenSS independently, we studied the luminescence properties upon the addition of excess of Zonyl FSA. No shift of the luminescence λmax was observed.
However, the luminescence lifetime of OsPhenSS was increased to 46 ns by the presence of Zonyl FSA in aerated water over the free complex in aerated water at 36 ns. This enhancement in lifetime is attributed to the interaction of Zonyl FSA with OsPhenSS resulting in protection of \(^3\)O\(_2\) quenching.\(^{62-64}\) Solvent interactions have been shown to lower the rate of diffusion of \(^3\)O\(_2\) resulting in stronger emission and luminescent lifetimes.\(^{37, 65}\) The singlet oxygen quantum yield of OsPhenSS was calculated as 0.20 ± 0.01. The singlet oxygen decay lifetime was measured as 31 ms which is in good agreement with the literature.\(^{66}\)

Table 1. Absorption and luminescence properties of OsPhenSS in aerated solution and Os(II)-decorated AuNP.

<table>
<thead>
<tr>
<th></th>
<th>Absorption (\lambda_{\text{abs}}) / nm ((\epsilon) M(^{-1}) cm(^{-1}))</th>
<th>Luminescence (\lambda_{\text{em}}) / nm</th>
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<tbody>
<tr>
<td>OsPhenSS</td>
<td>225 [61000], 266 (63400), 343sh (9200), 485 (17600)</td>
<td>770</td>
</tr>
<tr>
<td>OsPhenSS + Zonyl FSA</td>
<td>225 (59000), 266 (62000), 343sh (9200), 485 (17000)</td>
<td>770</td>
</tr>
<tr>
<td>OsPhenSS•AuNP13</td>
<td>521</td>
<td>785</td>
</tr>
<tr>
<td>OsPhenSS•AuNP25</td>
<td>524</td>
<td>785</td>
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</tbody>
</table>

The AuNP were decorated with OsPhenSS by titration of 5 µL quantities (1 mM) of OsPhenSS to a suspension of 4.5 nM Z•AuNP13 and 1.5 nM Z•AuNP25 monitoring the shift of the surface plasmon resonance (SPR) band characteristic of the changes on the surface of the AuNP, in order to determine full saturation of the surface (Figure 3a and Figure S15 for AuNP25). Additions of 35 µL and 18 µL of 1 mM OsPhenSS into 4.5 nM Z•AuNP13 and 1.5 nM Z•AuNP25 resulted in shifts of 4 and 5 nm of the SPR respectively. The particles were purified through a G25 Sephadex column and the luminescence properties were evaluated (Figure 3b, Table 1).

After isolation of the aqueous suspension of OsPhenSS•AuNP13 and OsPhenSS•AuNP25, the SPR band was not shifted indicating only excess complex was removed during the isolation process. This is confirmed though the reduction of the LC peak at 266 nm. The excitation spectra mirror the absorption profile of the free complex in aerated water showing the characteristic \(^1\)MLCT band at 488 nm (Figure 3b). Excitation of \(^3\)MLCT at 488 nm of OsPhenSS•AuNP13 and OsPhenSS•AuNP25 leads to an emission signal at 785 nm. Upon excitation at 488 nm OsPhenSS•AuNP13 and OsPhenSS•AuNP25, a 15 nm red shift is observed in their broad \(^3\)MLCT emission profiles which can be attributed to the change of the environment surrounding the metal complex and the influence of the SPR (Figure S18).\(^{52, 67}\) The OsPhenSS•AuNP13 and OsPhenSS•AuNP25 are spherical in nature with mean diameters of 14 ± 3 nm and 21 ± 5 nm as performed by DLS, respectively. TEM confirmed average sizes of 14 ± 1 nm (n = 50) for OsPhenSS•AuNP13 and 21 ± 1 nm (n = 50) for OsPhenSS•AuNP25 which is in good agreement with DLS data (Figure S16). Aqueous solutions of the OsPhenSS•AuNP13 display a luminescence lifetime of 55 ns, equating to a 19 ns increase in comparison to the free OsPhenSS complex in aerated water and a small increase of 9 ns in comparison with the influence of the presence of surfactant. This effect is consistent with similar polypyridine-coated ruthenium complexes attached to AuNP.\(^{30-34, 37, 39, 68, 69}\) Inductively Couple Mass spectrometry (ICP-MS) studies of the OsPhenSS•AuNP13 estimate ~1800 complexes per single AuNP, and ~4800 for OsPhenSS•AuNP25 demonstrating high loading on the nanoparticle surface ideal for cellular imaging.

The ICP-MS studies confirmed the loading of the nanoparticles which is consistent with the luminescence lifetimes of the isolated OsPhen•AuNP complexes and the properties of the synthesized AuNP. The absorbance of the OsPhenSS•AuNP complexes was measured with the use of a PerkinElmer Lambda 35 UV-Vis spectrometer.

The AuNP were characterized by DLS and TEM. DLS analysis showed that the DLS size distribution of the AuNP was monodisperse with mean diameters of 14 ± 3 nm and 21 ± 5 nm for OsPhenSS•AuNP13 and OsPhenSS•AuNP25, respectively. TEM images confirmed average sizes of 14 ± 1 nm (n = 50) for OsPhenSS•AuNP13 and 21 ± 1 nm (n = 50) for OsPhenSS•AuNP25 which is in good agreement with DLS data (Figure S16). Aqueous solutions of the OsPhenSS•AuNP13 display a luminescence lifetime of 55 ns, equating to a 19 ns increase in comparison to the free OsPhenSS complex in aerated water and a small increase of 9 ns in comparison with the influence of the presence of surfactant. This effect is consistent with similar polypyridine-coated ruthenium complexes attached to AuNP.\(^{30-34, 37, 39, 68, 69}\) Inductively Couple Mass spectrometry (ICP-MS) studies of the OsPhenSS•AuNP13 estimate ~1800 complexes per single AuNP, and ~4800 for OsPhenSS•AuNP25 demonstrating high loading on the nanoparticle surface ideal for cellular imaging.

The nanoparticle uptake and localization experiments were performed with an optimized nanoparticle dosage based on (Figure S19) in lung cancer cell line A549. Additionally MTT assays in a non-cancerous lung cell were also performed (Figure S20). Confocal microscopy of live A549 cells incubated with OsPhenSS•AuNP13 for 18 h revealed cytoplasmic and perinuclear localisation of the nanoparticles within the cells (Figure 4). Localisation was confirmed using a nuclear stain Hoescht 3368.
Furthermore, upon incubation of A549 cells with OsPhenSS•AuNP25 nanoparticles, osmium luminescence was observed within the cytoplasm and perinuclear area of live cells (Figure 5, Figure S21), similar to OsPhenSS•AuNP13 nanoparticles. Reflectance microscopy is also informative of localisation due to the scattering signal from the dense AuNP which is more prominent in the case of OsPhenSS•AuNP25. Colocalization between the osmium signal and gold reflectance (Figure 5 and Figure S22) confirmed that the recorded luminescence signal arises from the OsPhenSS complexes attached to AuNP25. Imaging studies of fixed cell imaging at 4 h showed localisation throughout the cells alongside perinuclear localisation rather than in a single compartment (Figure S23).

Figure 4. Representative live cell images of A549 cells treated with 0.9 nM OsPhenSS•AuNP13 for 18 h. (a) Osmium emission (purple); (b) brightfield overlapped with osmium emission (purple) and Hoescht 3368 (blue) and (c) overlap of osmium emission (purple) and Hoescht 3368 (blue). Channels: Osmium emission (λem = 488 nm, λexc = 650 – 800 nm); Hoescht 3368 λem = 402 nm, λexc = 420–470 nm. The scale bar is 50 µm.

Figure 5. Representative live cell images of A549 cells treated with 0.2 nM OsPhenSS•AuNP25 for 18 h. (a) Purple channel, osmium emission, (b) brightfield overlapped with both osmium emission (purple) and Hoescht 3368 (blue) and (c) overlap of osmium emission (purple) and Hoescht 3368 (blue) and reflectance (yellow). Channels: Osmium emission (λem = 488 nm, λexc = 650 – 800 nm); Hoescht 3368 λem = 405 nm, λexc = 623–643 nm. The scale bar is 50 µm.

To provide further validation of cellular uptake and red/NIR luminescence detection of the OsPhenSS•AuNP25, confocal imaging was also carried out in the human breast carcinoma cell line MCF-7 (Figure 6). Imaging analysis showed punctate intracellular luminescence in live MCF-7 cells (Figure 6b) after 24 h incubation with OsPhenSS•AuNP25 (Figure 6b and Figure S24). In serum-free medium. Incubation for 4h in contrast gave a lower signal by a factor of three. Cells were also incubated with the intracellular ROS probe 2′,7’-dichlorodihydroflourescein diacetate DCF-DA, which emits green fluorescence upon oxidation. On-stage illumination at 552 nm was used to selectively photoexcite the osmium complex. A comparison of the images (Figures 6 (e) and (f) for pre and post illumination) shows a marked increase in the green fluorescence, consistent with photo-induced intracellular ROS generation in the photosensitised cells. The initial punctate intracellular localisation is consistent with endocytic uptake of the nanoparticle which would be the expected uptake route.20, 32 However intracellular ROS generation will not be confined to endolysosomes since the vesicle membranes can be ruptured by ROS such as singlet oxygen resulting in redistribution of the NP within the cytosol.70 Although we did not attempt to quantify superoxide generation we note that even small quantum yields of this species can result in oxidative damage via Type 1 photocatalytic interactions.71, 72

Examination of bright-field images of cells photosensitised with OsPhenSS•AuNP25 showed that illumination at 402 nm induced morphological changes in the cells (eg swelling) consistent with cellular injury whereas illumination of cells without exposure to the nanoparticles elicited no evident changes. These observations are consistent with photooxidative damage via ROS generation. No morphological changes were observed in non-irradiated cells (Figure S22 and Figure S25).

Figure 6. Representative live cell images of MCF-7 cells for luminescence (a)-(d) and ROS generation studies (e)-(h), incubated with OsPhenSS•AuNP25 (a)+(b) and OsPhenSS•AuNP25 with DCF-DA (e)+(f) (24 h, [OsPhenSS•AuNP25] = 0.1 nM) and controls (c)+(d) and (g)+(h). (a) Bright-field image of cells in (b); (b) osmium luminescence (red channel); (c) bright-field image of cells without nanoparticles; (d) red channel control without nanoparticles; (e) green channel fluorescence before on-stage illumination of 300 s at 552 nm, of same field as (f); (f) green channel after on-stage illumination of 300 s at 552 nm, using same intensity scale as (e) and same field; (g) bright-field image of cells incubated with DCF-DA only for control shown in (h) and (h) green channel fluorescence image of cells incubated with DCF-DA only of same field as (g) after on-stage illumination of 300 s at 552 nm; Channels: Osmium red channel emission (λem = 552 nm, λexc = 680 – 780 nm); DCF-DA green channel (λem = 488, λexc = 510 – 550 nm); Scale bar is 50 µm.

We also studied the detection of singlet oxygen phosphorescence directly from OsPhenSS•AuNP13 (Figure 7). Since singlet oxygen is quenched efficiently by H2O giving a decay lifetime of only ~3 µs, we prepared AuNP in situ in D2O to minimise any H2O content (as described in Materials and Methods) and then performed the coating with OsPhenSS as illustrated in Figure 3. In D2O, the singlet oxygen lifetime is 20 times longer than for H2O and it is therefore much easier to detect the singlet oxygen phosphorescence using a D2O solution. This experiment was considerably more challenging technically than the singlet oxygen studies using the OsPhenSS
complex due to competing optical absorption from the AuNP at 532 nm and we had to use a short pathlength cuvette so that the laser excitation beam was not attenuated significantly. This short path length however restricted the signal that could be collected by the relay lens optics coupled to the detector. The use of a longer wavelength excitation beyond the SPR band would alleviate this problem.

Figure 7 shows the NIR signal detected with and without the addition of azide which is an efficient quencher of singlet oxygen.\textsuperscript{73} In the absence of azide, we observed a decay with a lifetime of approximately 50 µs whereas, in the presence of azide, the longer-lived phosphorescence is quenched, which is consistent with a calculated lifetime of < 1 µs at the 5 mM concentration of azide. The initial short-lived signal is unaffected by azide and is due to the residual NIR tail of fluorescence from the osmium signal. In the presence of azide, which is a physical quencher of singlet oxygen, the NIR phosphorescence tail is suppressed.

Figure 7 shows the NIR signal detected with and without the addition of azide; blue: with the addition of azide (5 mM). The initial short-lived signal is due to the residual NIR tail of fluorescence from the osmium signal. In the presence of azide, which is a physical quencher of singlet oxygen, the NIR phosphorescence tail is suppressed.

Conclusions

We have designed a luminescent osmium gold nanoparticle system for live cell imaging which shows far NIR luminescence at 785 nm with low nanoparticle dosage in both lung cancer and human breast carcinoma cells while displaying localisation in perinuclear regions. Cells dosed with the osmium-decorated gold nanoparticles upon irradiation at 532 nm displayed a marked activity of ROS generation which shows the strong potential of osmium-coated gold nanoparticles with therapeutic activity. The detection of singlet oxygen luminescence was confirmed for the osmium complex and the coated gold nanoparticles, even though the absorbance of AuNP SPR and the low concentrations of osmium employed lead to weaker signal detection. To our knowledge, this is the first design of osmium-coated gold nanoparticles for live cell imaging and singlet oxygen generation which offer potential applications in oncotheranostics and non-oncological indications. The combination of the dye complex with the nanoparticle enables new routes in targeting and codelivery of other agents.

Author contributions

The following authors contributed in the experimental parts as indicated: LW (synthesis, photophysical studies, imaging), JH (nanoparticles), ARM (cell imaging and analysis), PMG (nanoparticles preparation), SOA and GR (cell culture), STR (cell cultures and ROS generation) as well as in data analysis, project design and writing of the manuscript with support from NJH, AMR, EY and ZP.

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References


Data Availability Statement

The data supporting this article have been included as part of the Supplementary Information.