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Synthesis, Characterization and Biological Evaluation of New Ru(II) Polypyridyl Photosensitizers for Photodynamic Therapy

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4 ABSTRACT.
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8 Two Ru(II) polypyridyl complexes, Ru(DIP)₂(bdt) (**1**) and [Ru(dqpCO₂Me)(ptpy)]²⁺ (**2**) (DIP =
9 4,7-diphenyl-1,10-phenanthroline; bdt = 1,2-benzenedithiolate; dqpCO₂Me = 4-methylcarboxy-
10 2,6-di(quinolin-8-yl)pyridine); ptpy = 4'-phenyl-2,2':6',2''-terpyridine) have been investigated
11 as photosensitizers (PSs) for photodynamic therapy (PDT). In our experimental settings, the
12 phototoxicity and photo-index (PI) of **2** (IC₅₀(light): 25.3 μM, 420 nm, 6.95 J/cm²; PI: >4) and
13 particularly of **1** (IC₅₀(light): 0.62 μM, 420 nm, 6.95 J/cm²; PI: 80) are considerably superior
14 compared to the two clinically approved PSs porfimer sodium and 5-aminolevulinic. Cellular
15 uptake and distribution of these complexes was investigated by confocal microscopy (**1**) and by
16 inductively coupled plasma-mass spectrometry (**1** and **2**). Their phototoxicity was also
17 determined against the Gram-(+) *S. aureus* and Gram(-) *E. coli* for potential antimicrobial PDT
18 (aPDT) applications. Both complexes showed significant aPDT activity (420 nm, 8 J/cm²)
19 against Gram-(+) (*S. aureus*; >6 log₁₀ CFU reduction) and, for **2**, also against Gram(-) *E. coli*
20 (>4 log₁₀ CFU reduction).
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Introduction.

Cancer has arguably been one of the most studied disease in the last 100 years. Despite enormous research efforts, cancer has caused over eight million casualties or 13% of all deaths worldwide in 2012.¹ The cornerstones of cancer therapy are radiotherapy, surgery and chemotherapy. In the search for better approaches, photodynamic therapy (PDT) has proven to be a promising new, effective and non-invasive chemotherapeutic treatment modality. The general concept of PDT is based on a photosensitizer (PS), an ideally non-toxic molecule with a higher affinity for cancer cells over healthy cells, that can be excited by irradiation with light and reach a triplet excited state through intersystem crossing. In this state, the PS can react with a substrate or solvent molecule (Type I reaction), through hydrogen atom or electron transfer, generating radicals. The PS can also transfer energy to molecular oxygen (Type II reaction), forming most prominently singlet oxygen ($^1\text{O}_2$).^{2, 3} The products of these two types of reactions are highly reactive and have been shown to cause severe cellular stress and to lead to apoptosis and/or necrosis.⁴⁻⁶ The advantages of PDT over other cancer therapies are the high spatiotemporal control and the low systemic toxicity of the treatment.⁷ Recently, PDT has also been investigated as a new remedy against bacterial infections.⁸ The application of antimicrobial PDT (aPDT) is intriguing because, unlike conventional antibiotics, aPDT does not have one specific target but instead affects multiple sites. This drastically decreases the incidence of resistance. In fact, resistance against aPDT has not been observed yet.^{9, 10} With the imminent threat of widespread antibiotic resistance, aPDT could be a much needed new approach to fight the rapidly emerging, multidrug resistant superbugs. Since the approval of the first PDT drug (porfimer sodium) in 1993, multiple (13 as of 2003) PDT PSs have reached the market.² All of them are macrocyclic organic molecules, mostly porphyrin derivatives but also phthalocyanine-

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3 and chlorin-based molecules.² These PSs share several drawbacks such as a cumbersome
4 synthesis and purification, poor water solubility and slow clearance leading to prolonged
5 photosensitivity in patients.^{11, 12} There is therefore a need for novel PS with better photophysical
6 and biological properties. The biological, chemical and photolytic stability are key properties of
7 a PS for potential PDT applications. Additionally, the PS should also display a high phototoxic
8 index (PI = ratio between toxicity in the dark and upon light irradiation), a high ¹O₂ production
9 quantum yield as well as being active at red-NIR wavelengths to allow for a deeper tissue
10 penetration.
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22 Ruthenium complexes have been under investigation for their anticancer activity for
23 decades.¹³⁻¹⁸ They have gained widespread attention since two complexes, namely NAMI-A and
24 KP1019 (and the respective sodium salt KP1339), passed early clinical trials.¹⁹⁻²¹
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29 The use of ruthenium in PDT however, has been quite limited so far. There have been multiple
30 reports on porphyrin PSs decorated with ruthenium-based substituents. The resulting hybrid
31 complexes exhibited significantly higher PIs than the individual moieties.²²⁻²⁷ Charlesworth,²⁸
32 Carneiro *et al.*²⁹ also investigated organic PSs, phthalocyanines, conjugated to ruthenium
33 moieties. Although the increased PIs are promising, this approach is not ideal as it requires an
34 even longer synthetic pathway than the macrocyclic organic PSs alone. Following a similar
35 approach, Zhou and co-workers coordinated hypocrellin B, an easily prepared phototoxic
36 compound, to ruthenium. The resulting complex showed promising photosensitizing and
37 photodamage properties in the red-NIR region superior to the hypocrellin B alone.³⁰ Another
38 branch in the research of light-activated ruthenium complexes has investigated the ability of such
39 compounds to release ligands and/or undergo ligand exchanges upon light irradiation. For
40 instance Zayat,³¹ Salierno and co-workers,³² have reported complexes that release biologically
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3 active molecules upon light irradiation. On the other hand, Sun,³³ Goldbach,³⁴ Wachter,³⁵
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5 Sgambellone *et al.*³⁶ have described a series of ruthenium complexes which undergo ligand
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7 exchange and subsequent DNA binding or even cleavage upon irradiation at red-NIR
8
9 wavelengths. The use of ruthenium complexes for ¹O₂ production has gained attention only in
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11 recent years. Notably, Lincoln *et al.* have reported ruthenium polypyridyl complexes that
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13 efficiently produce ¹O₂ upon irradiation with white light and exhibit high phototoxic indices in a
14
15 metastatic melanoma model.³⁷ These promising, but very limited reports indicate the enormous
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17 potential of ruthenium-based PS. Still, the hitherto reported ruthenium PSs are not ideal. The
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19 conjugation of ruthenium to porphyrins does not facilitate their already cumbersome synthesis.
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21 Moreover, nuclear DNA might not be optimal target in PDT since DNA damage causes
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23 mutagenesis, which can result in resistance to further treatments.^{38, 39} Hence, there certainly is
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25 still much uncharted chemical space for ruthenium PSs in PDT.
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32 By comparison, in the realm of antibacterial research, ruthenium complexes have only
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34 sparingly been studied. There have been some reports on mono- and polynuclear Ru(II)
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36 compounds that effectively reduce the viability of different bacterial strains.⁴⁰⁻⁴³ However, the
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38 field of aPDT is still in its infancy and, to our knowledge, no ruthenium PSs have been
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40 investigated for this purpose. This motivates further investigations into ruthenium complexes for
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42 antimicrobial applications. Recently, we have been applying Ru(II) polypyridyl complexes as
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44 PSs in PDT using low light doses at 350/420 nm. The studied complexes showed promising
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46 properties with regard to their ¹O₂ yields, cellular uptake and phototoxic index.⁴⁴ Building on
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48 these promising preliminary results, we have embarked on a program to investigate in-depth the
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50 use of such complexes as PSs in PDT. Our aim is to develop biologically stable Ru(II)-based PSs
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3 with a straight-forward synthesis and purification, high $^1\text{O}_2$ production quantum yield, high PI
4 and possibly alternative target sites.
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8 In the search for novel ruthenium PSs in PDT, we turned our attention to the field of dye-
9 sensitized solar cell (DSSC). The role of ruthenium complexes in DSSCs is to absorb sunlight
10 and inject electrons into the conduction band of an electrode.^{45, 46} It has been shown that Ru(II)
11 polypyridyl complexes perform very efficiently in DSSCs.⁴⁷⁻⁵³ The complexes used for DSSCs
12 exhibit interesting photophysical properties, such as light absorption across the visible spectrum
13 and long excited-state lifetimes.⁵⁴⁻⁵⁷ These properties make this class of complexes highly
14 interesting as potential PS in PDT. Hence, with the vast number Ru(II) polypyridyl complexes
15 that have been investigated in the field of DSSC, we decided to probe this class of complexes as
16 PSs in PDT. It would not be the first time that metal complexes designed for a specific purpose
17 find a novel application in a completely unrelated field. For instance, compounds originally
18 envisioned for catalysis are being found to be promising drug candidates, e.g. Hoveyda-Grubbs
19 catalysts demonstrated antiproliferative activity against cancer cells similar to cisplatin.^{58, 59} We
20 designed our novel, but representative complexes inspired by the work of Islam^{54, 55} and
21 Abrahamson *et al.*⁵⁶ For complex **1**, we decided to use 4,7-1,10-diphenylphenanthroline (DIP) as
22 the polypyridyl ligand since $[\text{Ru}(\text{DIP})_3]^{2+}$ is a known PS with a high $^1\text{O}_2$ yield (0.97 in MeOD).⁶⁰
23 Islam *et al.* reported that the absorbance of ruthenium complexes of the type $(\text{Ru}(\mathbf{X})_2(\mathbf{L}))$, where
24 \mathbf{X} is a simple polypyridyl ligand, can be tuned by careful choice of \mathbf{L} (two examples,
25 **Ru(dcbpy)(NCS)₂** and **Ru(dcbpy)(bdt)** are shown in Fig. 1; dcbpy: 4,4'-dicarboxy-2,2'-
26 bipyridine, bdt: 1,2-benzenedithiol). For bidentate dithiol ligands in particular, extensive red-
27 shift of the complexes absorbance has reported. Based on these findings, we chose 1,2-
28 benzenedithiol (bdt) as the third ligand due to its structural simplicity. On the other hand, for
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complex **2**, we took into account the large body of research that indicated that tridentate polypyridyl ligands generally lead to broad absorption across the visible spectrum and perform inherently well in DSSC.^{57, 61-64} Also in this case, relatively simple ligands were used, with only one carboxylic acid functionality present. Herein we report the synthesis and characterization of two novel Ru(II) polypyridyl PS (**1** and **2**, Fig. 1), and their phototoxic activity against human cell lines and bacterial strains.

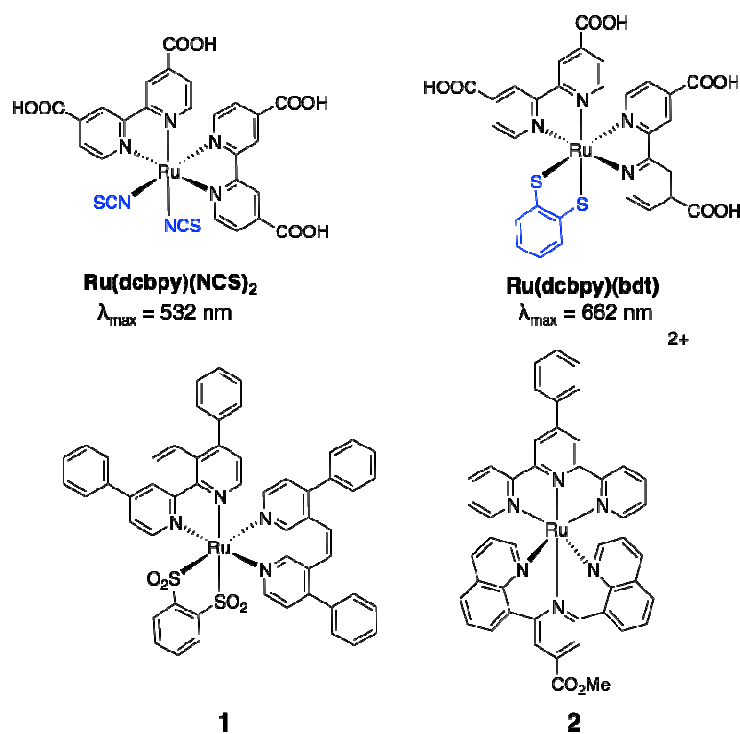
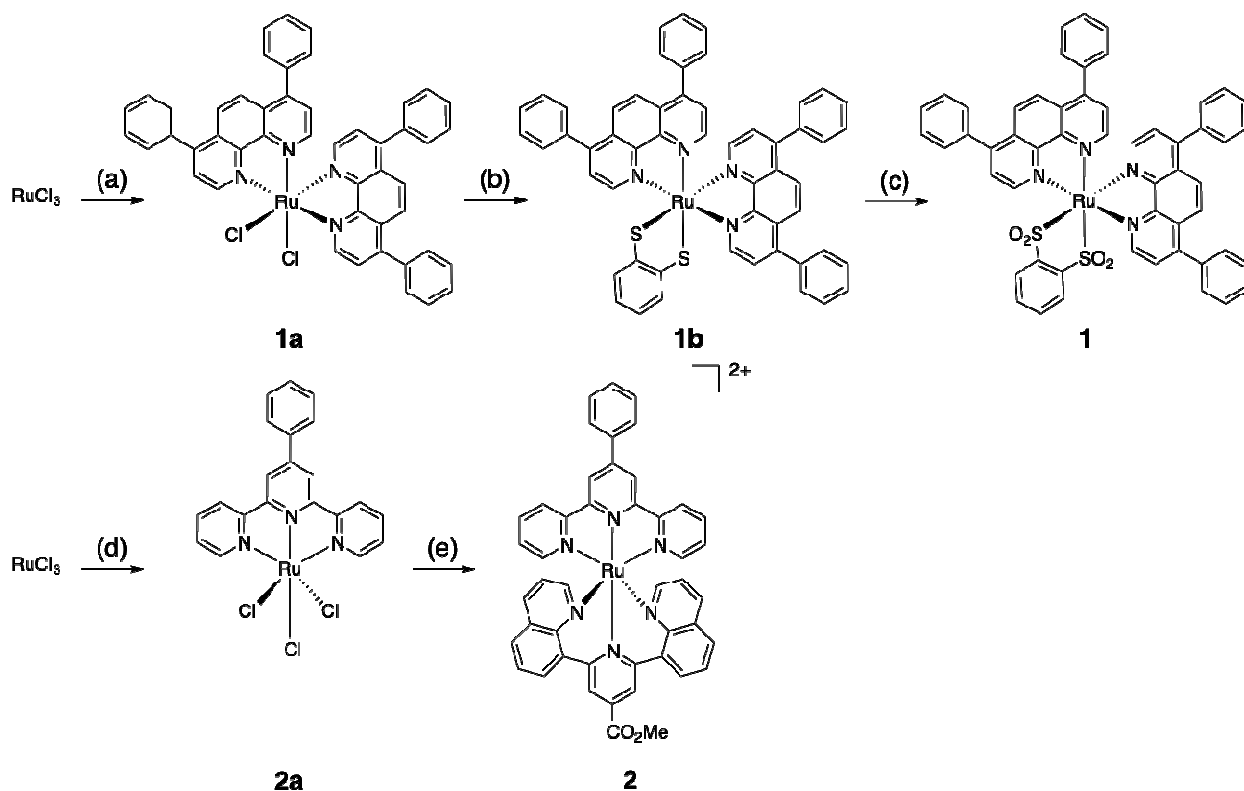


Figure 1. Structures of two representative complexes **Ru(dcbpy)(NCS)₂** and **Ru(dcbpy)(bdt)** reported by Islam *et al.*⁵⁴ and of the ruthenium polypyridyl complexes **1** and **2**.

Results and Discussion.

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Synthesis and Characterization. The ruthenium(II) polypyridyl complex **1** was synthesized from [Ru(DIP)₂Cl₂] (**1a**), which was itself obtained from RuCl₃ through a modified procedure reported by Caspar *et al.* (Scheme 1).⁶⁵ Due to the rapid oxidation of the sulfido ligand upon contact with air a complex mixture of products was formed preventing the isolation of **1b**. A similar observation was also reported by Begum *et al.*⁶⁶ for a related ruthenium complex. Consequently, the mixture of differently oxidized species obtained from **1b** was dissolved in acetonitrile and oxidized to the disulfinato complex **1** by addition of H₂O₂ and stirring at room temperature. After purification by column chromatography on silica, **1** could be obtained in 26% yield. The ligands, ptpy (ptpy = 4'-phenyl-2,2':6',2''-terpyridine) and dqpcO₂Me (dqpcO₂Me = 4-methylcarboxy-2,6-di(quinolin-8-yl)pyridine), were prepared according to literature procedures.^{67, 68} Starting from RuCl₃, **2b** was obtained and used without further purification for the next step. After column chromatography on silica and subsequent counterion exchange, complex **2** was obtained as a hexafluorophosphate salt in 47% yield. For **1**, the only ESI-MS (positive mode) peak at 970.9 *m/z* could be assigned to be [M+H]⁺ (calculated: 971.1 *m/z*). For **2**, the ESI-MS (positive mode) peak 401.0 *m/z* could be assigned to [M]²⁺ (calculated: 401.1 *m/z*). Furthermore, the presence of a single major peak in the UPLC analysis and the match of the elemental analysis with <0.3% deviation unambiguously confirmed the purity of **1** and **2**.



Scheme 1. Reagents and conditions: (a) 4,7-diphenyl-1,10-phenanthroline, LiCl, DMF, overnight, reflux, 50 %; (b) 1,2-benzenedithiol, EtOH overnight, reflux; (c) 30% H₂O₂(aq), CH₃CN, 30%, 48 h, r.t., 26%; (d) 4'-phenyl-2,2':6',2''-terpyridine, EtOH 3 h, reflux; (e) i) AgBF₄, acetone, 3 h, reflux; ii) 4-methylcarboxy-2,6-di(quinolin-8-yl)pyridine, butanol, overnight, reflux, 47 %.

X-ray Crystal Structure. Single crystals of **2** were obtained by slow evaporation of a water/acetonitrile solution (1:1 v/v). Compound **2** crystallized in the orthorhombic space group *Fdd2*. The ORTEP representation, shown in Figure 2, reveals that while the ptpy ligand is almost planar, the dqpcO₂Me ligand is strongly distorted out of the xy-plane. The Ru-N bond lengths and angles (see Table S1 in SI) are in good agreement with those for similar complexes reported in the literature.^{69, 70}

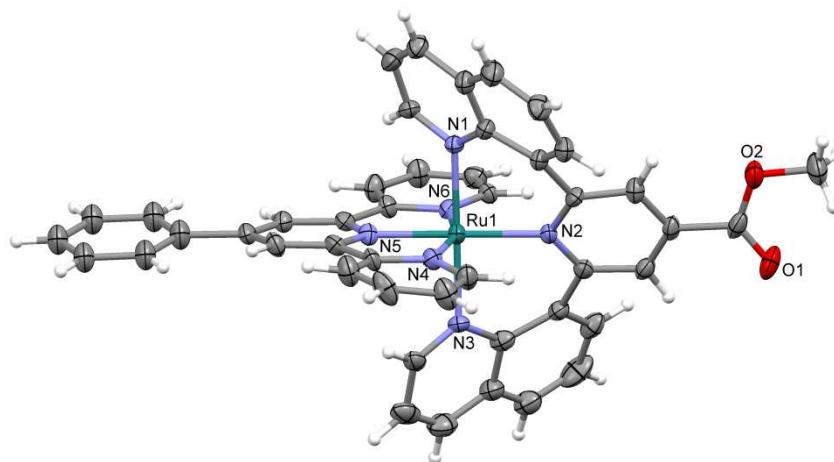


Figure 2. ORTEP representation of **2**. Ellipsoids are drawn at 20% probability level; Color code: carbon (grey), hydrogen (white).

Photophysical Properties. In order to determine if complexes **1** and **2** have properties favorable for photosensitization, a series of photophysical measurements was performed. The UV/Vis absorption and photoluminescence spectra were measured in acetonitrile (Fig. S1 in SI). From the emission spectrum of **1**, a luminescence quantum yield of 0.5% in acetonitrile could be calculated according to a standard procedure.⁷¹ Furthermore, the luminescence lifetime was determined in both air-equilibrated ($\lambda_{\text{exc}} = 440 \text{ nm}$; $189 \pm 4 \text{ ns}$) and degassed ($\lambda_{\text{exc}} = 440 \text{ nm}$; $1130 \pm 28 \text{ ns}$) acetonitrile solutions. The results are comparable to those reported for similar Ru(II) polypyridyl complexes, indicating a phosphorescence-type emission.⁷² Luminescence lifetimes in the μs -range implicate a long-lived triplet excited state, which is thought to be important for efficient photosensitization.³⁷ Altogether, complex **1** showed luminescence lifetimes favorable for photosensitization. The luminescence emission spectrum of **2** shows only weak intensity (Fig S1), which is reflected by a low emission quantum yield of $<0.1\%$. The

luminescence lifetime was measured in toluene since it was below the detection limit when measured in acetonitrile. The lifetime was found to be 12 ± 2 ns under aerated conditions and 30 ± 1 ns in degassed toluene ($\lambda_{\text{exc}} = 440$ nm). These values are in agreement with those reported by Abrahamsson *et al.*⁵⁶ for similar complexes, indicating a fluorescence-type emission.

Stability in Human Plasma. In order to obtain a preliminary insight into the stability of **1** and **2** under physiological conditions, they were incubated in human blood plasma at 37 °C, following our recently developed protocol.^{73, 74} No significant changes were observed either in the UV traces or in the ratio between diazepam (internal standard) and **1** and **2**, respectively, even after 48 h (Fig. 3). These results suggest that **1** and **2** are stable under physiological conditions for a therapeutically relevant time.

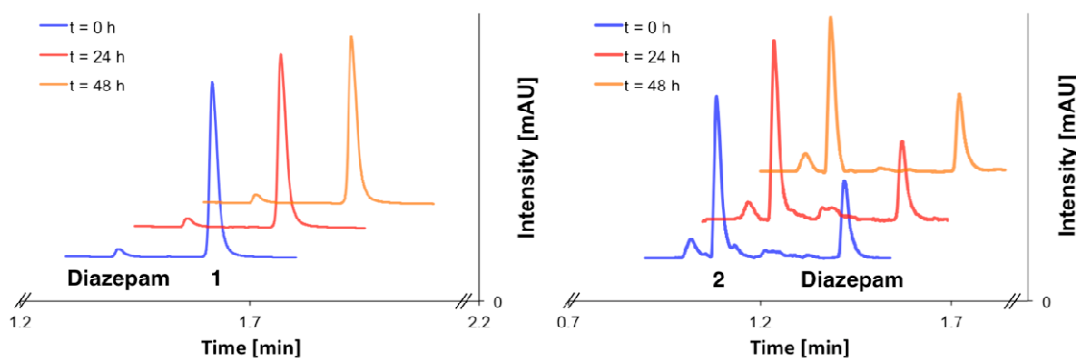


Figure 3. UV traces of UPLC analysis of **1** and **2** incubated in human plasma at 37 °C for 0 h, 24 h and 48 h using diazepam as an internal standard.

Singlet Oxygen Production. To assess the phototoxic potential of **1** and **2**, their $^1\text{O}_2$ production quantum yields (Φ_{Δ}) were determined in acetonitrile and phosphate buffered saline (PBS) by means of both an indirect and direct method as recently published by our group.⁷⁵ For

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3 both methods the complexes were irradiated with 420 nm light. In the first method, $^1\text{O}_2$
4 production is observed indirectly through the quenching of the absorbance at 420 nm
5 (acetonitrile) or 440 nm (PBS) of *N,N*-dimethyl-4-nitrosoaniline (RNO) by a *trans*-annular
6 peroxide adduct formed by the reaction of $^1\text{O}_2$ with histidine in PBS. In acetonitrile, imidazole is
7 used instead of histidine due to the low solubility of the latter in this solvent. By comparison of
8 the quenching rates of our compounds with a reference compound (phenalene at 420 nm) with
9 a known $^1\text{O}_2$ production rate⁷⁶ at a given wavelength, the $^1\text{O}_2$ quantum yield of **1** and **2** could be
10 determined in acetonitrile and PBS at an irradiation wavelength of 420 nm. It is well
11 acknowledged that the measurement of absorbance changes are not highly sensitive.⁷⁷ To
12 confirm the results obtained by the indirect assay, another method was employed. $^1\text{O}_2$ displays a
13 characteristic near-IR luminescence that can be observed at 1270 nm with an IR-sensitive
14 detector. This method could only be applied for **1** since **2** did not show a sufficiently high signal-
15 to-noise ratio to obtain meaningful results. By comparison of the luminescence intensity
16 measured for **1** with the one of phenalene, a second set of $^1\text{O}_2$ quantum yields could be
17 obtained for this complex. The measured $^1\text{O}_2$ quantum yields can be seen in Table 1. All values
18 are expressed as the mean of three independent experiments with a standard deviation of less
19 than 5%. Complex **1** showed an excellent $^1\text{O}_2$ production ($\Phi_{\Delta}(\mathbf{1}; \text{ACN})_{\text{indirect}} = 0.81$; $\Phi_{\Delta}(\mathbf{1};$
20 $\text{ACN})_{\text{direct}} = 0.92$) in acetonitrile. In PBS, both measurement techniques, direct and indirect, were
21 at the detection limit. It is well acknowledged that singlet oxygen in aqueous solution is short-
22 lived ($\approx 3.5 \mu\text{s}$) in comparison to acetonitrile (70-80 μs), which has a diminishing influence on
23 the signal intensity.⁷⁸ The low signal-to-noise ratio did not allow an estimation with the direct
24 method whereas the indirect method led to a low quantum yield $\Phi_{\Delta}(\mathbf{1}; \text{PBS})_{\text{indirect}} = 0.04$).
25 Complex **2** showed moderate $^1\text{O}_2$ quantum yields at 420 nm in acetonitrile ($\Phi_{\Delta}(\mathbf{2}; \text{ACN})_{\text{indirect}} =$
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0.15) but the direct measurement did not allow an evaluation of the quantum yield due to low signal-to-noise ratio. The different $^1\text{O}_2$ quantum yields for **1** and **2** are probably related to the difference in their luminescence lifetimes. A long luminescence lifetime indicates a long-lived triplet-excited state, which in turn is favorable for photosensitization purposes.³⁷ For both compounds, the highest $^1\text{O}_2$ quantum yields were measured in the more lipophilic solvent acetonitrile. Since cells do not only have polar but also lipophilic environments, compounds **1** and **2** could prove to be promising PSs.⁷⁵

Table 1. Singlet oxygen quantum yields of **1** and **2**, values expressed as mean of three independent experiments (with standard deviation <5%).

Compound	Solvent	Indirect Method	Direct Method
		$\Phi_{\Delta}(420 \text{ nm})$	$\Phi_{\Delta}(420 \text{ nm})$
1	ACN	0.81	0.92
	PBS	0.04	n.d.*
2	ACN	0.15	n.d.*
	PBS	0.03	n.d.*

*not detected

Cytotoxicity Studies. The cytotoxicity of **1** and **2** towards the human cervical cancer cell line (HeLa) was determined using a fluorometric cell viability assay (Resazurin). For comparison

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3 purposes, the cytotoxicity of the compounds was also determined towards the human fibroblast
4 (MRC-5) non-tumorigenic cell line with cisplatin as a reference. After 4 h incubation time, the
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6 medium was replaced with fresh medium (without complex) and the cells were irradiated at
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8 420 nm for 15 min. The corresponding light dose (6.95 J/cm^2) is very similar to that used for the
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10 clinically approved PS porfimer sodium in comparable experiments (5 J/cm^2).⁷⁹ The IC_{50} values
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12 for all measurements are shown in Table 2. It must be noted that for the IC_{50} values determined
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14 without irradiation, two different values were obtained (for HeLa cells) for incubation times of
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16 48 h and 4 h, respectively. This was done to compare the values with cisplatin (48 h) and with
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18 the irradiation experiments (4 h). Complex **1** shows elevated cytotoxicity against both MRC-5
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20 and HeLa cell lines. Notably, the cytotoxicity is significantly higher against the tumorigenic cell
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22 line. Irradiation at 420 nm for 15 min increased the cytotoxicity of **1** to a remarkable IC_{50} value
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24 of 620 nM. This corresponds to a PI of 80 relative to the dark experiments. These results are
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26 even more interesting if compared to clinically established anticancer PDT agents. Under the
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28 same experimental conditions, **1** and **2** displayed a significantly higher phototoxicity and PI
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30 compared to another clinically approved PDT drug, namely 5-aminolevulinic acid (ALA),⁸⁰⁻⁸²
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32 which is the precursor of protoporphyrin IX. Moreover, both the IC_{50} values and the PI of **1**
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34 represent a significant improvement with respect to porfimer sodium. The latter was found to
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36 have an IC_{50} value of $2.57 \pm 0.12 \text{ } \mu\text{g/ml}$ and a corresponding PI of >10 upon 24 h incubation in
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38 HeLa cells and irradiation with the appropriate wavelength and a comparable light dose (5 J/cm^2)
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40 ($\text{IC}_{50}(\text{dark}): >25 \text{ } \mu\text{g/ml}$; cf. values in brackets in Table 2).⁷⁹ Since cisplatin has a light-
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42 independent mode of action, the PI is not applicable for this compound.⁸³ Complex **2** displayed a
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44 very promising lack of activity towards non-tumorigenic cells (MRC-5) as well as towards
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46 cancerous cells (HeLa) in the dark in the range of concentrations measured in this study (up to
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100 μM), while still demonstrating a moderate toxicity ($\text{IC}_{50} = 25.3 \pm 4.7 \mu\text{M}$) upon irradiation and a PI of at least 4. The high phototoxicity observed for **1** upon irradiation at 420 nm is in agreement with the higher $^1\text{O}_2$ quantum yields and stronger absorption observed at this wavelength.

Table 2. IC_{50} values and phototoxic index (PI) for complexes **1** and **2**, in HeLa cancer cells and MRC-5 non-tumorigenic cells with the IC_{50} values of cisplatin as a positive control.

Compound	MRC-5	HeLa	HeLa	HeLa	PI
	[μM ($\mu\text{g}/\text{ml}$)] (48 h, dark) ^a	[μM ($\mu\text{g}/\text{ml}$)] (48 h, dark) ^a	[μM ($\mu\text{g}/\text{ml}$)] (4 h, dark) ^b	[μM ($\mu\text{g}/\text{ml}$)] (4 h, 420 nm) ^c	
1	15.6 ± 2.7 (15.1 ± 2.6)	5.7 ± 0.7 (5.5 ± 0.7)	49.7 ± 10.1 (48.2 ± 9.8)	0.62 ± 0.28 (0.60 ± 0.27)	80
2	>100 (>100)	>100 (>100)	>100 (>100)	25.3 ± 4.7 (30.0 ± 5.6)	>4
ALA ^f	>50	>50	>50	45.5 ± 3.2	>1
Cisplatin	7.9 ± 1.2	11.5 ± 2.9	n.d. ^d	22.2 ± 5.7	n.a. ^e

^a48 h incubation at 37 °C, 6% CO_2 ; ^b4 h incubation at 37 °C, 6% CO_2 ; ^c4 h treatment followed by 15 min irradiation at 420 nm ($6.95 \text{ J}/\text{cm}^2$) and 44 h incubation at 37 °C, 6% CO_2 ; ^dnot determined; ^enot applicable; ^fMeasured IC_{50} values were adjusted taking into account that four molecules of ALA are required for the formation of one molecule of protoporphyrin IX, which represents the active species.^{84, 85}

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7 **Cellular Localization.** Having demonstrated that complex **1** possesses favorable photo-
8 luminescence and phototoxicity properties as well as being stable under physiological conditions,
9 its cellular localization in HeLa cells was assessed by confocal microscopy. This cell line was
10 selected since it is considered to be a reliable and economic model for human cervical cancer.
11 Additionally, it is also a type of cancer that is accessible by fiber-optics, which is an essential
12 requirement for PDT applications.⁸⁶ Cells were stained with DAPI (Fig. 4a) and with the
13 Mitotracker green FM (Fig. 4b). Complex **1** was visualized with an excitation at 400 nm (Fig.
14 4c), which does not interfere with the other dyes. As can be seen in Fig. 4c, the luminescence of
15 **1** is highly visible. Fig. 4d shows the overlay of Fig 4a-4c. It can be observed that the area of the
16 emission of **1** superimposes extremely well with the emission of the Mitotracker green FM,
17 which localizes in mitochondria. Accumulation of the PS in the mitochondria is promising as
18 they are important cell organelles and their damage can trigger different paths of cell death.^{73, 87}
19 We note that very poor photoluminescence of **2** precluded confocal microscopy studies.
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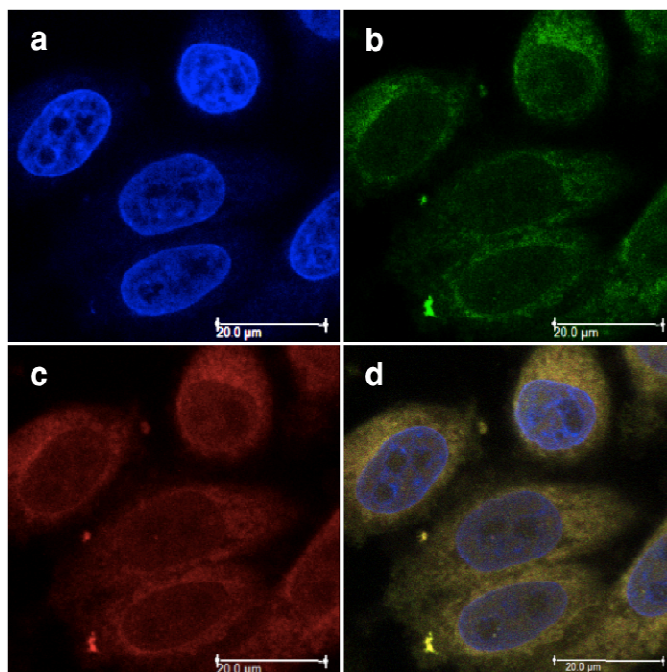
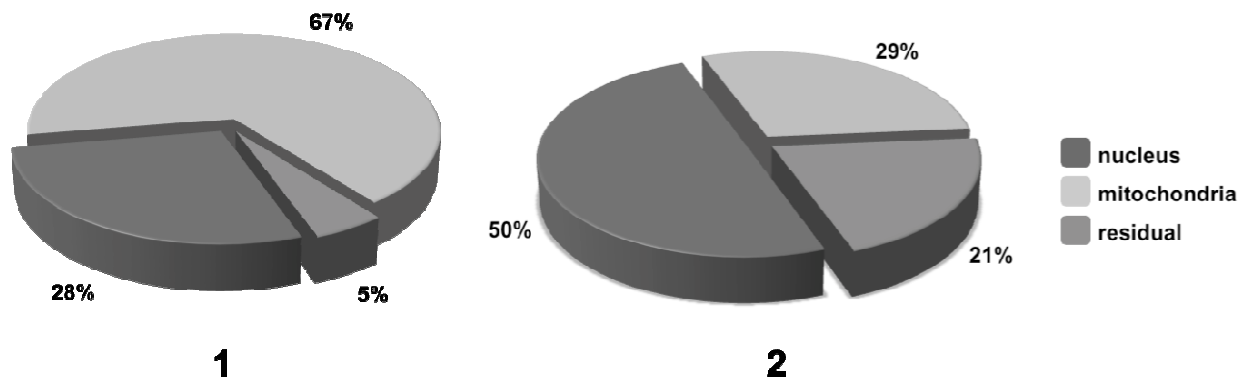


Figure 4. Fluorescence confocal microscopy images of HeLa cells incubated with 40 μM of **1** for 4 h: a) DAPI staining; b) Mitotracker green FM staining; c) visualization of **1** by excitation at 405 nm. d) overlay of a-c.

Cellular Uptake. Taking advantage of the presence of a metal in our systems, the accumulation of complexes **1** and **2** in cancer cells was investigated using inductively coupled plasma-mass spectrometry (ICP-MS). HeLa cells were incubated for different periods of time (0h, 4h and 48h) with the ruthenium compounds. **1** and **2** displayed a time dependent accumulation which is most pronounced for **1**. **1** reached a 30% higher Ru content (35.0 ng/mg protein) than **2** (23.6 ng/mg protein) after 48 h. Although **1** and **2** demonstrated considerable to high phototoxicity, it has to be acknowledged that their cellular uptake into HeLa cells is quite moderate compared to other Ru(II) complexes.^{44, 88, 89}

To obtain more detailed information about the localization of **1** and **2** their subcellular accumulation was investigated. Briefly, HeLa cells were incubated with **1** and **2** for 4 h and subsequently the nuclei and mitochondria of the cells were isolated while the remaining cell material was kept as a residual fraction. The two complexes displayed a quite different cellular distribution profile (Fig. 5). For **1**, the results confirmed the data obtained by the microscopy studies with 67 % of the total Ru taken up by mitochondria (9.1 ± 1.3 ng/mg protein). We have previously observed a similarly high mitochondrial uptake with another class of Ru(II) polypyridyl complexes.⁷³ In contrast to the microscopy results, a significant amount of Ru could also be observed in the nuclear fraction (28%, 3.8 ± 1.3). The residual cellular fraction contained only 5% of Ru (0.7 ± 0.3 ng/mg protein). For **2**, the total ruthenium content of the isolated cell nuclei was 50 % of the total amount of up taken ruthenium (8.27 ± 0.27 ng/mg protein) while the mitochondria contained 29% (4.85 ± 0.42 ng/mg protein). The residual fraction contained 21% (3.44 ± 0.36 ng/mg protein). Taken together, these results indicate an overall moderate cellular uptake for both complexes **1** and **2**. Nevertheless, both complexes displayed significant toxicity upon light irradiation (and also in the dark for **1**) and chemical modifications (compounds (e.g. by coupling them to a targeting molecule) to improve their cellular uptake could further increase their phototoxicity.



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3 **Figure 5.** Ruthenium uptake in the different cellular compartments of HeLa cells treated for 4 h
4 with 20 μM of **2** and quantified by ICP-MS.
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11 **Antibacterial Studies.** To investigate the potential of complexes **1** and **2** as aPDT agents, their
12 phototoxicity was determined against two bacterial strains, the Gram-(+) *S. aureus* and the Gram-
13 (-) *E. coli*. The efficacy of a PS in aPDT can vary substantially depending on whether the
14 bacterial strain is a Gram-(-) or Gram-(+) species, with Gram-(-) strains being less vulnerable to
15 certain PS.⁹⁰ The phototoxicity of **1** and **2** was determined according to a method recently
16 published by Eichner *et al.*⁹¹ Briefly, solutions of each bacterial strain were incubated with the
17 respective compound for 15 min at different PS concentrations. The cells were then irradiated for
18 10 min with visible light (380-480 nm, $\lambda_{\text{max}} = 420 \text{ nm}$, 8 J/cm^2) and the fraction of bacteria still
19 alive was determined according to the Miles, Misra and Irwin method as the number of colony-
20 forming units (CFU) per ml.⁹² Control experiments were performed to exclude any additional
21 toxicity by the solvent (DMSO) used to dissolve the complexes. The results are expressed as the
22 mean of three independent experiments. In experiments where the bacteria were not irradiated,
23 no significant change in CFU/ml was observed. For both **1** and **2**, a reduction of $> 6 \log_{10}$
24 ($\geq 99.9999\%$) in cell viability was observed at concentrations of $50 \mu\text{M}$ (Figure 6) against the *S.*
25 *aureus* strain. Considering the light dose of 8 J/cm^2 and the short incubation time used in these
26 experiments, the results are very promising, particularly with regard to those recently reported by
27 Schastak *et al.*⁹³ for a porphyrin PS. Complex **1** showed no detectable phototoxic effect against
28 the *E. coli* strain while complex **2** reduced cell viability by $> 4 \log_{10}$ ($\geq 99.99\%$) at $50 \mu\text{M}$. This is
29 interesting because Gram-(-) strains (like *E. coli*) are known to be less sensitive to certain types
30 of PS. It has been reported that positively charged PS are more effective at killing Gram-(-)
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bacteria and our findings are well in agreement with this hypothesis.⁹⁰ Another series of Ru(II) polypyridyl complexes was tested against *E. coli* by Lei *et al.*⁹⁴ In both cases, phototoxicity was observed but, since no light dose is reported, the results are not easily comparable. The decrease in cell viability against *S. aureus* is similar for **1** and **2**, which is in contrast to the difference in IC₅₀ values observed in the HeLa cell assay. This finding can be attributed to the 16-fold longer incubation time (15 min compared to 4 h) in the human cell experiments. Also, in contrast to the procedure with the human cells, the medium was not exchanged prior to the irradiation in these experiments, thereby possibly allowing the fraction of the compound that did not enter the bacteria to also damage the cells. Both complexes showed high phototoxicity against the Gram-(+) strain *S. aureus* and **2** also effectively reduced the cell viability of the Gram-(−) strain *E. coli*. This makes **1** and particularly **2** promising candidates for aPDT applications, where topical application and irradiation wavelengths in the 400-500 nm range can be used.

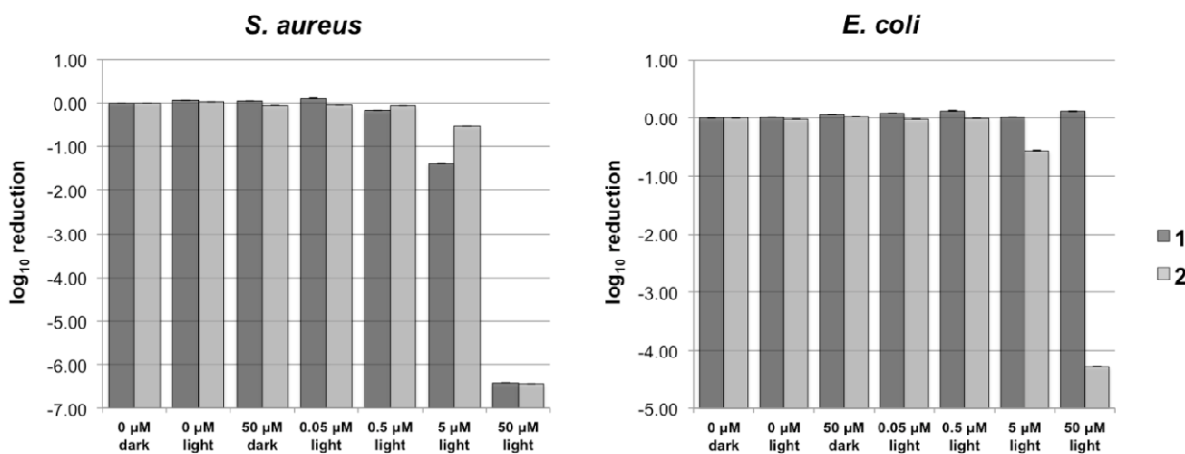


Figure 6. Antibacterial activity of complexes **1** and **2** against the two bacterial strains, *E. coli* and *S. aureus* (conditions: 15 min treatment followed by 10 min irradiation at 420 nm (8 J/cm²) and 24 h incubation at 37 °C).

Conclusions

In a first step to probe the large library of ruthenium compounds used in DSSC in the field of PDT, two novel ruthenium(II) polypyridyl complexes (**1** and **2**) have been prepared and characterized, including by X-ray crystallography for **2**. Their stability in biological media, photophysical properties and $^1\text{O}_2$ production quantum yields have been determined. Both complexes were shown to produce $^1\text{O}_2$. Furthermore, their phototoxicity was evaluated against the human cervical cancer cell line HeLa. Complex **2** displayed phototoxicity in the low micromolar range against HeLa cells and, most importantly, no significant toxicity in dark experiments. Complex **1** showed phototoxicity in the nanomolar range with a PI of 80 against HeLa cells. This result is even more impressive when compared to the clinically approved PS ALA and porfimer sodium which display both lower phototoxicity and PIs in similar experimental settings.⁷⁹ With the help of confocal microscopy experiments, **1** was shown to accumulate in the cytoplasm, particularly in mitochondria. These results were confirmed by ICP-MS experiments, which showed an accumulation of around 67% of the total Ru taken up by the cell into the mitochondria. In comparison, the cellular uptake of **2** was shown to be quite more diffuse. In fact, **2** could be detected in all cellular compartments, with a slight preference for the cellular nucleus. Both complexes showed an overall cellular uptake 10-100 times lower than for other ruthenium complexes.^{44, 88, 89} Remarkably, **2** and particularly **1** still exhibited moderate to high toxicity upon light irradiation. Improving the cellular uptake of these compounds (e.g. by coupling them to a targeting molecule) could further increase both their toxicity and selectivity against cancer cells.

In the light of the novel up-and-coming field of aPDT, the phototoxicity of **1** and **2** was also tested against the two bacterial strains *S. aureus* and *E. coli*. The former effectively reduced cell

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3 viability in the Gram-(+) strain *S. aureus* whereas no toxicity was observed against the Gram-(−)
4 strain *E. coli* within the experimental conditions. On the other hand, **2** effectively reduced cell
5 viability in both, the Gram-(+) *S. aureus* and Gram-(−) *E. coli*, bacterial strains. The phototoxic
6 profile of **2** against bacteria is particularly promising as Gram-(−) bacterial strains are reported to
7 be inherently less affected by aPDT compared to Gram-(+) bacteria.⁹⁰ Taken together, these
8 results further emphasize the enormous potential of ruthenium complexes in PDT and also in the
9 nascent field of aPDT. While the wavelength of irradiation used in this work is suitable for
10 topical applications, further work will focus on the development of novel ruthenium PS that are
11 active in the red-NIR region, where deeper tissue penetration can be achieved.
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28 **Experimental section.**

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30 **Materials.** All chemicals were of reagent grade quality or better, obtained from commercial
31 suppliers and used without further purification. The Ligands dqpCO₂Me and ptpy were prepared
32 according to literature procedures.^{67, 68} The purity of all final compounds was shown to be 95%
33 or higher by elemental microanalysis. Solvents were used as received or dried over molecular
34 sieves. All preparations were carried out using standard Schlenk techniques.
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42 **Instrumentation and Methods.** ¹H and ¹³C NMR spectra were recorded in deuterated solvents
43 on 400 (¹H: 400 MHz, ¹³C: 100.6 MHz) or 500 (¹H: 500 MHz, ¹³C: 126 MHz) MHz
44 spectrometers at room temperature. The chemical shifts, δ, are reported in ppm (parts per
45 million). The residual solvent peaks have been used as an internal reference. The abbreviations
46 for the peak multiplicities are as follows: s (singlet), d (doublet), dd (doublet of doublets), t
47 (triplet), q (quartet), m (multiplet), and br (broad). ESI-MS and UPLC-MS were obtained with a
48 Bruker Esquire 6000 mass spectrometer. LC-MS and UPLC-MS spectra were measured on an
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3 Acquity™ from Waters system equipped with a PDA detector and an auto sampler using an
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5 ACQUITY UPLC BEH C18 Gravity 1.7 μm (2.1 × 50 mm) reverse phase column. A total of 2 μl
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7 of the solution was injected into the HPLC that was connected to a mass spectrometer operated
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9 in ESI mode The UPLC runs (flow rate: 0.6 ml/min) were performed with a linear gradient of A
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11 (acetonitrile (Sigma Aldrich HPLC-grade)) and B (distilled water containing 0.1% formic acid): t
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13 = 0–0.25 min, 5% A; t = 1.5 min, 100% A; t = 2.5 min, 100% A. Elemental microanalyses were
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15 performed on a LecoCHNS-932 elemental analyser. IR spectra were obtained with a Perkin
16
17 Elmer Spectrum Two spectrometer. UV/Vis spectra were measured on a Varian Cary50Scan
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19 UV-Visible Spectrophotometer and Luminescence spectra on a Perkin Elmer LS 50 using
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21 fluorescence quartz cuvettes (width 1 cm).
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26 27 **Synthesis.**

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29 **Ru(DIP)₂Cl₂:** RuCl₃ (110 mg, 0.42 mmol), 4,7-diphenyl-1,10-phenanthroline (DIP, 266 mg,
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31 0.8 mmol) and LiCl (100 mg, 2.36 mmol) were dissolved in DMF (10 ml). The mixture was
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33 heated to reflux overnight and then allowed to cool down to room temperature. Acetone (50 ml)
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35 was added to the solution to initialize recrystallization. The mixture was kept in the fridge for
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37 another day. The precipitate was collected by filtration and washed with diethylether (20 ml) and
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39 water (20 ml). The solid residue was dissolved in dichloromethane and collected. The solvent
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41 was removed *in vacuo* yielding a dark purple solid of Ru(DIP)₂Cl₂. Yield: 174 mg (50%).
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46 The analytical data matched that reported previously.⁶⁵
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49 **Ru(DIP)₂(bdt) (1):** Ru(DIP)₂Cl₂ (180 mg, 0.22 mmol) was dissolved in degassed EtOH (15
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51 ml). 1,2-dimercaptobenzene (94 mg, 0.66 mmol) was added and the solution heated to reflux
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53 under nitrogen atmosphere overnight. The solvent was evaporated to dryness. The dark solid was
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55 then dissolved in dichloromethane (30 ml) and extracted with 1M NaHCO₃ (2x 20 ml). The
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3 combined organic phases were dried over MgSO_4 and the solvent removed on a rotary
4 evaporator. The dry dark solid was dissolved in acetonitrile (30 ml). Aqueous H_2O_2 (1 ml, 30%)
5 was then added to the mixture. The solution was stirred under nitrogen at room temperature for
6 48 h. The solution was then cooled in an ice bath and MnO_2 (1.0 g, 11.5 mmol) was added to the
7 mixture. The mixture was left standing for 30 min before it was filtered (filter paper) multiple
8 times to remove the insoluble MnO_2 . The remaining clear solution was evaporated to dryness.
9 The resulting yellow solid was purified by column chromatography on silica (acetone/ CH_2Cl_2
10 4:1, $R_f = 0.3$). The product was obtained as an orange powder. Yield: 57 mg (26%). Anal. Calcd.
11 for $\text{C}_{54}\text{H}_{36}\text{N}_4\text{O}_4\text{RuS}_2$ (%): C, 66.86; H, 3.74; N, 5.78. Found: C, 67.02; H, 4.02; N, 5.59; IR
12 bands (Golden Gate, cm^{-1}): ν 1559, 1428, 1141, 1052, 1005, 829, 764, 735; ^1H NMR (500 MHz,
13 CD_2Cl_2): δ (ppm) 10.60 (d, $^3J = 5.6$ Hz, 2H), 8.15–8.12 (m, 4H), 8.04–8.01 (d, 2H), 7.83–7.80
14 (m, 4H), 7.83–7.45 (m, 24H); ^{13}C NMR (125 MHz, CD_2Cl_2): δ (ppm) 155.54, 153.54, 151.73,
15 150.29, 150.14, 149.41, 148.45, 137.28, 137.00, 131.20, 130.90, 130.72, 130.33, 130.31, 130.00,
16 129.85, 129.18, 128.76, 126.61, 126.34, 125.99, 125.83, 120.65; MS (ESI $^+$): m/z 971.1 $[\text{M}+\text{H}]^+$,
17 993.3 $[\text{M}+\text{Na}]^+$. HR-ESI mass spectrum ($\text{CH}_3\text{CN} + \text{NaI}$): found 993.11267; calcd. for
18 $[\text{C}_{54}\text{H}_{36}\text{N}_4\text{NaO}_4\text{RuS}_2]$ 993.11266; UV-Visible spectrum (CH_3CN): λ_{max} (ϵ_{max}) = 396, 440(sh) nm
19 (26300, 19200 $\text{M}^{-1}\text{cm}^{-1}$).
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43 **Ru(dqpCO₂Me)(ptpy) (2).** A solution containing ptpy (0.15 g, 0.50 mmol) and RuCl_3 (0.13 g,
44 0.51 mmol) in absolute EtOH (50 mL) was heated to reflux for 3 h. The solid formed was
45 isolated by filtration, washed with EtOH (10 ml) and Et_2O (10 ml) and dried to yield the
46 intermediate product, $[\text{Ru}(\text{ptpy})\text{Cl}_3]$ as a red solid compound which was used directly in the next
47 step of the synthesis. To 25 ml of acetone $[\text{Ru}(\text{ptpy})\text{Cl}_3]$ (0.10 g, 0.21 mmol) and AgBF_4 (0.14 g,
48 0.70 mmol) were added and the mixture was refluxed for 3 h. After cooling to room temperature,
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3 the mixture was filtered and the filtrate was evaporated to dryness on a rotary evaporator. To the
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5 residue dqpCO₂Me (0.78 g, 0.21 mmol) and butanol (25 ml) were added. The mixture was
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7 heated to reflux overnight. After cooling to room temperature, 1 M aqueous KPF₆ (2 ml) was
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9 added and half of the solvent evaporated on the rotary evaporator to precipitate the product,
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11 which was then collected by filtration. The obtained solid was subjected twice to flash column
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13 chromatography on silica gel (ACN: H₂O: 1M NaNO₃ 18:1:1 v/v/v, R_f = 0.7). The darkest red
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15 band was collected and the solvent removed under reduced pressure. The residue was suspended
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17 in acetonitrile to dissolve the complex and to separate it from the insoluble NaNO₃. After
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19 filtration, the ACN was removed on a rotary evaporator. The counterion was exchanged by
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21 addition of 1 M aqueous NH₄PF₆ (2 ml) and the precipitate was collected by filtration and
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23 washed with water. The product was dried *in vacuo* to yield the desired complex as a dark red
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25 powder. Yield: 110 mg, (47%). Anal. Calcd. for C₄₆H₃₂F₁₂N₆O₂P₂Ru₃ H₂O·1 CH₃CN (%): C,
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27 48.57; H, 3.48; N, 8.26. Found: C, 48.50; H, 3.46; N, 8.32; IR bands (neat, cm⁻¹): ν 3060, 1718,
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29 1604, 1560, 1508, 1405, 1268, 1209, 1019, 845, 828; ¹H NMR (400 MHz, CD₃CN): δ (ppm)
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31 8.74 (dd, ³J = 7.7, 1.1, 2H), 8.72 (s, 2H), 8.61 (s, 2H), 8.35 (dd, ³J = 8.4, 7.6, 2H), 8.27 (d, ³J =
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33 7.3, 2H), 8.18 (dd, ³J = 8.1, 6.5, 2H), 8.04 (m, w = 11.2, 4H), 7.84 (m, w = 8.1, 4H), 7.68 (t, ³J =
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35 8.1, 1H), 7.60-7.65 (dd, ³J = 7.9, 2H), 7.30 (dd, ³J = 5.2, 1.4, 2H), 7.19 (m, w = 15.1, 2H), 6.98
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37 (dd, ³J = 8.1, 5.2, 2H), 4.1 (s, 3H); ¹³C NMR (400 MHz, CD₃CN): δ (ppm) 121.8, 124.1, 126.5,
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39 127, 127.5, 127.6, 127.7, 129.2, 130.3, 132.5, 132.9, 135.7, 135.9, 138, 138.1, 138.5, 145.6,
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41 148.6, 154.2, 154.5, 156.9, 157.4, 157.8, 52.8; ESI-MS (pos. detection mode): m/z: 401.1 [M]²⁺.
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43 UV-Visible spectrum (CH₃CN): λ_{max} (ε_{max}) = 321, 362(sh), 460, 530, 570 nm (36700, 14800,
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45 10400, 8900, 7200, M⁻¹ cm⁻¹).

55 Singlet Oxygen Production.

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3 ***N,N*-Dimethyl-4-nitrosoaniline/histidine assay.** An air-saturated acetonitrile solution
4 containing the complex (OD = 0.1 at irradiation wavelength), *N,N*-dimethyl-4-nitrosoaniline
5 aniline (RNO) 24 μ M, imidazole 12 mM or an air-saturated PBS buffer solution containing the
6 complex (OD = 0.1 at irradiation wavelength), RNO 20 μ M, histidine 10 mM were irradiated for
7 different time intervals in a luminescence quartz cuvette at 420 nm in a RPR200 Rayonet
8 Chamber Reactor (Southern New England Ultraviolet Company). The absorbance of RNO at
9 440/420 nm was then plotted as a function of irradiation time and the quantum yields of singlet
10 oxygen formation (Φ_{sample}) were calculated using phenalenone (for irradiation at 420 nm) as the
11 standard ($\Phi_{\text{reference}} = 0.95$)⁷⁶ with the formula:
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$$\Phi_{\text{sample}} = \Phi_{\text{reference}} \frac{S_{\text{sample}} I_{\text{reference}}}{S_{\text{reference}} I_{\text{sample}}}$$

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30 where S is the slope of the absorbance vs. irradiation time and I is the amount of light
31 absorption calculated as the overlap of the lamp emission spectrum and absorption spectrum of
32 the compound according to the following formula:
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$$I = \int_{\lambda} I_0 [1 - 10^{-A(\lambda)}] d\lambda$$

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42 where I_0 is the light-flux intensity of the lamp and A is the absorbance of the compound. In
43 control experiments, using the same experimental conditions, phenalenone was shown to be
44 photostable for the relevant irradiation times.
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49 **Near-IR Luminescence.** Luminescence measurements were performed on a Fluorolog-3
50 Spectrofluorometer (JobinYvon Horiba, Model FL3-11) fitted with a 450 W xenon lamp light
51 source and single-grating excitation and emission spectrometers. For high beam intensity, the
52 excitation slits were set to a maximum value of 29.4 nm. A colored glass filter was placed
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3 between the sample and the detector to cut off light below 695 nm. The emission signal was
4 collected at right angle to the excitation path with an IR-sensitive liquid nitrogen cooled
5 germanium diode detector (Edinburgh Instruments, Model EI-L). The detector was bias at -
6 160V. The signal-to-noise ratio of the signal detected by the Ge-diode was improved with a lock-
7 in amplifier (Stanford Research Systems, model SR510) referenced to the chopper frequency of
8 126 Hz. Data-acquisition was done with DataMax. In practice, a 20 mM stock solution of each
9 compound dissolved in DMSO was diluted with PBS or acetonitrile (DMSO content of final
10 solution <0.1%) to reach approximately an absorbance of 0.2 at the irradiation wavelength. This
11 solution was then irradiated in fluorescence quartz cuvettes (width 1 cm) using a UV lamp (420
12 nm, slit 29.4 nm). Singlet oxygen near-IR luminescence at 1271 nm was measured by recording
13 spectra from 1200 to 1350 nm (emission slit 5 nm, detector sensitivity 100, integration 3 (1)).
14 The intensity of irradiation was varied via neutral density filters. Singlet oxygen luminescence
15 peaks at different irradiation intensities were integrated and the resulting areas were plotted vs.
16 irradiation intensities. The quantum yields were calculated by applying the formulas as used for
17 the *N,N*-dimethyl-4-nitrosoaniline/histidine assay with phenalenone as a reference.⁷⁶

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39 **Spectroscopic Studies.** UV-Vis spectra were measured on a Varian Cary 50-Scan UV-Vis
40 Spectrophotometer. To determine the luminescence quantum yields of the PSs, emission spectra
41 were recorded on a Varian Cary Eclipse Fluorescence Spectrophotometer equipped with a
42 Hamamatsu R3896 photomultiplier tube as detector, where the sample temperature can be
43 controlled by a Peltier thermostatic system. Emission spectra were corrected for the spectral
44 sensitivity of the detection system by standard correction curves. The emission intensities were
45 normalized to a nominal absorption value of 0.1. Quantum yields in aerated acetonitrile were
46 determined by comparison with the emission of [Ru(bipy)₃]Cl₂ in aerated water ($\Phi = 0.042$).⁷¹
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3 Luminescence lifetime measurements were recorded on an Edinburgh LP920 Laser Flash
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Luminescence lifetime measurements were recorded on an Edinburgh LP920 Laser Flash
Photolysis transient absorption spectrometer using a flashlamp pumped Q-switched Nd:YAG
laser (355 nm) as excitation source.

Stability in Human Plasma. The stability of the compounds in human plasma at 37 °C was
evaluated following a slightly modified procedure to that recently reported by our group.^{73, 74}
The human plasma was provided by the Blutspendezentrum, Zurich, Switzerland. Diazepam was
obtained from Sigma Aldrich (internal standard). Stock solutions of the complexes (20 mM) and
diazepam (3.2 mM) were prepared in DMSO. For a typical experiment, an aliquot of the
respective stock solutions and DMSO were added to the plasma solution (975 µl) to a total
volume of 1000 µl and final concentrations of 40 µM for the complexes and diazepam (final
concentration of DMSO < 0.5%). The resulting plasma solution was incubated for either 0, 24 or
48 h at 37°C with continuous and gentle shaking (ca. 600 rpm). The reaction was stopped by
addition of 2 ml of methanol, and the mixture was centrifuged for 45 min at 650 g at room
temperature. The methanol solution was evaporated and the residue was suspended in 500 µl of
1:1 (v/v) acetonitrile/H₂O solution. The suspension was filtered and analyzed using UPLC–MS
(as described in the instrumentation and methods part of this section).

X-ray Crystallography. Single-crystal X-ray diffraction data were collected at 183(2) K on an
Agilent Technologies SuperNova area-detector diffractometer using a single wavelength
Enhance X-ray source with Cu K α radiation ($\lambda = 1.5418 \text{ \AA}$)⁹⁵ from a micro-focus X-ray source
and an Oxford Instruments Cryojet XL cooler. The selected suitable single crystal was mounted
using polybutene oil on a flexible loop fixed on a goniometer head and immediately transferred
to the diffractometer. Pre-experiment, data collection, data reduction and analytical absorption
correction⁹⁶ were performed with the program suite CrysAlisPro.⁹⁷ Using Olex2,⁹⁸ the structure

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3 was solved by the Superflip⁹⁹ structure solution program using Charge Flipping and refined with
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5 the SHELXL2013¹⁰⁰ program package by full-matrix least-squares minimization on F^2 .
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7 PLATON¹⁰¹ was used to check the result of the X-ray analysis. Crystal Data for
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9 $C_{46}H_{32}F_{12}N_6RuP_2O_2$ ($M = 1091.78$): orthorhombic, space group $Fdd2$ (no. 43), $a = 43.6636(10)$
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11 \AA , $b = 43.3688(7) \text{\AA}$, $c = 9.2311(2) \text{\AA}$, $V = 17480.4(6) \text{\AA}^3$, $Z = 16$, $T = 182(2) \text{K}$, $\mu (\text{CuK}\alpha) =$
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13 4.489 mm^{-1} , $D_{\text{calc}} = 1.659 \text{ g/mm}^3$, 16177 reflections measured ($5.744 \leq 2\Theta \leq 136.418$), 6703
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15 unique ($R_{\text{int}} = 0.0275$, $R_{\text{sigma}} = 0.0308$) which were used in all calculations. The final R_1 was
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17 0.0782 ($I > 2\sigma(I)$) and wR_2 was 0.2110 (all data). The supplementary crystallographic data for
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19 this paper has been deposited with the Cambridge Crystallographic Data Centre as CCDC-
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21 990555. These data can be obtained free of charge from the Cambridge Crystallographic Data
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23 Centre via www.ccdc.cam.ac.uk/data_request/cif.
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30 **Cell Culture.** Human cervical carcinoma cells (HeLa) cells were maintained in DMEM
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32 (Gibco) with 5% fetal calf serum (FCS, Gibco), 100 U/ml penicillin, 100 $\mu\text{g/ml}$ streptomycin at
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34 37°C and 5% CO_2 . Normal lung fibroblasts (MRC-5) were cultured in F-10 medium (Gibco)
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36 supplemented with 10 % fetal calf serum (FCS, Gibco), 100 U/ml penicillin, 100 $\mu\text{g/ml}$
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38 streptomycin at 37°C and 5% CO_2 .
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42 **Cytotoxicity Studies.** Cytotoxicity studies of the effect of irradiation on human cervix HeLa
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44 cancer cell and MRC-5 non-tumorigenic cell lines treated with complexes **1** and **2** were
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46 performed by a fluorometric cell viability assay using Resazurin (Promocell GmbH). Briefly, one
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48 day before treatment cells were plated in triplicates in 96-well plates at a density of 4×10^3 cells
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50 / well in 100 μL . Upon treating cells with increasing concentrations of the ruthenium complex
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52 (complex dissolved in DMSO, concentration of DMSO $< 0.5\%$) cells were incubated for 4 h. The
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54 medium was then replaced by fresh medium, which does not contain complexes **1** and **2** and the
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3 plates were irradiated for 15 minutes at 420 nm (6.95 J/cm²) or at 575 nm (6.23 J/cm²) in a
4 RPR200 Rayonet Chamber Reactor (Southern New England Ultraviolet Company). Upon further
5 incubation at 37°C / 6% CO₂ for 44 h, the medium was removed, and 100 μL of complete
6 medium containing resazurin (0.2 mg/ml final concentration) was added. After 4 h of incubation
7 at 37 °C / 6% CO₂, the fluorescence of the highly red fluorescent resorufin product was
8 quantified at 590 nm emission with 540 nm excitation wavelength in a SpectraMax M5
9 microplate Reader.
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12 **Microscopy Studies.**

13 **In Vitro Fluorescence Evaluation.** Cellular localization of **1** was performed by fluorescence
14 microscopy. HeLa cells were grown on 18 mm Menzel-Gläser coverslips in 2 ml complete
15 medium at a density of 2.5×10^5 cells/ml and incubated for 2 h with **1** at 40μM (DMSO
16 concentration < 0.5%). Cells were fixed in 4% formaldehyde solution (10% formaldehyde in
17 90% PBS) and mounted on slides for viewing by confocal microscopy on a CLSM Leica SP5
18 microscope. The ruthenium complex was excited at 456 nm and emission above 610 nm was
19 recorded.
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22 **Nuclear and Mitochondrial Staining.** Co-localization of complex **1** into the nucleus and
23 mitochondria was examined by means of Mito-tracker green FM (Molecular Probes, excitation:
24 490 nm, emission: 516 nm), a mitochondria-specific dye and DAPI (excitation: 358 nm,
25 emission: 461 nm). Briefly, a 1 mM Mitotracker Green FM stock solution made in DMSO was
26 diluted to 10 μM working concentration in cell medium (DMEM, 5% FCS). Staining of
27 mitochondria was accomplished by adding a 50 nM final concentration of Mito-tracker Green
28 FM to the culture medium for the last 45 min incubation. The medium was removed and cells
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3 were fixed in 4% formaldehyde solution before being mounted on slides added with 8 μl of
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5 DAPI (Invitrogen) for viewing by confocal microscope.
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8 **Uptake Studies.**

9 **Sample Preparation for ICP-MS.**

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14 *Whole Cells.* HeLa cells were seeded two days before treatment at a concentration of 1×10^6
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16 cells/ml in 25 cm^2 cell culture flask till 80% of confluence and incubated with the target
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18 complexes at 20 μM for 0, 4 and 48 hours (DMSO concentration $< 0.1\%$). The medium was
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20 removed, the cells washed with PBS and trypsinized. After re-suspension in PBS, the pellet was
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22 collected by centrifugation at 5500 rpm for 4.5 minutes. Pellets were redissolved in 500 μL of
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24 PBS, lysed by a freeze-thaw cycle and treated on ultrasonic bath for 20 minutes (Digitana AG).
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26 The lysates were lyophilized on an Alpha 2-4 LD plus (CHRIST).
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32 *Cellular Fractions.* HeLa cells were seeded two days before treatment at a concentration of
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34 1×10^6 cells/ml in 175 cm^2 cell culture flask till 80% of confluence and incubated with the target
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36 complexes at 20 μM for 4 hours (DMSO concentration $< 0.1\%$). The medium was removed, the
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38 cells washed with PBS and trypsinized. After re-suspension in PBS, the pellet was collected per
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40 centrifugation (5910R, Eppendorf) at 500 g for 5 min at 4 $^\circ\text{C}$. Mitochondria were isolated using
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42 a mitochondria isolation kit (Cat. Nr.: MITISO2, Sigma Aldrich) following the producer
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44 instructions. Briefly, the collected pellets were redissolved in 1.5 ml of lysis buffer (delivered
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46 with the kit) and allowed to react for 15 min on ice. The samples were homogenized with a pre-
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48 chilled dounce homogenizer (7 ml, tight pestle A, 30 strokes) and centrifuged at 600 g for 10 min
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50 at 4 $^\circ\text{C}$. The supernatant was transferred in a fresh tube and centrifuged at 11000 g for 10 min at
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52 4 $^\circ\text{C}$. The obtained pellets represented pure mitochondrial fractions. For nucleus isolation nuclei
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3 of HeLa cells were obtained following an established procedure with minor modifications.¹⁰² All
4 the fractions were isolated from the same cellular sample for direct comparative purposes. After
5 homogenization, the pellet obtained was redissolved in 2 ml of a sucrose solution (0.25 M
6 sucrose, 10 mM MgCl₂) and layered with 3 ml of a second hypertonic sucrose solution (0.35 M
7 sucrose, 0.5 mM MgCl₂). The suspension was centrifuged at 1450 g and 4 °C for 5 min. The
8 pellet was re-suspended in 3 ml of the second sucrose solution and centrifuged at 1450 g and 4
9 °C for 5 min to obtain the pure nuclear extract. All the steps of the isolation procedure were
10 monitored under phase contrast microscope on Menzel-Gläser coverslips (Olympus IX81
11 microscope). The supernatant phases discarded during the isolation of nuclei and mitochondria
12 procedures were collected and formed the rest fraction. An aliquot of crude lysate supernatant,
13 nuclear, mitochondrial and rest fraction was each used for protein quantification using the
14 Bradford method.¹⁰³ The isolated samples were lyophilized on an Alpha 2-4 LD plus (CHRIST).

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32 **ICP-MS Studies.** ICP-MS measurements were performed on an Agilent QQQ 8800 Triple
33 quad ICP-MS spectrometer (Agilent Technologies) with a ASX200 autosampler (Agilent
34 Technologies), equipped with standard nickel cones and a “micro-mist” quartz nebulizer fed with
35 0.3 ml/min analytic flow (as a 2% HNO₃ aqueous solution). Ruthenium was measured against a
36 Ru single element standard (Merck 170347) and verified by a control (Agilent5188-6524 PA
37 Tuning 2). Ruthenium content of the samples was determined by means of a 7-step serial dilution
38 in the range between 0 and 100 ppb in Ru (R=1.0) with a background equivalent concentration of
39 BEC: 3.3 ppt and a detection limit of DL: 5.4 ppt. The isotope ¹⁰¹Ru (17.06% abundance) was
40 evaluated in “no-gas” mode. Spiking the samples with 1% methanol (to account for eventual
41 carbon content from the biological samples) resulted in equivalent values within error ranges.
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3 The results are expressed as ng Ru / mg protein (correction due to the different mass of the
4 observed cellular compartments), as mean \pm error of different independent experiments.
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8 **Bacteria Culture and Phototoxicity.** An overnight bacteria culture (5 ml) was harvested by
9 centrifugation (200 g, 15 min), washed with 0.01 mM phosphate-buffered saline (PBS;
10 Biochrom, Berlin, Germany) at pH 7.4 containing 0.027 mol/l KCl and 0.14 mol/l NaCl, and
11 suspended in PBS at an optical density of 0.6 at 600 nm, which corresponded to $\sim 10^8$ bacteria
12 ml^{-1} , for use in the phototoxicity experiments. The bacterial suspensions were incubated with the
13 respective PS and then irradiated using an incoherent light source (UV236, k_{em} : 380–480 nm;
14 max 420 nm; Waldmann Medizintechnik, Villingen-Schwenningen, Germany). To minimize
15 scattering, the 96 -well plates were exposed to the PS-bacteria suspension from the bottom of the
16 plates. 100 μl of a bacterial suspension (*S. aureus* (atcc 25923) or *E. coli* (atcc 25922)) with a
17 concentration of $\approx 10^8$ bacteria per ml were incubated in a 96 -well plate with different PS
18 concentrations (each 100 μl) for 15 min at room temperature under exclusion of light.
19 Immediately thereafter, the bacteria were irradiated with a total light dose of 8 J/cm^2 (time
20 period: 10 min). Control samples were either incubated with PS only or irradiated only without
21 any PS incubation. After irradiation, the surviving bacteria were determined by plating out and
22 enumeration of the colony forming units (CFU per ml). Therefore, serially diluted aliquots of
23 treated and untreated cells were plated on Müller-Hinton agar and the number of CFU per ml
24 was counted after 24 h at 37 °C. The method used to determine the growth of bacteria was
25 originally described by Miles, Mirsa & Irwin.⁹² A Müller-Hinton agar plate was divided into six
26 quadrants and three drops of 20 μl each per quadrants were applied of the serially diluted
27 suspensions. After each three drops, the pipette tips were changed. After the droplets were dried,
28 the agar plates were inverted and incubated at 37 °C for 24 h. The day after the surviving
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3 colonies were counted, and the three values of the respective dilution steps were summed up and
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5 an average value was calculated. A reduction of at least three orders of magnitude (i.e., 3 log₁₀
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7 units) of viable mean numbers of bacteria was stated as biologically relevant with regard to the
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9 guidelines of hand hygiene.¹⁰⁴
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12 ASSOCIATED CONTENT

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15 **Supporting Information.** UV/Vis and luminescence spectra of **1** and **2**, control experiments
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17 for confocal microscopy for **1**, ¹H-NMR spectra of **1** and **2**, time dependent cellular uptake curves
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19 for **1** and **2** and selected bond lengths for the X-ray crystal structure of **2**. This material is
20
21 available free of charge via the Internet at <http://pubs.acs.org>
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39
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41 †These authors contributed equally.

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44 The manuscript was written through contributions of all authors. All authors have given approval
45
46 to the final version of the manuscript.
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ABBREVIATIONS

DIP: 4,7-diphenyl-1,10-phenanthroline, bdt: 1,2-benzenedi-thiolate, dqpCO₂Me: 4-methylcarboxy-2,6-di(quinolin-8-yl)pyridine, ptpy = 4'-phenyl-2,2':6',2''-terpyridine, PS: photosensitizer, PDT: photodynamic therapy, ICP-MS: inductively coupled plasma-mass spectrometry, ROS: reactive oxygen species, aPDT: antimicrobial PDT, PI: phototoxic index, RNO: *N*-dimethyl-4-nitrosoaniline, ACN: acetonitrile, CFU: colony-forming unit.

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TOC Figure.

