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NO Releasing and Anticancer Properties of Octahedral Ruthenium–Nitrosyl Complexes with Equatorial 1*H*-Indazole Ligands

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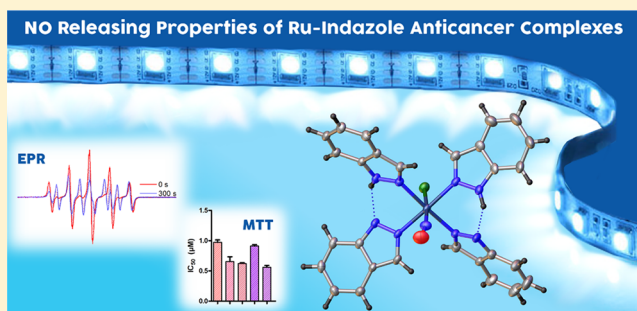
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Supporting Information

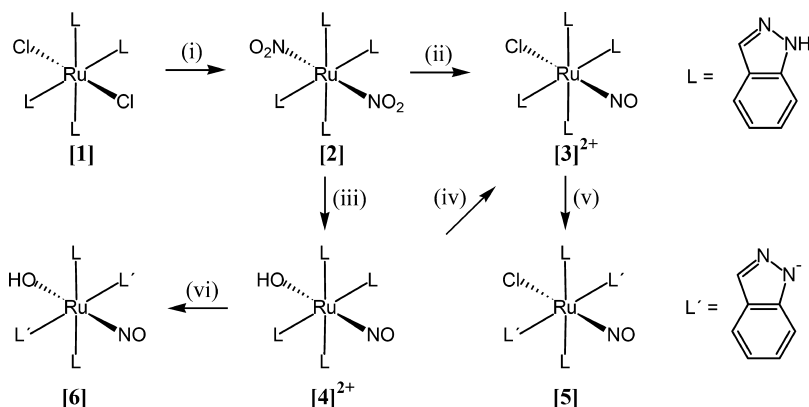
ABSTRACT: With the aim of enhancing the biological activity of ruthenium–nitrosyl complexes, new compounds with four equatorially bound indazole ligands, namely, *trans*-[RuCl(Hind)₄(NO)]Cl₂·H₂O ([3]Cl₂·H₂O) and *trans*-[RuOH(Hind)₄(NO)]Cl₂·H₂O ([4]Cl₂·H₂O), have been prepared from *trans*-[Ru(NO₂)₂(Hind)₄] ([2]). When the pH-dependent solution behavior of [3]Cl₂·H₂O and [4]Cl₂·H₂O was studied, two new complexes with two deprotonated indazole ligands were isolated, namely [RuCl(ind)₂(Hind)₂(NO)] ([5]) and [RuOH(ind)₂(Hind)₂(NO)] ([6]). All prepared compounds were comprehensively characterized by spectroscopic (IR, UV–vis, ¹H NMR) techniques. Compound [2], as well as [3]Cl₂·2(CH₃)₂CO, [4]Cl₂·2(CH₃)₂CO, and [5]·0.8CH₂Cl₂, the latter three obtained by recrystallization of the first isolated compounds (hydrates or anhydrous species) from acetone and dichloromethane, respectively, were studied by X-ray diffraction methods. The photoinduced release of NO in [3]Cl₂ and [4]Cl₂ was investigated by cyclic voltammetry and resulting paramagnetic NO species were detected by EPR spectroscopy. The quantum yields of NO release were calculated and found to be low (3–6%), which could be explained by NO dissociation and recombination dynamics, assessed by femtosecond pump–probe spectroscopy. The geometry and electronic parameters of Ru species formed upon NO release were identified by DFT calculations. The complexes [3]Cl₂ and [4]Cl₂ showed considerable antiproliferative activity in human cancer cell lines with IC₅₀ values in low micromolar or submicromolar concentration range and are suitable for further development as potential anticancer drugs. p53-dependence of Ru–NO complexes [3]Cl₂ and [4]Cl₂ was studied and p53-independent mode of action was confirmed. The effects of NO release on the cytotoxicity of the complexes with or without light irradiation were investigated using NO scavenger carboxy-PTIO.



■ INTRODUCTION

Nitric oxide (NO) is known both as an air pollutant,¹ as well as a physiological regulator,² essential for neurotransmission, blood

Scheme 1. Synthesis of Complexes^a



^aReagents and conditions: (i) NaNO₂, acetone/DCM/H₂O reflux, 12 h; (ii) 12 M HCl, MeOH; (iii) 3 M HCl, MeOH; (iv) 12 M HCl, MeOH; and (v and vi) pH 6–9 in 50% ethanol/water.

pressure control, antioxidant action, and immunological responses.³ In cells, NO is mainly produced by conversion of L-arginine to L-citrulline in the presence of nitric oxide synthase (NOS). The down-regulation of NO synthesis in a variety of normal cells and in tumor cells is mediated by intracellular transforming growth factor- β 1 (TGF- β 1).⁴ The control of cellular NO concentration, either by inhibiting its production or by targeted delivery can be achieved by using suitable metal complexes, and consequently, NO-scavenging and NO-releasing metal complexes are of great therapeutic interest.⁵ NO as a ligand readily binds to transition metals, such as iron or ruthenium, forming stable M–NO adducts. Recently, it was reported that the anticancer effects of Ru(III)-based clinical lead candidates, KP1019/NKP1339 and NAMI-A, were at least in part due to their NO-scavenging properties, stemming from high affinity of Ru(III) to NO.^{6,7} Scavenging of endogenous NO produced from NOS depletes its local concentration, thereby diminishing subsequent interactions with cellular targets.

Since the role of NO in tumor development can also be inhibitory, NO-donating compounds which release free NO hold great promises as anticancer agents. For example, high NO levels (>500 nM) induce apoptosis as a result of p53 activation and therefore, the exogenous delivery of cytotoxic levels of NO by NO-releasing drugs might be beneficial for the induction of apoptosis via p53 pathway.⁸ Some NO-releasing compounds display spontaneous release of NO, while other compounds require external stimuli, such as enzymatic, photo, or thermal activation or redox events.⁹ Ruthenium–nitrosyl complexes are excellent candidates for the delivery of exogenous NO, since the efficacy of NO release can be fine-tuned by modifying the structure of Ru complexes. Ruthenium exists in several oxidation states, whereas NO acts as a noninnocent ligand either as NO⁺, NO, or NO[−], availing a series of alternative oxidation state combinations.¹⁰ Furthermore, NO-release in ruthenium–nitrosyl complexes is dependent on the redox potential of the complex and trans-effect of the ligand in trans position to NO,¹¹ and NO release can be triggered by one-electron reduction¹² or by photolysis.¹³

Previously, we have already reported the preparation and biological properties of Ru–NO complexes with various amino acids coordinated in bidentate fashion.¹⁴ All compounds demonstrated only moderate cytotoxicity in a micromolar concentration range against human ovarian carcinoma cells (CH1), which was presumably related to their low lipophilicity and

insufficient intracellular accumulation. In a different series, amino acids were replaced by more lipophilicazole ligands in trans- and cis-positions to the NO ligand, yielding compounds with the general formula (cation)[*cis*-RuCl₄(Hazole)(NO)] and (cation)[*trans*-RuCl₄(Hazole)(NO)].¹⁵ The cytotoxicity of the complexes against CH1 cells varied greatly from sub-micromolar to high micromolar range. The differences in the cytotoxicity were defined by theazole heterocycle and the most active Ru–NO compounds contained indazole ligands. The contribution of NO in the antiproliferative activity of mono-indazole Ru–NO complexes was not confirmed. However, no external stimuli was applied; therefore, the release of NO was unlikely.

Inspired by the elevated cytotoxicity of Ru–NO complexes upon the inclusion of indazole ligands into the structure of the complexes, we hypothesized that incorporation of several indazole ligands would result in the augmented intracellular accumulation of Ru–NO complexes and further increase of antiproliferative activity. Since correlation between the number of indazole ligands and the cytotoxicity of the complexes with the general formula [Ru^{III}Cl_(6−n)(indazole)_n]^{(3−n)−} was noticed,¹⁶ higherazole-to-chlorido ratio could lead to stabilization of lower ruthenium oxidation states, improved cellular uptake and enhancement of antiproliferative activity.

Herein, we report on the synthesis of compounds *trans*-[Ru^{II}(NO)₂(Hind)₄] ([2]), *trans*-[RuCl(Hind)₄(NO)]Cl₂ ([3]Cl₂), and *trans*-[RuOH(Hind)₄(NO)]Cl₂ ([4]Cl₂) (Scheme 1), their characterization by spectroscopic methods and single crystal X-ray diffraction. Upon characterization of aqueous solution behavior of these complexes, new inner-sphere Ru–NO complexes [RuCl(ind)₂(Hind)₂(NO)] (5) and [RuOH(ind)₂(Hind)₂(NO)] (6) were isolated and characterized. The redox properties were investigated as well and supporting DFT calculations were performed to assess the IR, UV–vis, and EPR behavior of [3]Cl₂. The ability of the target complexes [3]Cl₂ and [4]Cl₂ to release NO upon photo-excitation has been studied by various methods. The contribution of NO to the anticancer properties and p53 induction by new Ru–NO complexes with or without irradiation has been evaluated.

EXPERIMENTAL SECTION

Chemicals and Materials. Solvents and reagents were obtained from commercial sources and used as received. [Ru^{II}Cl₂(Hind)₄] ([1])

was prepared as reported previously.¹⁶ Ultrapure water was obtained by using a Milli-Q UV purification system (Sartorius Stedim Biotech SA). Gibco Trypsin/EDTA solution and 10% sodium dodecyl sulfate (SDS) solution was purchased from Life Technologies. Glycine, HyClone™ Trypsin Protease 2.5% (10×) solution, RPMI 1640, DMEM medium, fetal bovine serum (FBS), Pierce™ Protease, Phosphatase Inhibitor Mini Tablets, and carboxy-PTIO were purchased from Thermo Fisher Scientific. HyClone™ Dulbecco's Phosphate-Buffered Saline (10×) was purchased from Ge Healthcare Life Sciences. Biorad Protein Assay Dye Reagent Concentrate, 40% acrylamide/bis solution, 10× Tris/glycine buffer, TEMED, and nitrocellulose membrane 0.2 and 0.45 μm were purchased from Biorad Laboratories. Luminata™ Classico, Crescendo and Forte Western HRP Substrate were purchased from Merck Millipore Corporation. Oxaliplatin was purchased from Merlin Chemicals Ltd. (Liphook, UK). Clinical-grade cisplatin (1 mg/mL) was purchased from Hospira Pty Ltd. (Melbourne, Australia). All solvents for solution equilibrium studies were of analytical grade and used without further purification. KCl, HCl, HNO_3 , KOH, dimethyl sulfoxide (DMSO), and other chemicals used were purchased from Sigma-Aldrich in *puriss* quality.

Synthesis of Complexes. *trans*-[Ru(NO)₂(Hind)₄] ([2]). A solution of NaNO₂ (0.2 g, 2.6 mmol) in H₂O (8 mL) was added to a solution of [RuCl₂(Hind)₄] (0.6 g, 0.93 mmol) in acetone/dichloromethane (DCM) 1:1 (100 mL). The reaction mixture was refluxed under stirring for 12 h and cooled to room temperature. The organic phase was separated in a separating funnel and washed with water (3 × 30 mL). The volume of the separated organic phase was reduced to ~20 mL. After 2 h, the precipitated yellow crystals were filtered off, washed with acetone (5 mL), and dried in air. Yield: 0.28 g, 46%. X-ray diffraction quality single crystals were grown in DCM/hexane (solvent/vapor diffusion). ¹H NMR in DMSO-*d*₆: 13.32 (s, 4NH), 8.09 (s, 4H), 7.73 (d, 4H, *J* = 8.5 Hz), 7.61 (d, 4H, *J* = 8.5 Hz), 7.34 (t, 4H, *J* = 7.5 Hz), 7.13 (t, 4H, *J* = 7.5 Hz). Elem. Anal. Calcd for C₂₈H₂₄N₁₀O₄Ru (*M*_r = 665.62), %: C, 50.52; H, 3.63; N, 21.04; O, 9.61. Found, %: C, 50.61; H, 3.39; N, 21.12; O, 9.52. ESI-MS in MeOH (negative): *m/z* 665 [Ru(NO)₂(Hind)₄][−], 647, 556 541. IR, $\tilde{\nu}$, cm^{−1}: 3303, 3117, 1517, 1469, 1403, 1349, 1257, 1122, 1046, 1026, 755, 602. UV–vis (DCM), λ_{max} nm (ϵ , M^{−1} cm^{−1}): 231 (18108), 293 (17513), 325 (21281), 382 (1108).

trans-[RuCl(Hind)₄NO]Cl₂·H₂O ([3]Cl₂·H₂O). To a suspension of [2] (0.17 g, 0.25 mmol) in MeOH (20 mL), 12 M HCl (2.5 mL) was added. The mixture was refluxed under argon for 1 h and cooled to room temperature. Then the dark-orange solution was filtered, and its volume was reduced to ~3–5 mL. A small amount of precipitate was removed by filtration and washed with about 10 mL of water. The mother liquor was allowed to crystallize in air at room temperature. Next day the dark-red crystals were filtered off, washed with diethyl ether (10 mL), and dried in vacuo at room temperature (r.t.). Yield: 0.097 g, 52%. Elem. Anal. Calcd for C₂₈H₂₄Cl₃N₉O₄Ru·4H₂O (*M*_r = 782.04), %: C, 43.00; H, 4.12; N, 16.12. Found, %: C, 43.08; H, 3.93; N, 15.91. ESI-MS in MeOH (positive): *m/z* 638 [RuCl(Hind)₄(NO)]⁺. ¹H NMR in DMSO-*d*₆: 14.47 (s), 8.48 (s), 7.92 (d), 7.67 (dd); 7.61 (m), 7.34 (t). IR, $\tilde{\nu}$, cm^{−1}: 2658, 1925 (NO), 1629, 1515, 1476, 1439, 1359, 1288, 1239, 1146, 1088, 999, 966, 902, 840, 783, 737, 614. UV–vis (H₂O), λ_{max} nm (ϵ , M^{−1} cm^{−1}): 257 (99175), 365 (53287), 482 (22994). The monohydrate was obtained by drying the compound in vacuo at room temperature for 8 h. X-ray diffraction quality single crystals were grown in acetone.

trans-[Ru(OH)(Hind)₄(NO)]Cl₂·H₂O ([4]Cl₂·H₂O). To a suspension of [2] (0.17 g, 0.25 mmol) in MeOH (20 mL) a 3 M HCl (2.5 mL) was added. The mixture was refluxed under argon for 40 min and cooled to room temperature. Then the dark-orange solution was filtered and the filtrate concentrated under the reduced pressure to ca. 3 mL. The precipitate was filtered off and washed with water (10 mL). The product was recrystallized from acetone (40 mL), washed with diethyl ether (10 mL), and dried in vacuo at r.t. Yield: 0.11 g, 62%. Elem. Anal. Calcd for C₂₈H₂₅Cl₂N₉O₅Ru·H₂O (*M*_r = 704.53), %: C, 47.40; H, 3.83; N, 17.77; O, 6.76; Found, %: C, 47.07; H, 3.62; N, 17.57; O, 6.25. ESI-MS in MeOH (positive): *m/z* 620 [Ru(NO)(OH)(Hind)₄]⁺, 484 [Ru(Hind)₃]⁺, 310 [Ru(NO)(OH)(Hind)₄]²⁺. ¹H NMR in DMSO-*d*₆:

14.27 (br.s, 4NH), 8.56 (s, 4H), 7.89 (d, 4H, *J* = 8.5 Hz), 7.66 (d, 4H, *J* = 8.5 Hz), 7.56 (t, 4H, *J* = 7.5 Hz), 7.29 (t, 4H, *J* = 7.5 Hz). IR, $\tilde{\nu}$, cm^{−1}: 3354, 1879 (NO), 1657, 1585, 1512, 1474, 1441, 1378, 1358, 1334, 1272, 1242, 1151, 1126, 1081, 1003, 964, 830, 784, 746, 656, 619. UV–vis (H₂O), λ_{max} nm (ϵ , M^{−1} cm^{−1}): 257 (99175), 365 (53287), 482 (22994). X-ray diffraction quality single crystals were grown in acetone.

trans,*cis*,*cis*-[RuCl(ind)₂(Hind)₂(NO)] [5] and [RuOH(ind)₂(Hind)₂(NO)] [6]. To a solution of 20 mg of [3]Cl₂·H₂O or [4]Cl₂·H₂O in 8 mL of 50% (v/v) ethanol/water 0.1 M KOH solution was added until the measured pH was between 6 and 9. The microcrystalline precipitate was centrifuged, washed with 50% (v/v) ethanol/water (4 × 4 mL), and dried in air. Yield: 50 and 52%, respectively. X-ray diffraction quality single crystals of [5]·0.8CH₂Cl₂ were grown in DCM. ¹H NMR in CDCl₃ [RuCl(ind)₂(Hind)₂(NO)] [5]: 8.04(s), 7.84 (d), 7.69 (d); 7.43 (dd), 7.14 (dd). [Ru(OH)(ind)₂(Hind)₂(NO)] [6]: 7.86(s), 7.78 (d), 7.64 (d); 7.39 (dd), 7.11 (dd). ESI-MS in MeOH (positive): [RuCl(ind)₂(Hind)₂(NO)] ([5]): *m/z* 638 [M + H]⁺; [RuOH(ind)₂(Hind)₂(NO)] ([6]): *m/z* 620 [M + H]⁺. IR, $\tilde{\nu}$, cm^{−1} [5]: 1871, 1722, 1624, 1509, 1448, 1365, 1095, 733. [6]: 1850, 1624, 1583, 1358, 1313, 1075, 783, 747.

Physical Measurements. Elemental analyses were performed by the Microanalytical Service of the Faculty of Chemistry of the University of Vienna with a PerkinElmer 2400 CHN Elemental Analyzer. ¹H NMR (500.10 MHz) spectra were measured on a Bruker Avance III instrument at 25 °C. Chemical shifts for ¹H were referenced to residual protons present in DMSO-*d*₆. IR spectra were obtained by using an ATR unit with a PerkinElmer 370 FTIR 2000 instrument (4000–400 cm^{−1}). Electrospray ionization mass spectrometry was carried out with a Bruker Esquire3000 instrument (Bruker Daltonics, Bremen, Germany) by using methanol as solvent. Infrared spectroscopy measurements with irradiation were performed using a Nicolet 5700 FT-IR spectrometer with a resolution of 2 cm^{−1} in the range 350–4000 cm^{−1}. The sample was grinded, mixed with KBr, and pressed into pellets. KBr pellets were bonded by silver paste on the coldfinger of a closed cycle cryostat (Oxford Optistat V01) and irradiated through KBr windows with light of different wavelengths in the range 365–660 nm. The cryostat allows controlling the temperature in the range of 9–320 K.

X-ray Crystallography. X-ray diffraction measurements were performed on a Bruker X8 APEXII CCD and Bruker D8 Venture diffractometers. Single crystals were positioned at 35, 40, 35, and 28 mm from the detector, and 767, 1872, 1904, and 2500 frames were measured, each for 30, 2, 7.2, and 48 s over 1, 0.25, 0.4 and 0.5° scan width for [2], [3]Cl₂·2(CH₃)₂CO, [4]Cl₂·2(CH₃)₂CO, and [5]·0.8CH₂Cl₂, respectively. The data were processed using SAINT software.¹⁷ Crystal data, data collection parameters, and structure refinement details are given in Table S1. The structures were solved by direct methods and refined by full-matrix least-squares techniques. Non-hydrogen atoms were refined with anisotropic displacement parameters. Hydrogen atoms were inserted in calculated positions and refined with a riding model. The following computer programs and hardware were used: structure solution, SHELXS-97 and refinement, SHELXL-97;¹⁸ molecular diagrams, ORTEP;¹⁹ computer, Intel CoreDuo. Disorder observed for the nitro group in [2] and two indazole, NO and OH ligands in [3]²⁺ was resolved by using SADI and EADP restraints and DFIX constraints implemented in SHELXL. Crystallographic data for these complexes have been deposited with the Cambridge Crystallographic Data Center as supplementary publications no. CCDC-1835290 ([2]), -1835292 ([3]Cl₂·2(CH₃)₂CO), -1835291 ([4]Cl₂·2(CH₃)₂CO), and -1835289 ([5]·0.8CH₂Cl₂). Copy of the data can be obtained free of charge on application to The Director, CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (email: deposit@ccdc.cam.ac.uk).

Solution Equilibrium Studies. Aqueous stability and proton dissociation processes of complexes [3]Cl₂ and [4]Cl₂ were investigated in detail. Because of the photosensitivity of the complexes their solutions were kept in the dark. A Hewlett-Packard 8452A diode array spectrophotometer was used to record the UV–vis spectra in the 200–800 nm window. The path length was 0.2, 0.5, 1, or 4 cm. Spectrophotometric measurements were performed in water, 50% (v/v) ethanol/water or 30% (v/v) DMSO/water solvent mixtures at 25.0 ± 0.1 °C and the concentration of the complexes was 4–5 or 100 μM .

The ionic strength was 0.1 M (KCl). Measurements in the presence of HNO_3 (pH \sim 3) without additional background electrolyte were carried out as well. pH dependent titrations were performed between pH 2.0 and 11.5 and an Orion 710A pH-meter equipped with a Metrohm combined electrode (type 6.0234.100) was used for the titrations. The electrode system was calibrated in aqueous solution to the $\text{pH} = -\log[\text{H}^+]$ scale according to the method suggested by Irving et al.²⁰ ^1H NMR studies were carried out on a Bruker Ultrashield 500 Plus instrument. ^1H NMR spectra of samples containing water were recorded with the WATERGATE water suppression pulse scheme using 4,4-dimethyl-4-silapentane-1-sulfonic acid (DSS) as an internal standard. Complexes were dissolved in 50% (v/v) $\text{CD}_3\text{OD}/\text{H}_2\text{O}$ mixture to yield a concentration of 0.5 mM and were titrated at 25 °C, in the absence of KCl in the pH range from 2.0 to 11.1. ^1H NMR spectra were recorded on samples containing $[\text{4}]\text{Cl}_2$ (0.5 mM) and increasing amounts of KCl (0.0, 0.44, 0.68 M) after 2 h of incubation. Fluorescence spectra were recorded on a Hitachi-F4500 fluorometer in 1 cm quartz cell at $\lambda_{\text{EX}} = 290$ nm, $\lambda_{\text{EM}} = 300\text{--}500$ nm and at 25.0 ± 0.1 °C. Solutions were prepared in pure water at 5 μM complex concentration. Ionic strength was 0.1 M (KCl), and samples were titrated between pH 2.0 and 11.5.

Electrochemistry and Spectroelectrochemistry. The cyclic voltammetric studies were performed using a platinum wire as working and auxiliary electrodes, and silver wire as pseudoreference electrode with a Heka PG310USB (Lambrech, Germany) potentiostat. Ferrocene/ferricenium couple served as the internal potential standard. In situ spectroelectrochemical measurements were performed on Avantes, Model AvaSpec-2048 \times 14-USB2 spectrometer under an argon atmosphere with the Pt-microstructured honeycomb working electrode, purchased from Pine Research Instrumentation (spectroelectrochemical cell kit AKSTCKIT3). IR spectroelectrochemistry was performed in the optically transparent thin layer electrochemical (OTTLE) cell (UF-SEC, LabOmak, Italy) with CaF_2 window and Pt mesh working electrode. Spectra were recorded at room temperature in the $400\text{--}4000$ cm^{-1} with 4 cm^{-1} resolution using Nicolet NEXUS 470 FT-IR spectrometer. Further details are provided as [Supporting Information](#) (SI) material.

EPR Spectroscopy. X-band (9.4 GHz) and Q-band (34 GHz) EPR spectra were recorded with the EMX line EPR spectrometers (Bruker, Germany) equipped with the ER 4102ST and ER 5106 QT resonators, respectively and with the ER 4141 VT variable temperature unit. The simulated spectra were calculated with EasySpin, the Matlab toolbox.²¹ Further details are provided as SI.

Solution Photochemistry in Minutes Time Scale. NO scavenging EPR experiments were performed with 33 μM solution of $[\text{3}]\text{Cl}_2$ and an equimolar concentration of carboxy-2-phenyl-4,4,5,5-tetramethyl-imidazoline-1-oxyl-3-oxide (cPTIO) nitronyl nitroxide in Ar saturated MeCN. The solution was filled in an EPR flat cell and irradiated in situ in the resonator of the EPR spectrometer (vide supra) at room temperature with a visible light source ($\lambda_{\text{max}} = 400$ nm; Bluepoint LED, Hönle UV Technology). The photolysis of 30–35 μM stirred complex solutions was additionally followed by UV–vis spectroscopy in situ in the LED photoreactor equipped with two $\lambda_{\text{max}} = 365$ or 405 nm LED arrays (KEVA Brno, Czech Republic), in a perpendicular arrangement using 1 cm \times 1 cm quartz cuvette (1 cm optical irradiation path). The UV–vis Avantes spectrometer described above was used to record the spectra. The light intensity provided by the LED arrays (irradiance value) was determined using ferrioxalate actinometry under identical conditions (yielding 7.81×10^{-4} einstein $\text{s}^{-1} \text{dm}^{-2}$ and 1.18×10^{-4} einstein $\text{s}^{-1} \text{dm}^{-2}$ at 365 and 405 nm, respectively).²² The spectra were corrected for the irradiation light artifacts, by subtracting a record obtained with the pure solvent. The molar absorption coefficient of the photogenerated products and the photochemical quantum yields were determined by kinetic modeling. The Global Analysis of the spectral series recorded in the photolysis experiment was performed using the Ultrafast Spectroscopy Modeling Toolbox,²³ by employing a first order kinetics model. The rate constants and concentration profiles obtained were then used to evaluate the quantum yield as described in the text.

Femtosecond Pump–Probe Spectroscopy. The experimental details for the femtosecond transient absorption measurements have

already been described elsewhere.²⁴ Briefly it is a Ti:sapphire laser (Mai Tai HP, Spectra Physics, USA) centered at 800 nm having pulse width of <110 fs with 80 MHz repetition rate. The amplified laser was split into two beams in the ratio of 75:25%. The high energy beam was used to convert to the required wavelength (470 nm) for exciting the sample by using TOPAZ (Prime, Light Conversion). The white light continuum (340–1000 nm) was generated by focusing the part of amplified beam (200 mW) on a 1 mm thick CaF_2 plate which split into two beams (sample and reference probe beams). The sample cell (0.4 mm path length) was refreshed by rotating in a constant speed. Finally, the white light continuum was focused into a 100 μm optical fiber coupled to imaging spectrometer after passing through the sample cell. The pump probe spectrophotometer (ExciPro) setup was purchased from CDP Systems Corp, Russia. Normally transient absorption spectra were obtained by averaging about 2000 excitation pulses for each spectral delay. All the measurements were carried out at the magic angle (54.7°). The time resolution of the pump–probe spectrometer is found to be about ≤ 120 fs.

Computational Details. Geometry optimizations of all species generated from $[\text{3}]^{2+}$ (i.e. $[\text{RuCl}(\text{Hind})_4(\text{NO})]^{2+}$, its reduced form, $^2[\text{RuCl}(\text{Hind})_4]^{2+}$ form after NO release, etc.) have been performed at the B3LYP^{25–28} level of theory employing SVP and/or TZVP basis sets²⁹ with SDD pseudopotential for the Ru atom.³⁰ The energy-based criterion of the SCF convergence was set to 10^{-8} Hartree in all systems. Vibrational analysis was employed to confirm that the optimal geometries correspond to energy minima (no imaginary frequencies). Time-dependent density functional theory (TD DFT) has been utilized for calculations of electron excitation energies and oscillator strengths at the same levels of theory as mentioned above. Herein, the 40 lowest electron excitations have been taken into account. All these calculations were carried out in Gaussian09 program package.³¹ The single point calculations of EPR parameters of the optimized structures were performed at the B3LYP^{25–28}/UDZ³² level of theory in ORCA 3.0.2 program package,^{33–35} where UDZ stands for uncontracted double- ζ basis set. The EPR calculations employed a scalar quasi-relativistic Douglas–Kroll–Hess Hamiltonian^{33,36–39} with the unrestricted Kohn–Sham formalism and using the point charge nucleus model. Picture change error⁴⁰ correction of the g -tensor and hyperfine coupling constant of N3 atom was accounted for as implemented in the ORCA 3.0.2 program package. Visualization of the optimal structures and molecular orbitals as well as spin densities was performed in Molekel⁴¹ software suite.

Cell Lines and Culture Conditions. Human colorectal carcinoma HCT116 and HCT116 p53^{−/−} cell lines were gifts from Professor Shen Han-ming (NUS). Human ovarian carcinoma cells A2780 and human embryonic kidney cells HEK293 were obtained from ATCC. A2780 cells were cultured in RPMI 1640 medium containing 10% fetal bovine serum (FBS). HCT116 and HEK293 were cultured in DMEM medium containing 10% FBS. Adherent cells were grown in tissue culture 25 cm^2 flasks (BD Biosciences, Singapore). All cell lines were grown at 37 °C in a humidified atmosphere of 95% air and 5% CO_2 . Experiments were performed on cells within 30 passages. All drug stock solutions were prepared in DMSO and the final concentration of DMSO in medium did not exceed 1% (v/v) at which cell viability was not inhibited. The amount of actual Ru concentration in the stock solutions was determined by ICP-OES.

Inhibition of Cell Viability Assay. The cytotoxicity of the compounds was determined by colorimetric microculture assay (MTT assay). The cells were harvested from culture flasks by trypsinization and seeded into Cellstar 96-well microculture plates (Greiner Bio-One) at the seeding density of 6×10^3 cells per well. After the cells were allowed to resume exponential growth for 24 h, they were exposed to drugs at different concentrations in media for 72 h. The drugs were diluted in complete medium at the desired concentration and 100 μL of the drug solution was added to each well and serially diluted to other wells. After exposure for 72 h, drug solutions were replaced with 100 μL of MTT in media (5 mg mL^{-1}) and incubated for additional 45 min. Subsequently, the medium was aspirated and the purple formazan crystals formed in viable cells were dissolved in 100 μL of DMSO per well. Optical densities were measured at 570 nm with a microplate

reader. For cell viability assays involving inhibitors, the cells were pre-incubated with pifithrin- α (10 μ M) or carboxy-PTIO (2.5 or 10 μ M) for 30 min and then coincubated with drugs for 72 h. Cell viability in the absence and presence of inhibitor was normalized against untreated control. For the irradiation experiments, drug stock solutions were prepared in MeCN and their concentrations were independently verified by ICP-OES. The concentration of MeCN in medium did not exceed 1% (v/v) at which cell viability was not inhibited. Drug stock solutions were irradiated by 18 W blue LED strips (maximum emission at around 470 nm) for 5 min and quickly diluted in complete medium at the desired concentration and MTT assay was carried out as described. The irradiation of drug solutions was characterized by the appearance of blue color. The quantity of viable cells was expressed in terms of treated/control (T/C) values by comparison to untreated control cells, and 50% inhibitory concentrations (IC_{50}) were calculated from concentration-effect curves by interpolation. Evaluation was based on means from at least three independent experiments, each comprising six replicates per concentration level.

Western Blot Analysis. A2780 cells were seeded into Cellstar 6-well plates (Greiner Bio-One) at a density of 6×10^5 cells per well. After the cells were allowed to resume exponential growth for 24 h, they were exposed to [1], [3] Cl_2 , [4] Cl_2 , cisplatin, and oxaliplatin at different concentrations for 24 h. The cells were washed twice with 1 mL of PBS and lysed with lysis buffer [100 μ L, 1% IGEPAL CA-630, 150 mM NaCl, 50 mM Tris-HCl (pH 8.0), protease inhibitor] for 5–10 min at 4 $^{\circ}$ C. The cell lysates were scraped from the wells and transferred to separate 1.5 mL microtubes. The supernatant was then collected after centrifugation (13000 rpm, 4 $^{\circ}$ C for 15 min) and total protein content of each sample was quantified via Bradford's assay. Equal quantities of protein (50 μ g) were reconstituted in loading buffer [5% DDT, 5 \times Laemmli Buffer] and heated at 105 $^{\circ}$ C for 10 min. Subsequently, the protein mixtures were resolved on a 10% SDS-PAGE gel by electrophoresis (90 V for 30 min followed by 120 V for 60 min) and transferred onto a nitrocellulose membrane (200 mA for 2 h). The protein bands were visualized with Ponceau S stain solution and the nitrocellulose membranes were cut into strips based on the protein ladder. The membranes were washed with a wash buffer (0.1% Tween-20 in 1 \times DPBS) three times for 5 min. Subsequently, they were blocked in 5% (w/v) nonfat milk in wash buffer (actin and p53 antibodies) or 5% BSA (w/v) in wash buffer (p21 antibody) for 1 h and subsequently incubated with the appropriate primary antibodies in 2% (w/v) nonfat milk in wash buffer (actin and p53 antibodies) or 5% BSA (w/v) in wash buffer (p21 antibody) at 4 $^{\circ}$ C overnight. The membranes were washed with a wash buffer 3 times for 7 min. After incubation with horseradish peroxidase-conjugated secondary antibodies (r.t., 1.5 h), the membranes were washed with a wash buffer 4 times for 5 min. Immune complexes were detected with Luminata HRP substrates and analyzed using enhanced chemiluminescence imaging (PXi, Syngene). Actin was used as a loading control. The following antibodies were used: p53 (FL-393) (sc-6243) and p21 (F-5) (sc-6246) from Santa Cruz Biotechnologies, β -Actin (ab75186) from Abcam, ECL.

■ RESULTS AND DISCUSSION

Synthesis of Complexes. The complexes *trans*-[RuCl(Hind) $_4$ (NO)] $Cl_2 \cdot H_2O$ ([3] $Cl_2 \cdot H_2O$), *trans*-[RuOH(Hind) $_4$ (NO)] $Cl_2 \cdot H_2O$ ([4] $Cl_2 \cdot H_2O$), [RuCl(ind) $_2$ (Hind) $_2$ (NO)]([5]), and [RuOH(ind) $_2$ (Hind) $_2$ (NO)]([6]) were synthesized as shown in Scheme 1. Metathesis reaction of *trans*-[RuCl $_2$ (Hind) $_4$]([1]) with a 50% molar excess of NaNO $_2$ afforded the complex *trans*-[Ru(NO) $_2$ (Hind) $_4$]([2]) in 46% yield. Treatment of the latter with 12 and 3 M HCl in methanol resulted in formation of [3] $Cl_2 \cdot H_2O$ and [4] $Cl_2 \cdot H_2O$ in 52% and 62% yields, respectively. These two compounds were found to deprotonate at pH 6–9 (vide infra) with formation of [5] and [6], in \sim 50% yield. By reacting [4] Cl_2 with 12 M HCl an incomplete conversion into [3] Cl_2 was observed. The composition and structure for all new compounds reported in this work were proposed from elemental analyses, 1H NMR, IR and UV–vis

spectra, ESI mass spectrometry (see Experimental Section) and confirmed by single crystal X-ray diffraction measurements (vide infra). It should, however, be noted that the compounds used in all investigations described below are anhydrous or hydrated compounds (see Experimental Section), while those characterized by single crystal X-ray diffraction are either anhydrous or contain cocrystallized solvent used for crystal growth.

X-ray Crystallography. The results of X-ray diffraction studies of [2], [3] $Cl_2 \cdot 2(CH_3)_2CO$, [4] $Cl_2 \cdot 2(CH_3)_2CO$, and 5 $\cdot 0.8CH_2Cl_2$ are shown in Figures S1 and 1, details of data collection and refinement are given in Table S1, while selected bond lengths (\AA) and angles (deg) are quoted in the legends to Figures S1 and 1. Complex [2] crystallized in the tetragonal space group $I4_1/a$, while the other three compounds in the monoclinic space group $P2_1/n$ (or $P2_1/c$) (Table S1). All four complexes adopt a distorted octahedral coordination geometry with four indazole ligands coordinated to ruthenium in the equatorial plane and two nitrito groups ([2]), NO and chlorido ([3] Cl_2) and [5] or NO and hydroxido ([4] Cl_2) as axial ligands. Interestingly, in [5] two adjacent indazole ligands are deprotonated at N6 and N8 acting as proton acceptors in intramolecular hydrogen bonds N4–H \cdots N6 [N4 \cdots N6 2.800(2) \AA , N4–H \cdots N6 170 $^{\circ}$] and N2–H \cdots N8 [N2 \cdots N8 2.800(2) \AA , N2–H \cdots N8 170 $^{\circ}$] (Figure 1C).

Note that X-ray diffraction structures of complexes with deprotonated indazole are rare in the literature. Two examples can be mentioned, namely the platinum complex [PtCl(N-indazolato)(PPh $_3$) $_2$] 42 and the osmium-arene complex [(η^6 -*p*-cymene)Os(oxine)(ind)] 43 . The Ru–NO moiety is almost linear with the corresponding angle varying from 168.7(5) $^{\circ}$ to 171.0(9) $^{\circ}$. In addition to X-ray diffraction data the linear geometry of Ru–NO unit in [3] Cl_2 , [4] Cl_2 , [5], and [6] was also obvious from IR spectra, where strong absorption bands with ν_{NO} at 1925, 1879, 1871, and 1850 cm^{-1} were measured. The photoreactivity of this moiety in the solid state was also investigated.

Solid-State Photochemistry. Metal nitrosyl complexes are sometimes characterized by a competition between NO release and the generation of photoinduced NO linkage isomers (PLI). These PLI were first discovered in Na $_2$ [Fe(CN) $_5$ (NO)] 44,45 and termed long-lived metastable states (MS). Since then a number of ruthenium complexes have been prepared with similar photophysical behavior. $^{46-50}$ To evaluate the ability of the complexes to form PLI or release NO, we performed a systematic analysis by infrared spectroscopy as a function of temperature, which are detailed in Supporting Information (Figures S2–S4). In summary, upon light irradiation, solid [3] $Cl_2 \cdot H_2O$ did not exhibit significant metastable isomer population, but considerable NO release at room temperature. In contrast, for [4] $Cl_2 \cdot H_2O$ and [5] we observed both phenomena: NO release at room temperature and linkage isomerism at low temperature, which in case of [5] is reversible.

Solution Chemistry of Complexes [3] Cl_2 and [4] Cl_2 in Aqueous Media. Structural and spectroscopic characterization of compounds is usually performed in the solid state or in organic solvents. However, for the drug development it is important to collect the information about the stability and reactivity of the drug candidates in aqueous media, especially at physiological pH. It is known that pH in solid tumors is usually lower than in normal tissues and acidosis in cancer cells is mediated by glycolysis, induced by limited oxygen supply. 51 Typical extracellular pH ranges are 6.5–6.9 in tumors and 7.0–7.5 in normal tissues; however, in some tumors pH values of 6.0 or even lower were

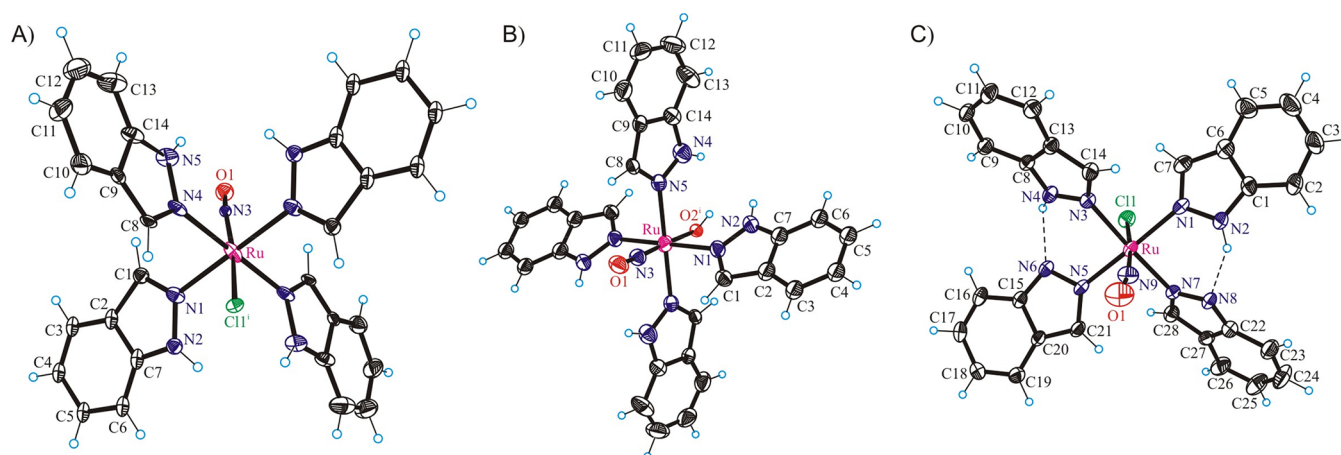
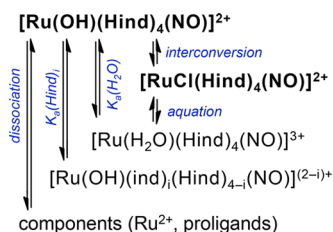


Figure 1. (A) ORTEP view of the cation $[\text{RuCl}(\text{NO})(\text{Hind})_4]^{2+}$ in the crystal structure of $[\text{3}]\text{Cl}_2 \cdot 2(\text{CH}_3)_2\text{CO}$ with atom labeling scheme and thermal ellipsoids at 50% probability level; only the major components of the disordered over two positions Cl^- and NO are shown. Counterions and solvent molecules in the crystal structure are omitted for clarity. Selected bond distances (Å) and angles (deg): $\text{Ru}-\text{N1}$ 2.080(6), $\text{Ru}-\text{N4}$ 2.085(7), $\text{Ru}-\text{Cl1}^i$ 2.214(7), $\text{Ru}-\text{N3}$ 1.806(19), $\text{N3}-\text{O1}$ 1.174(19), $\text{Ru}-\text{N3}-\text{O1}$ 168.9(17), $\text{Cl1}^i-\text{Ru}-\text{N3}$ 174.5(6); i denotes atom generated by symmetry transformation $1-x, -y, -z$. (B) ORTEP view of the cation $[\text{Ru}(\text{OH})(\text{NO})(\text{Hind})_4]^{2+}$ in the crystal structure of $[\text{4}]\text{Cl}_2 \cdot 2(\text{CH}_3)_2\text{CO}$ with atom labeling scheme and thermal ellipsoids at 50% probability level; only the major components of the disordered over two positions OH^- , NO , and two indazole ligands are shown. Counterions and solvent molecules in the crystal structure are omitted for clarity. Selected bond distances (Å) and angles (deg): $\text{Ru}-\text{N1}$ 2.078(3), $\text{Ru}-\text{N4}$ 2.078(3), $\text{Ru}-\text{O2}^i$ 1.996(9), $\text{Ru}-\text{N3}$ 1.702(11), $\text{Ru}-\text{N3}-\text{O1}$ 171.0(9), $\text{N3}-\text{Ru}-\text{O2}^i$ 178.1(6); i denotes atom generated by symmetry transformation $-x+1, -y+2, -z$. (C) ORTEP view of the inner-sphere complex $[\text{RuCl}(\text{ind})_2(\text{Hind})_2(\text{NO})]^{5+}$ with atom labeling scheme and thermal ellipsoids at 50% probability level. Co-crystallized solvent is omitted for clarity. Selected bond distances (Å) and angles (deg): $\text{Ru}-\text{N1}$ 2.090(4), $\text{Ru}-\text{N3}$ 2.094(4), $\text{Ru}-\text{N5}$ 2.081(4), $\text{Ru}-\text{N7}$ 2.073(4), $\text{Ru}-\text{Cl1}$ 2.2959(13), $\text{Ru}-\text{N9}$ 1.774(5), $\text{N9}-\text{O1}$ 1.127(6), $\text{Ru}-\text{N9}-\text{O1}$ 168.7(5), $\text{N9}-\text{Ru}-\text{Cl1}$ 174.68(15).

Scheme 2. Possible Transformation Processes of $[\text{Ru}(\text{OH})(\text{Hind})_4(\text{NO})]^{2+}$ ($[\text{4}]^{2+}$) Including Interconversion to $[\text{RuCl}(\text{Hind})_4(\text{NO})]^{2+}$ ($[\text{3}]^{2+}$) and Aquation of the Latter as Well^a



^aThe same protonation and dissociation equilibria are valid for $[\text{3}]^{2+}$.

detected.⁵² Therefore, the behavior of drug candidates should also be assessed at acidic conditions. Complexes $[\text{3}]\text{Cl}_2$ and $[\text{4}]\text{Cl}_2$ may participate in several interactions in aqueous media. Besides the (partial) decomposition of the complexes (i.e., loss of NO or Hind ligands, Cl^-/OH^- exchange), protonation of the coordinated OH^- in $[\text{4}]\text{Cl}_2$ or stepwise deprotonation of Hind ligands in both complexes $[\text{3}]\text{Cl}_2$ and $[\text{4}]\text{Cl}_2$ may take place in aqueous solution by varying the pH as it is shown in Scheme 2 for $[\text{4}]^{2+}$.

The chlorido co-ligand often behaves as a leaving group, especially in the case of platinum-group metal complexes.^{53–55} Correct interpretation of the actual form of a compound at physiological conditions requires detailed investigations under variation of different parameters (pH, ionic strength, etc.) in aqueous media.

The aqueous solubility of complexes $[\text{3}]\text{Cl}_2$ and $[\text{4}]\text{Cl}_2$ at pH 7.4 was extremely poor and precipitate formation was observed even at $5\ \mu\text{M}$ complex concentration, thereby hindering detailed investigation in neat water at this pH due to the concentration requirements of the chosen experimental methods. The aqueous solubility increased under acidic conditions (pH 2–4)

but was still limited ($\sim 100\ \mu\text{M}$). Because of the low solubility of $[\text{3}]\text{Cl}_2$ and $[\text{4}]\text{Cl}_2$ in water, their solution chemistry was investigated in 30% (v/v) DMSO/water or 50% (v/v) ethanol/water solvent mixtures. First, the interconversion between the two complexes was investigated. UV–vis spectra recorded in 50% (v/v) ethanol/water or 30% (v/v) DMSO/water mixture showed different spectral shapes at pH 2.3 (Figure S5) and spectra remained unaltered over 1 h. ^1H NMR spectra measured for $[\text{4}]\text{Cl}_2$ at various KCl concentrations (0–0.68 M) in 50% (v/v) CD_3OD /water at pH = 4.9 provide further evidence that no $\text{Cl}^-/\text{H}_2\text{O}$ or Cl^-/OH^- exchange occurred after incubation for 2 h (Figure S6). The same conclusion can be drawn from ESI-MS measurements: mass spectra of $[\text{3}]\text{Cl}_2$ and $[\text{4}]\text{Cl}_2$ showed the exclusive presence of the original complexes in the samples even after 8 days incubation in diluted nitric acid (pH ~ 3), accordingly, no aquation of $[\text{3}]\text{Cl}_2$, no interconversion and no decomposition of the complexes occur in aqueous media. Next, we studied the behavior of complexes $[\text{3}]\text{Cl}_2$ and $[\text{4}]\text{Cl}_2$ upon pH increase from ~ 2 to ~ 11 in 50% ethanol/water by UV–vis spectroscopy. As shown in Figure 2A, considerable changes in charge transfer bands occur in UV–vis spectra of $[\text{4}]\text{Cl}_2$ at pH 2.2–5.3, while practically no measurable changes were observed for the chlorido complex $[\text{3}]\text{Cl}_2$ in this pH range (see Figure S7). This may be explained by the protonation of OH^- in $[\text{4}]\text{Cl}_2$ at more acidic conditions to give the aqua complex $[\text{Ru}(\text{H}_2\text{O})(\text{Hind})_4(\text{NO})]^{3+}$.

At pH above 5.3 intraligand bands of $[\text{4}]\text{Cl}_2$ in Figure 2B show significant spectral changes indicating the involvement of Hind ligands into a pH-dependent process. To assess if the incubation of complexes $[\text{3}]\text{Cl}_2$ and $[\text{4}]\text{Cl}_2$ at different pH was associated with the release of indazole ligands, ^1H NMR spectra at different pH in 50% CD_3OD /water were recorded. $[\text{4}]\text{Cl}_2$ demonstrated high field shifts of proton signals at pH above 5 in Figure 3, but no free indazole could be detected at any pH ruling out the release of indazole from the complex.

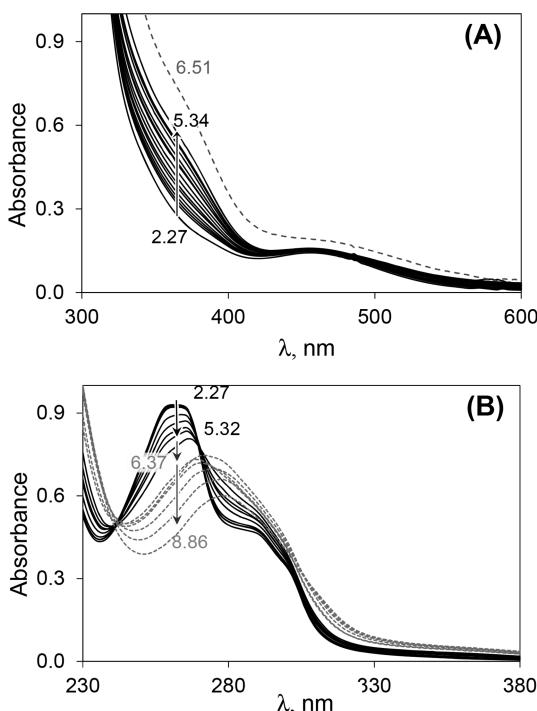


Figure 2. Visible (A) and UV (B) spectra of $[4]\text{Cl}_2$ recorded at various pH values in 50% (v/v) ethanol/water. Dashed spectra indicate precipitate formation, pH values are indicated in the figure. $\{c_{\text{complex}} = 102 \mu\text{M}$ (A), $5.1 \mu\text{M}$ (B); $l = 4 \text{ cm}$, $I = 0.1 \text{ M KCl}\}$.

This assumption was supported by spectrofluorimetric experiments, which indicated high stability of Ru-Hind bond (Figure S8). The proton shifts of coordinated indazole in ^1H NMR spectra upon pH changes were associated with indazole deprotonation. Increase of pH above 6.5 was accompanied by precipitation of both complexes with partial redissolution at $\text{pH} \approx 11$. Complexes $[3]\text{Cl}_2$ and $[4]\text{Cl}_2$ were found to deprotonate with the formation of $[\text{RuCl}(\text{ind})_2(\text{Hind})_2(\text{NO})]$ ($[5]$) and $[\text{RuOH}(\text{ind})_2(\text{Hind})_2(\text{NO})]$ ($[6]$), respectively. The solid-state structure of $[5]$ was confirmed by X-ray diffraction analysis (Figure 1C, vide supra). To conclude, solution studies revealed the high aqueous stability (or kinetic inertness) of both complexes. Thus, Hind ligands underwent stepwise deprotonation in $[3]\text{Cl}_2$ and $[4]\text{Cl}_2$ resulting in the inner-sphere

complexes $[5]$ and $[6]$, respectively at physiological pH. However, the low solubility of these species at physiological pH hindered further investigation of their aqueous behavior and biological activity.

Electrochemical and Spectroscopic Studies. Redox properties of the ruthenium nitrosyl complexes have been characterized in organic solvents, since these media provide considerably larger potential windows for electrochemical investigations, compared to aqueous environments. The first reduction step for $\text{trans-}[\text{RuCl}(\text{Hind})_4(\text{NO})]^{2+}$ ($[3]^{2+}$) in a $0.2 \text{ M } n\text{Bu}_4\text{NPF}_6/\text{MeCN}$ is electrochemically reversible with $E_{1/2} = -0.11 \text{ V}$ vs Fc^+/Fc (Figure S9A) and is followed by the less reversible one at $E_{1/2} = -0.80 \text{ V}$ vs Fc^+/Fc . Notably, a very similar behavior was reported for a number of other ruthenium nitrosyl complexes suggesting that redox events mainly involve the NO ligand, namely the reduction of formal $\text{Ru}^{\text{II}}\text{-NO}^+$ to $\text{Ru}^{\text{II}}\text{-NO}^\bullet$ in the first step and the $\text{Ru}^{\text{II}}\text{-NO}^\bullet$ transformation to the $\text{Ru}^{\text{II}}\text{-NO}^-$ in the next step.⁵⁶ Cyclic voltammogram of $\text{trans-}[\text{Ru}(\text{OH})(\text{Hind})_4(\text{NO})]^{2+}$ ($[4]^{2+}$) in a $0.2 \text{ M } n\text{Bu}_4\text{NPF}_6/\text{MeCN}$ shows the first reduction peak at $E_{\text{pc}} = -0.47 \text{ V}$ vs Fc^+/Fc at scan rate of 100 mV s^{-1} and a strongly shifted reoxidation peak at $E_{\text{pa}} = -0.08 \text{ V}$ vs Fc^+/Fc . The second electron transfer occurs at $E_{\text{pc}} = -0.8 \text{ V}$ vs Fc^+/Fc (Figure S9B). Similar redox behavior for $[4]^{2+}$ was observed also in DCM and ethanol solutions (Figure S10). The one-electron reduction for $[3]^{2+}$ was confirmed by coulometric measurements and is in line with the reduction of either $\text{trans-}[\text{Ru}^{\text{III}}\text{Cl}(\text{Hind})_4(\text{NO}^0)]^{2+}$ or $\text{trans-}[\text{Ru}^{\text{II}}\text{Cl}(\text{Hind})_4(\text{NO}^+)]^{2+}$ to the corresponding monocation, which can be formulated as $\text{trans-}[\text{Ru}^{\text{II}}\text{Cl}(\text{Hind})_4(\text{NO}^0)]^+$ ($[3]^+$). The latter is a paramagnetic species of $\{\text{Ru}(\text{NO})\}^7$ type according to the Enemark–Feltham notation.⁵⁷ The formation of paramagnetic $\{\text{Ru}(\text{NO})\}^7$ species upon one-electron reduction was also confirmed for inner-sphere complexes $[5]$ and $[6]$ by EPR spectroscopy, even though the first cathodic step is less electrochemically reversible (Figure S11).

The parent $[3]\text{Cl}_2$ and $[4]\text{Cl}_2$ were found to be EPR silent both in the solid state, as well as in the frozen solutions at 100 K . For both electrochemically generated $[3]^+$ and $[4]^+$ cations, a characteristic $\{\text{Ru}(\text{NO})\}^7$ EPR signal, featuring a rhombic g tensor ($g_1 > 2$, $g_2 \approx 2.0$, $g_3 < 2$) and a well-resolved nitrogen hyperfine splitting in the g_2 range ($A_2 \approx 92 \text{ MHz}$ or 3.3 mT), was observed (Figure S12A).^{58,59} Annealing of the $[4]^+$ sample up to 220 K resulted in a progressive line broadening, and collapse of

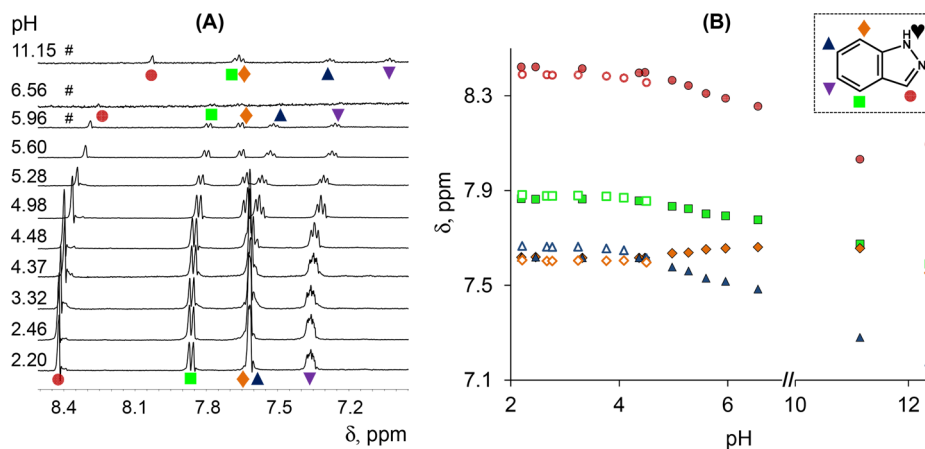


Figure 3. ^1H NMR spectra of $[4]\text{Cl}_2$ recorded at various pH values (A) and chemical shift values (δ) of $[3]\text{Cl}_2$ (empty symbols) and $[4]\text{Cl}_2$ (full symbols) plotted against the pH. $\{c_{\text{complex}} = 0.5 \text{ mM}$; $50\% \text{ (v/v) CD}_3\text{OD/water}\}$ #: magnified spectral intensities.

the resolved features into a single broad singlet (Figure S12B). These results are in line with the formulation of a closed shell $\{\text{Ru}(\text{NO})\}^6$ state containing $\text{Ru}^{\text{II}} (S=0)$ bonded to $\text{NO}^+ (S=0)$ for the parent complexes $[3]^{2+}$ or $[4]^{2+}$. The reduction of the complexes then results in $\{\text{Ru}(\text{NO})\}^7 (S=1/2)$ species, which bears an unpaired electron and shows EPR activity.⁶⁰ The rather positive value of the first reduction potential of $[3]^{2+}$ offers an alternative method for convenient generation of the paramagnetic one-electron reduced species $[3]^+$ by using decamethyl ferrocene (Fc^*) as reductant. The X- and Q-band EPR spectra of frozen solutions of $[3]^+$, prepared in this manner, are shown in Figure S13A and B, respectively. The EPR spectra obtained by chemical reduction in $\text{MeCN}/n\text{Bu}_4\text{NPF}_6$ solutions (black lines in Figure S13A and B) perfectly matched the records of electrogenerated $[3]^+$. The X-band EPR signal of $[3]^+$ resembles well the spectra of several $\{\text{Ru}(\text{NO})\}^7$ systems known from the literature, for example, the extensively studied porphyrin complexes $[\text{Ru}(\text{OEP})(\text{NO})(\text{THF})]$,⁶¹ $[\text{Ru}(\text{OEP})(\text{NO})(\text{py})]$,⁶² or $[\text{Ru}(\text{TPP})(\text{NO})(\text{py})]$.⁶³ The reduction with Fc^* was also successfully used to generate the one electron reduced $\{\text{Ru}(\text{NO})\}^7$ species from $[4]^{2+}$, $[5]^0$, and $[6]^0$. Their EPR spectra are summarized in Figures S13–S20 and the estimated spin Hamiltonian parameters are listed in Table S2. By simulation of the corresponding EPR spectra, two components were taken into account (see discussion in Figures S15–S17 and Table S2). The major component can be clearly assigned to the authentic species $[3]^+$ and $[4]^+$. Detailed analysis of the minor component is beyond the scope of this paper and further detailed experimental and theoretical studies are currently underway in one of our laboratories.

The reversibility and redox mechanism in the region of the first reduction peak for $[3]^{2+}$ and $[4]^{2+}$ were investigated by the in situ spectroelectrochemical UV–vis cyclic voltammetric experiments in $\text{MeCN}/n\text{Bu}_4\text{NPF}_6$. Upon the in situ reduction of $[3]^{2+}$ at a scan rate of 10 mV s^{-1} , in the region from $+0.15$ to $-0.51 \text{ V vs Fc}^+/\text{Fc}$, the UV–vis absorption bands at 260 nm (strong absorption) and 460 nm (weak absorption) decreased, and simultaneously, a new optical band at 360 nm emerged (Figure 4A). Fully reversible spectroelectrochemical behavior confirmed the high stability of cathodically generated monocation $[3]^+$ (see response for the two consecutive CV scans in Figure 4B). Difference optical spectra (taking the initial sample solution spectrum as the reference) are shown for clarity since the transformations of the low intensity bands are easier to follow in this case (absolute spectra are shown in Figure S21). Similar spectroelectrochemical response was observed for $[4]^{2+}$ (Figure S22). The potential dependence of UV–vis spectra measured for the two consecutive cyclic voltammetric scans in thin layer cell is shown in Figure S22B. Upon the in situ reduction of $[4]^{2+}$ in MeCN at a scan rate of 10 mV s^{-1} in the region from $+0.3$ to $-0.6 \text{ V vs Fc}^+/\text{Fc}$, the UV–vis absorption band at 264 nm decreased, while new optical bands at 284 and $\sim 360 \text{ nm}$ via an isosbestic point at 272 nm appeared (Figure S22C). The isosbestic points in the forward and the reverse voltammetric scans (Figure S22C and D) indicate the chemical reversibility of the first reduction step and the stability of the paramagnetic reduced species $[4]^+$.

The IR spectra recorded upon the one-electron reduction of $[3]^{2+}$ showed a decrease of the N–O stretching band of the parent complex at 1920 cm^{-1} accompanied by an increase of the monocation $[3]^+$ NO band at 1630 cm^{-1} (Figure 4C). The N–O vibrational frequency of $[3]^{2+}$ falls well within the range considered for NO^+ state of the ligand, thus implying a $2+$ oxidation state of

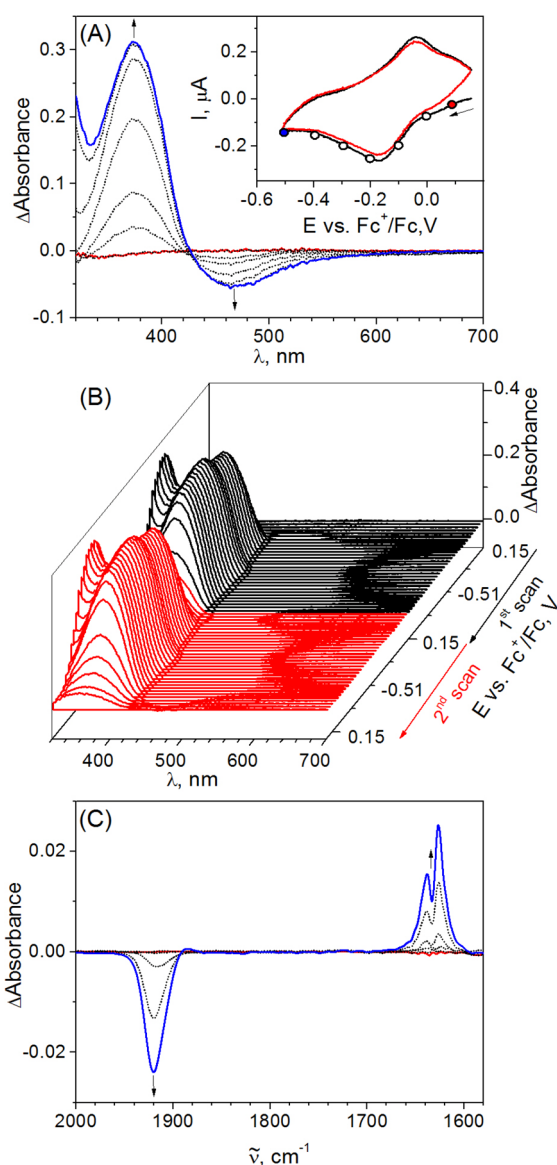


Figure 4. In situ UV–vis spectroelectrochemistry for $[3]^{2+}$ in $0.2 \text{ M } n\text{Bu}_4\text{NPF}_6/\text{MeCN}$ (scan rate 10 mV s^{-1}): (A) Difference UV–vis spectra observed upon reduction of $[3]^{2+}$ going to the first reduction peak. Inset: The corresponding cyclic voltammogram (two consecutive scans) with selected potentials marked with colored circles corresponding to the identically colored optical spectra. (B) Difference UV–vis spectra detected simultaneously upon the reduction of $[3]^{2+}$ in the region of the first cathodic peak (from $+0.15$ to $-0.51 \text{ V vs Fc}^+/\text{Fc}$) upon two consecutive cyclic voltammetric scans. (C) In situ IR spectroelectrochemistry of $[3]^{2+}$ in $0.2 \text{ M } n\text{Bu}_4\text{NPF}_6/\text{MeCN}$ performed in an OTTLE cell. Difference spectra recorded before (red line), upon (dotted lines) and after 30 s reduction at constant potential of $-0.5 \text{ V vs Fc}^+/\text{Fc}$ (blue line). The N–O stretching band of the generated $[3]^+$ at 1630 cm^{-1} overlaps with the scissor vibration band of H_2O in MeCN , thus producing an artifact apparent splitting.

ruthenium.^{58,64} On the other hand, a marked 290 cm^{-1} drop of the $\tilde{\nu}_{\text{NO}}$ upon reduction agrees well with the transformation of the linear $\text{Ru}^{\text{II}}\text{--NO}^+ \{\text{Ru}(\text{NO})\}^6$ moiety in $[3]^{2+}$ to the bent $\text{Ru}^{\text{II}}\text{--NO}^\bullet \{\text{Ru}(\text{NO})\}^7$ unit in $[3]^+$, supporting the redox mechanism proposed above.⁶⁵ A prolonged reduction of the sample, still in the range of the first electron transfer, resulted in a slow evolution of an additional band at about 1890 cm^{-1} . It is unlikely that this band would correspond to the double reduced

$\text{Ru}^{\text{II}}-\text{NO}^-$, $\{\text{Ru}(\text{NO})\}^8$ type, $[3]^0$ species. A similar behavior was recently reported for a porphyrin complex $[\text{Ru}(\text{OEP})(\text{NO})\text{Cl}]$.⁶¹

Femtosecond Pump–Probe Spectroscopy. To understand the excited state relaxation and NO liberation and recombination dynamics of $[3]\text{Cl}_2$ and $[4]\text{Cl}_2$ complexes in solution, the femtosecond time-resolved transient absorption spectra were measured by laser excitation at 470 nm in acetonitrile at room temperature. The transient absorption spectra of $[3]\text{Cl}_2$ at various time delays are shown in Figure 5. At early time scale

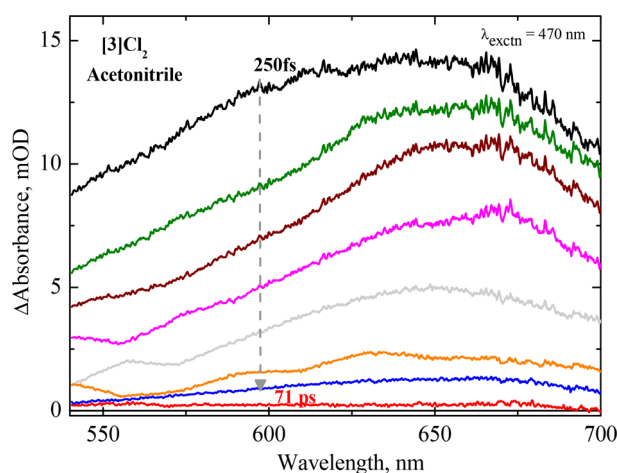


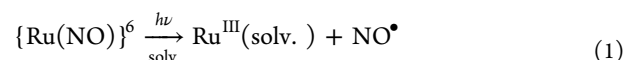
Figure 5. Femtosecond time-resolved transient absorption spectra of $[3]\text{Cl}_2$ in MeCN upon excitation at 470 nm measured at different time delays.

of 250 fs, a broad transient absorption maximum at around 650 nm is observed. The intensity of the absorption is decreased with increase of delay time and attaining to equilibrium within 30 ps. Similarly transient absorption of $[4]\text{Cl}_2$ in MeCN was measured (the data is not shown) and signal intensity is weak due to its poor solubility. To compare the effect of the trans ligand in the excited state dynamics of the compounds, the kinetic decays of $[3]\text{Cl}_2$ and $[4]\text{Cl}_2$ at probing wavelength of 612 nm obtained by exciting at 470 nm are shown in Figure S23. It is observed that the kinetic profiles of both the complexes are similar. The analysis of the femtosecond transient absorption spectra consisting of a three-dimensional data set (wavelength, time, and change in absorbance) was performed with the global analysis program GLOTARAN.⁶⁶ Three exponential components, 120 ± 20 fs (τ_1), 570 ± 50 fs (τ_2) and 6.21 ± 0.05 ps (τ_3) were optimally obtained to fully describe the relaxation dynamics of complexes in MeCN.

The excitation of the MLCT band in the ground state absorption spectra using 470 nm irradiation generates the highest singlet charge transfer state by transferring the charge from the metal to the ligand and followed by the internal conversion leading to the lowest vibrational state of first singlet state $^1\text{MLCT}$. This leads to the formation of $^3\text{MLCT}$ by intersystem crossing. The time constant of these processes could be around or less than the τ_1 which is within the instrumentation limit. The decay of the triplet state ($^3\text{MLCT}$) is attributed to the time constants of τ_2 . Here it is to be noted that though $^3\text{MLCT}$ of $[\text{Ru}(\text{bpy})_3]^{2+}$ in MeCN solution formed within 100 fs with conversion efficiency of nearly 100% having lifetime of $\sim 1 \mu\text{s}$,⁶⁷ few Ru complexes with short-lived or absence of triplet state have already been reported.⁶⁸ It was observed that the lifetime of triplet state depends on the Ru–N distance and strength of

ligand field.^{68a} In addition the contribution of $^3\text{LMCT}$ transitions from the unreduced ligand to formerly oxidized Ru(III) center cannot be ruled out.⁶⁹ Based on the theoretical studies,⁷⁰ it is proposed that the Ru–NO dissociates in the triplet state and the dynamics of NO rebinding occurring with the time constant of τ_3 .

Solution Photochemistry in Minutes Time Range. The photochemical behavior of $[3]^{2+}$, $[4]^{2+}$, $[5]^0$, and $[6]^0$ was additionally probed in solution in seconds to minutes time regime. The photoinduced reactivity of a number of $\{\text{Ru}(\text{NO})\}^6$ systems at minutes time scale has been previously reviewed,⁵⁸ and the typical reaction encountered upon excitation with UV or visible light, is the photorelease of NO^\bullet with successive formation of a $\text{Ru}^{\text{III}}(\text{solv.})$ complex (eq 1).



We have utilized the specific reaction of NO^\bullet with carboxy-2-phenyl-4,4,5,5-tetramethyl-imidazoline-1-oxyl-3-oxide (carboxy-PTIO or cPTIO) nitronyl nitroxide (NN^\bullet),⁷¹ to follow its expected release upon photolysis of $[3]^{2+}$. After the reaction with NO^\bullet , the NN^\bullet transforms to an iminonitroxide (IN^\bullet), both exhibiting distinct EPR spectra. The solution of $[3]^{2+}$ with equimolar amount of cPTIO NN^\bullet radical was irradiated in the cavity of the EPR spectrometer with 400 nm LED, and the obtained spectra are shown in Figure 6A. The typical quintet signal of the cPTIO NN^\bullet radical ($A_{\text{N1}} = A_{\text{N3}} = 0.76$ mT, red line in Figure 6A), gradually transformed to the septet signal of the corresponding IN^\bullet ($A_{\text{N1}} = 0.93$ mT, $A_{\text{N3}} = 0.43$ mT, blue line in Figure 6A), confirming thus the NO^\bullet photorelease.

The quantification of the NO^\bullet photorelease was performed based on the analysis of the UV–vis spectra. The solution of $[3]^{2+}$ in MeCN was irradiated with 405 nm light in a LED photoreactor and the in situ recorded UV–vis spectra are shown in Figure 6B. The irradiation conditions as well as the sample concentration closely resembled the previous EPR experiment, and since the time scales of the spectral changes observed by both methods correlate, an identical reaction of NO^\bullet photocleavage was monitored in both cases. The isosbestic points observed in the series of UV–vis spectra (243 nm, 272 nm, Figure 6A) indicate on a clean 1:1 conversion. This was confirmed by the Global Analysis of the obtained data. The first order reaction model according to eq 1, with the rate constant of $6.94 \times 10^{-3} \text{ s}^{-1}$ matches well with the spectral changes observed under given experimental conditions. The spectral contribution of the reactant and the product, extracted by the fitting of the kinetic model, are shown in Figure 6C, together with their concentration profiles. The data was treated analogously from the photolysis experiment in DCM (Figure S24C). An axial coordination of a solvent molecule in the photo-generated $\text{Ru}^{\text{III}}(\text{solv.})$ is suggested by eq 1. Accordingly, the spectrum of the photoproduct in DCM shows a different distribution of the intensities of the vis bands, when compared to the photoproduct in MeCN. Similar results were also obtained for $[4]^{2+}$, $[5]^0$, and $[6]^0$ and the spectra are presented in Figures S25–S27.

For the whole series of the ruthenium nitrosyl tetrazole complexes the quantum yields of NO^\bullet release obtained for vis irradiation at 405 nm vary between 3–6% and tend to be slightly lower in DCM as compared to the MeCN solutions. These numbers place the investigated compounds into the medium to lower-performing category, among the NO photodelivering $\{\text{Ru}(\text{NO})\}^6$ systems.⁵⁸ Similar $\Phi_{(\text{NO}^\bullet)}$ was achieved with UVA light, as briefly explored for the $[3]^{2+}$ (Table 1). The NO

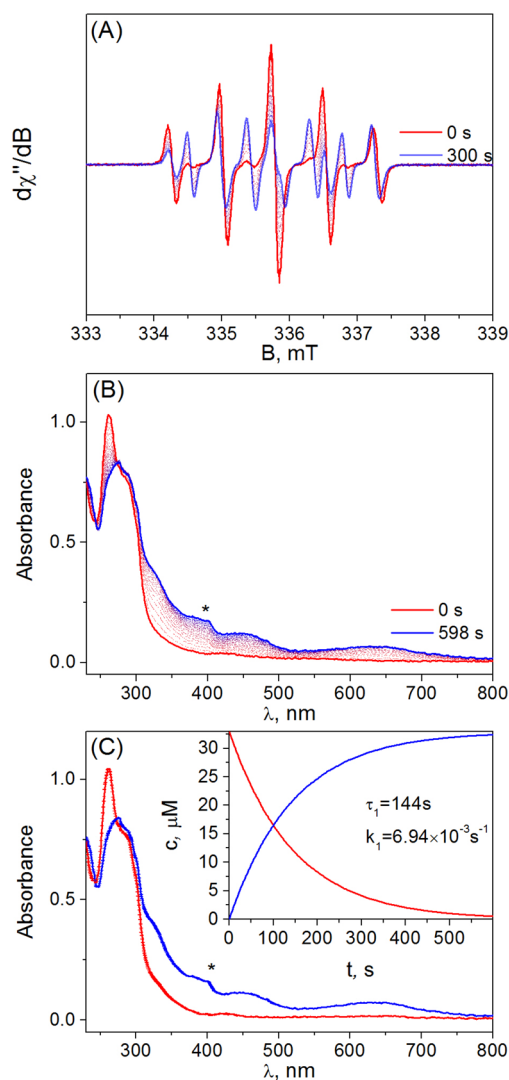


Figure 6. (A) EPR spectra detected upon photolysis (400 nm LED) of 33 μM $[3]^{2+}$ in the presence of equimolar cPTIO in Ar saturated MeCN. The quintet of cPTIO NN^{\bullet} radical ($A_{\text{N1}} = A_{\text{N3}} = 2.7$ MHz or 0.76 mT, red line) transforms to a septet of the corresponding IN^{\bullet} ($A_{\text{N1}} = 3.3$ MHz or 0.93 mT $A_{\text{N3}} = 1.5$ MHz or 0.43 mT, blue line) yielding $\sim 60\%$ conversion after 300 s illumination. (B) UV-vis spectra detected in situ during photolysis of 33 μM $[3]^{2+}$ MeCN solution with 405 nm light in a LED photoreactor. (C) The spectra of the $[3]^{2+}$ (red line) and the photoproduct $[3']^{2+}(\text{MeCN})$ (blue) obtained by the Global Analysis of the spectral series from (B). Inset shows the corresponding concentration-time profiles. * marks an artifact signal.

liberation efficiency of studied ruthenium nitrosyl tetrazoles is likely limited by the rapid NO rebinding suggested from the investigation of the compound by femtosecond pump-probe spectroscopy. Regarding the influence of the trans ligands on the NO photo release efficiency, no apparent correlation is evident at first glance, and further discussion of the trans effect seems to be redundant.

DFT Calculations. The optimized geometries of the initial $[3]^{2+}$, $[4]^{2+}$, and $[5]^0$ (singlet states) complexes agree well with the established crystal structures (see Table S3). The additional modes of NO binding to Ru, documented in the literature (T-shape and $\{\text{Ru}-\text{ON}\}$)^{46–50,72,73} are energetically not favored (see Table S4). Nevertheless, the calculated NO vibration of T-shape geometry $[3]^{2+}(\text{T})$ ($\nu_{\text{NO}} = 1673$ cm^{-1}) and the experimentally obtained band found at 1630 cm^{-1}

Table 1. Quantum Yields of NO^{\bullet} Release

complex	solvent	$\Phi_{(\text{NO}^{\bullet})}$ at 365 nm	$\Phi_{(\text{NO}^{\bullet})}$ at 405 nm
$[3]^{2+}$	MeCN	0.038 ± 0.006	0.045 ± 0.005
	DCM		0.033 ± 0.006
$[4]^{2+}$	MeCN		0.040 ± 0.005
	DCM		0.034 ± 0.006
$[5]^0$	MeCN		0.038 ± 0.003
	DCM		0.032 ± 0.004
$[6]^0$	MeCN		0.062 ± 0.005
	DCM		0.032 ± 0.004

(Figure 4C) are in a good agreement. The situation is the same for the other relevant structures (see Table S4).

The reduced system $[3]^+$ (doublet state) has a bent structure⁷⁴ (with Ru–N3–O1 angle around 140°) due to the antibonding Ru–(NO) π^* -character of closely degenerate LUMO/LUMO+1 (see Figure S29). In addition, this geometry of the $[3]^+$ is further stabilized by O1 \cdots H–N_{ind} hydrogen bond. Most of the spin density of $[3]^+$ ($\sim 77\%$) is localized on the NO group, while $\sim 17\%$ of spin is on the Ru atom, see Figure 7A.

After the release of the NO radical (NO^{\bullet}) from $[3]^{2+}$, the unpaired electron of the $^2[\text{RuCl}(\text{Hind})_4]^{2+}$ residue (from hereafter labeled as $[3']^{2+}$) is with $\sim 74\%$ of spin density localized on Ru (in the nonbonding $4d_{xy}$ orbital), see Figure 7B. This holds also for the $[3']^{2+}(\text{MeCN})$ species (where the released NO^{\bullet} is replaced by MeCN solvent molecule), see Figure S30B. The formal electronic structure of Ru^{III} atom in $[3']^{2+}$ is $[\text{Kr}^{54}]4d_{xz}^2 4d_{yz}^2 4d_{xy}^1$. The formal single reference electron configuration of $\{\text{Ru}-\text{NO}\}^6$ moiety when taking into account the 5d electrons of Ru^{III} and the unpaired electron of NO in $[3]^{2+}$ is $[\text{Kr}^{54}]4\pi_x^2 4\pi_y^2 4d_{xy}^2$. The d-populations (physical electronic configuration/structure) of Ru in $[3]^+$, $[3]^{2+}$, and $[3']^{2+}$ are $[\text{Kr}^{54}]4d_{xz}^{1.75} 4d_{yz}^{1.52} 4d_{xy}^{1.89}$, $[\text{Kr}^{54}]4d_{xz}^{1.45} 4d_{yz}^{1.45} 4d_{xy}^{1.94}$, and $[\text{Kr}^{54}]4d_{xz}^{1.91} 4d_{yz}^{1.91} 4d_{xy}^{1.27}$, respectively. Hence, one can see the significant change of the electronic configuration of Ru upon the NO^{\bullet} release.

TD-DFT level of theory was used to qualitatively interpret the experimental vis absorption spectrum of $[3]^{2+}$. The most prominent excitations can be assigned to transitions from the frontier orbitals of Hind character (HOMO–3–HOMO) into the unoccupied π^* (LUMO and LUMO+1, see Figure S29) and σ^* (LUMO+2, see Figure S29) Ru–NO antibonding orbitals, where the π^* transitions have been previously identified in a similar $\{\text{Ru}(\text{NO})\}^6$ system.⁷⁰ The transitions into π^* Ru–NO antibonding orbital are red-shifted (500–650 nm), whereas the transitions to σ^* Ru–NO antibonding orbitals are blue-shifted (400 nm). (The visualization of the difference densities and relaxed densities is shown in Figure S31.) The π^* and σ^* Ru–NO excitations are the initial channels of the Ru–NO dissociation pathway upon photolysis.

Collectively ^1H NMR, ESI MS, and UV-vis solution equilibrium studies revealed that $[3]\text{Cl}_2$ and $[4]\text{Cl}_2$ are compatible with aqueous media. There were no major changes of $[3]\text{Cl}_2$ and $[4]\text{Cl}_2$ (no ligand-exchange), only deprotonation of Hind ligands occurred at $\text{pH} > 5$ in 50% ethanol/water solution. For $[4]\text{Cl}_2$ protonation of OH^- at more acidic conditions is envisaged, and the involvement of Hind ligands into a pH dependent process, namely, deprotonation, without liberation of indazole proligands, as evidenced by ^1H NMR and spectrofluorimetric measurements. These investigations along with the ability of the compounds to release NO in solution upon excitation encouraged us to further investigate their biological potential.

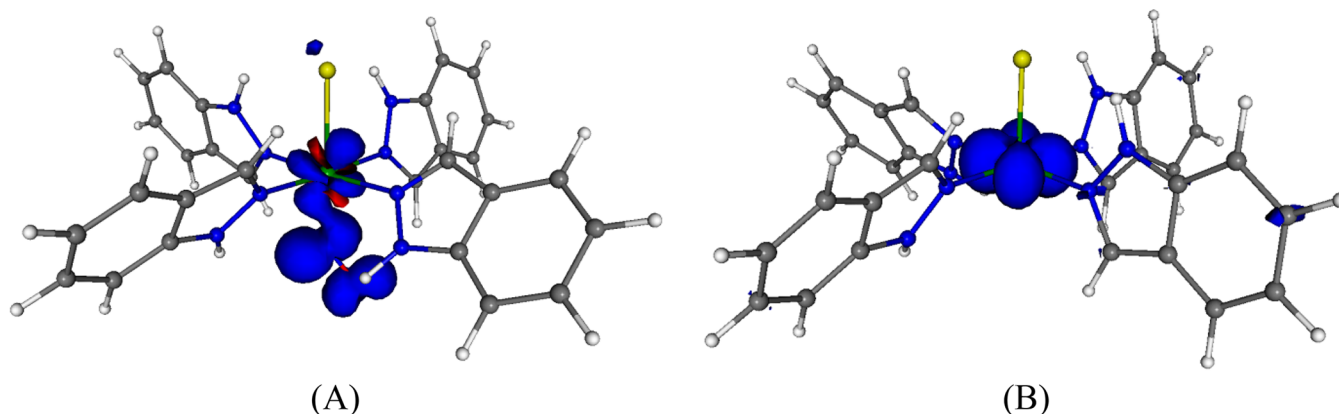


Figure 7. B3LYP/SVP(SDD) spin densities of $[3]^{+(1)}$ lower in energy (A) and of $[3']^{2+}$ (B), isovalue ± 0.005 .

Antiproliferative Activity in Cancer Cell Lines. The antiproliferative effects of complexes $[1]$, $[3]Cl_2$, and $[4]Cl_2$ in comparison with cisplatin were determined by colorimetric cell viability assay (MTT assay) against a panel of cancer cell lines. The IC_{50} values are quoted in Table 2 and the concentration-effect curves are shown in Figure S32.

Table 2. Cytotoxicities of Complexes $[1]$, $[3]Cl_2$, $[4]Cl_2$, Cisplatin, and KP1019

compound	IC_{50}^a [μM]			
	HCT116	A2780	HEK293	SF
$[1]$	1.1 ± 0.2	0.25 ± 0.04	0.53 ± 0.03	2.1
$[3]Cl_2$	0.65 ± 0.19	0.33 ± 0.02	0.61 ± 0.10	1.8
$[4]Cl_2$	1.1 ± 0.5	0.23 ± 0.03	1.2 ± 0.2	5.2
cisplatin	0.86 ± 0.16	0.60 ± 0.05	3.8 ± 1.3	6.3
KP1019	31 ± 8	16 ± 2	29 ± 5	1.8

^a50% inhibitory concentrations in human colorectal carcinoma cells HCT116, human ovarian carcinoma cell lines A2780 and non-cancerous HEK293 cells, determined by MTT assay. Values are means plus/minus standard deviations obtained from at least three independent experiments with exposure time of 72 h. Selectivity Factor (SF) is determined as $IC_{50}(HEK293)/IC_{50}(A2780)$.

In general, all tested complexes demonstrated high antiproliferative activity in the submicromolar or low micromolar concentration range in cancerous cell lines and no significant differences between the cytotoxicity of complexes $[1]$, $[3]Cl_2$, and $[4]Cl_2$ were observed. The antiproliferative activity of complex $[1]$ in CH1 and SW480 after 96 h exposure has been previously reported¹⁶ and the IC_{50} values were comparable to those obtained in the present work. Monoindazole ruthenium-nitrosyl complexes, which bear some structural resemblance to complexes $[3]Cl_2$ and $[4]Cl_2$, were tested in CH1/PA-1, SW480, and A549 cells after 96 h exposure and also demonstrated antiproliferative activity in a micromolar concentration range.¹⁵ Importantly, the complexes displayed higher activity than KP1019 and cisplatin in all tested cell lines. Next, the selectivity of $[1]$, $[3]Cl_2$, and $[4]Cl_2$ was tested toward cancer cells vs healthy cells. On the basis of our results, all complexes showed some degree of selectivity toward A2780 cells over embryonic kidney cells HEK293, but lower than that of cisplatin. Surprised by these results, the selectivity factor for KP1019 was also determined, which is known to demonstrate uniquely low toxicity in cancer patients in comparison with highly toxic cisplatin.^{75–77} As can be seen from Table 2, the selectivity of

KP1019 toward cancer cells over healthy cells was lower than that of cisplatin. Therefore, even though HEK293 cells are very commonly used for the assessment of toxicity in noncancerous cell lines, the results should be treated with caution.

Role of NO Ligand in the Anticancer Activity. To determine the effects of NO ligand on the cytotoxicity of Ru nitrosyl complexes, we assessed the antiproliferative activity of complexes $[3]Cl_2$ and $[4]Cl_2$ in the presence of cPTIO as NO[•] scavenger (vide supra).⁷¹ cPTIO is also used to determine if NO[•] plays a role in various biological processes, such as DNA fragmentation,⁷⁸ platelet aggregation,⁷⁹ endotoxin shock,⁷⁸ and cytotoxic effects.⁸⁰ To choose the appropriate concentration of cPTIO for subsequent experiments with Ru–NO complexes, its cytotoxicity was determined by MTT assay in A2780 cells with exposure time of 72 h. Further, complexes $[3]Cl_2$ and $[4]Cl_2$ were coincubated with 2.5 and 10 μM of carboxy-PTIO for 72 h and their cytotoxicity was determined by MTT assay. On the basis of the results of MTT (Figure S32), the cytotoxicity of complexes $[3]Cl_2$ and $[4]Cl_2$ was not inhibited in the presence of cPTIO. Subsequently, complexes $[3]Cl_2$ and $[4]Cl_2$ were irradiated by blue LED light (max emission at around 470 nm) for 5 min and their cytotoxicity was compared to the activity of the same complexes when not irradiated. To mimic the conditions of NO photorelease experiments, $[3]Cl_2$ and $[4]Cl_2$ were dissolved in MeCN, and it was ensured that the cell viability was not affected by the presence of organic solvent. As can be seen in Figure S33, the cytotoxicity of $[3]Cl_2$ and $[4]Cl_2$ upon irradiation increased by ~30%. Thereafter, the activity of the complexes upon irradiation was evaluated in the presence of carboxy-PTIO and no changes in cytotoxicity were detected. Thus, based on the results of the MTT experiments, the role of NO ligand in the cytotoxicity of $[3]Cl_2$ and $[4]Cl_2$ was not confirmed.

p53 Dependence. p53 protein plays the key role in determining cell fate, and, in the case of excessive damage, p53 triggers cell death.^{81,82} However, most cancer cells are able to cause p53 mutations leading to the loss of its protective function and resistance to common chemotherapies. For example, the chemoresistance of some cancer cell lines toward oxaliplatin or doxorubicin was related to mutated p53-encoding genes of deficient p53 levels, which are less effective in inducing apoptosis even during excessive DNA damage.⁸³ Hence, the very design of the traditional anticancer treatment is often defeated by cancer cells properties and the identification of p53-independent compounds is highly desirable. In order to assess the role of p53 protein in the antiproliferative activity of ruthenium complexes, the cytotoxicities of compounds in

Table 3. Cytotoxicity of [1], [3]Cl₂, [4]Cl₂, Cisplatin, and Oxaliplatin

compound	IC ₅₀ ^a [μM]				
	HCT116 wt	HCT116 wt + pifithrin α	ratio IC ₅₀ with/without inhibition	HCT116 p53 ^{-/-}	ratio IC ₅₀ p53 ^{-/-} /wt
[1]	1.1 ± 0.2	1.1 ± 0.3	1.0	1.5 ± 0.2	1.5
[3]Cl ₂	0.65 ± 0.19	0.52 ± 0.11	0.8	0.66 ± 0.15	1.0
[4]Cl ₂	1.1 ± 0.5	1.4 ± 0.3	1.3	0.9 ± 0.2	0.8
cisplatin ^b	5.2 ± 1.3	9.0 ± 1.2	1.7	12 ± 2	2.3
oxaliplatin ^b	0.86 ± 0.16	1.9 ± 0.4	2.2	4.1 ± 0.9	4.8

^a50% inhibitory concentrations in colorectal carcinoma cells HCT116wt (wild type) and HCT116 p53^{-/-} determined by MTT assay. Values are means plus/minus standard deviations obtained from at least three independent experiments with exposure time of 72 h. ^bThe results were compared to cisplatin and oxaliplatin, which are known to be p53-dependent.

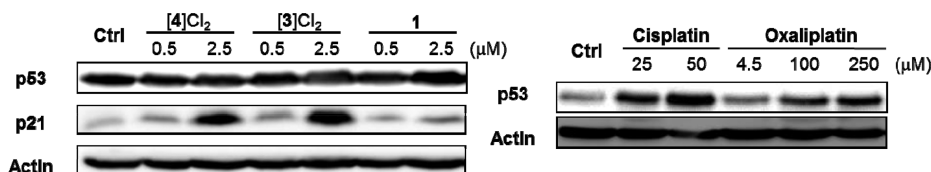


Figure 8. Western blot analysis of p53 and p21 proteins. A2780 cells were collected after incubation with compounds of interest at indicated concentrations for 24 h. Total lysates were isolated and examined by Western blot. Actin was used as a loading control.

HCT116 colorectal cancer cell line and its resistant analogue HCT116 p53^{-/-}, where p53 gene was knocked out, were determined (Table 3).

As expected, both cisplatin and oxaliplatin demonstrated strong dependence on p53, and their activity in p53-null cell line was 2–5 times lower than in the parental HCT116 cell line. On the contrary, all ruthenium complexes were equally potent in both HCT116 cell lines, indicating their independence from p53. To further confirm the observed effects, the cytotoxicity of compounds was tested in the presence of p53 inhibitor, pifithrin α. Pifithrin α is known to inhibit both p53-mediated apoptosis and p53-mediated gene transcription such as cyclin G1 and p21/waf1 expression.^{84,85} In agreement with the results of MTT assay in isogenic HCT116 cell lines, the activity of cisplatin and oxaliplatin was suppressed by p53 inhibition albeit to a lesser extent than by p53 gene knock out, whereas ruthenium complexes were not affected by pifithrin α. Additionally, the effects of metal complexes on p53 protein expression were evaluated by Western Blot in A2780 cells (Figure 8). As expected, cisplatin and oxaliplatin caused significant overexpression of p53, whereas ruthenium complexes had no effect on p53 expression. Therefore, it can be concluded that p53-independent mode of action of ruthenium complexes is retained in various cell lines. It should be noted that other ruthenium compounds were also shown to be independent from p53 cellular status.^{74,86,87}

When the cell's DNA is damaged, various cell mechanisms are activated in order to repair the damage or trigger the cell to systematically kill itself. As mentioned previously, the key role in determining the cell fate is played by the p53 protein; however, the decision whether cells live or die is also dependent on p53 downstream effector p21. The cyclin-dependent kinase (cdk) inhibitor p21 plays an important role in genomic stability, apoptosis, senescence and DNA repair.⁸⁸ It is also known that p21 can be activated in a p53-dependent and independent manner. To understand if the observed antiproliferative effects of [1], [3]Cl₂, and [4]Cl₂ were related to the induction of overexpression of p21, we performed Western Blot analysis of p21 marker. Incubation of cells with complexes of interest at various concentrations for 24 h caused a dose-dependent increase in the magnitude of induction of p21 protein.

Therefore, the regulation of p21 might be the reason for antiproliferative action of novel ruthenium complexes.

CONCLUSIONS

By reaction of *trans*-[Ru(NO)₂(Hind)₄] ([2]) with 12 and 3 M hydrochloric acid in methanol new complexes *trans*-[RuCl(Hind)₄(NO)]Cl₂·H₂O ([3]Cl₂·H₂O) and *trans*-[RuOH(Hind)₄(NO)]Cl₂·H₂O ([4]Cl₂·H₂O), respectively, were synthesized in good yields. Deprotonation at pH 6–9 led to isolation of two other compounds, namely [RuCl(ind)₂(Hind)₂(NO)] ([5]) and [RuOH(ind)₂(Hind)₂(NO)] ([6]), respectively. These results might also shed light on the nature of the green species generated from KP1019 at physiological pH, which posed a problem upon intravenous administration in cancer patients.

Upon light irradiation, solid [3]Cl₂·H₂O did not exhibit significant metastable isomer population, but considerable NO release at room temperature. In contrast, for [4]Cl₂·H₂O and [5] we observed both phenomena: NO release at room temperature and reversible linkage isomerism at low temperature.

[3]Cl₂ was found to be redox active in MeCN, undergoing one reversible one-electron reduction confirmed by coulometric measurements at *E*_{1/2} = −0.11 V followed by a second quasireversible one-electron reduction at *E*_{1/2} = −0.80 V vs Fc⁺/Fc. Both reductions are predominantly NO centered as was also confirmed by IR-spectroelectrochemistry, X- and Q-band EPR spectroscopy and DFT calculations. In particular, the first reduction step is accompanied by a decrease of NO stretching band at 1920 cm^{−1} and appearance and increase of a new NO band at 1630 cm^{−1}. This drop of *ν*_{NO} is due to bending of linear Ru^{II}–NO⁺ moiety into Ru^{II}–NO[•] (calcd Ru–N–O 141.29°).

The photoinduced release of NO upon irradiation of [3]Cl₂ and [4]Cl₂ in solution with 400 nm LED has been confirmed by EPR spectroscopy by monitoring the specific reaction of NO[•] with nitronyl nitroxide (NN[•]) to give iminonitroxide (IN[•]). The quantification of the NO release performed by analysis of the UV–vis spectra indicated 3–6% based on calculated quantum yields at 405 nm (Table 1). These numbers are quite reasonable given the low excitation coefficients at 405 nm (~500 M^{−1}cm^{−1}) and are in accordance with femtosecond pump probe spectroscopy

data, which indicated almost cyclic liberation and rebinding of NO to ruthenium upon excitation. To increase the biological utility of this type of compounds we are going to explore one of the strategies proposed previously for photosensitizing the Ru–NO bond to visible light,⁵⁸ namely by modifying the azole heterocycles in order to increase their electron donating ability. In particular, replacement of 1*H*-indazole ligands by 3,5-dimethyl-1*H*-pyrazole is envisaged.

The complexes [3]Cl₂·H₂O and [4]Cl₂·H₂O showed high antiproliferative activity, which is p53-independent. However, the compounds caused overexpression of p21 and the regulation of its status might be the reason for activity at the molecular level. Release of NO, if any, does not contribute significantly to antiproliferative activity.

■ ASSOCIATED CONTENT

● Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.inorgchem.8b01341.

ORTEP view of [2], IR spectra measured under light irradiation, UV–vis spectra, ¹H NMR spectra, and fluorescence emission spectra of [3]Cl₂ and [4]Cl₂ under different conditions, cyclic voltammetry of new complexes, EPR spectra, UV–vis spectra of [3]²⁺ and [3]⁺, UV–vis spectra of [4]²⁺ detected simultaneously upon reduction, kinetic data from femtosecond transient absorption spectra of [3]Cl₂ and [4]Cl₂, UV–vis spectra of complexes detected in situ during photolysis, TDDFT calculated UV–vis spectra, other results of DFT calculations, concentration–effect curves from MTT assays and IC₅₀ values without and with illumination, crystal data and details of data collection (PDF)

Accession Codes

CCDC 1835289–1835292 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Notes

The authors declare no competing financial interest.

Dedication

Dedicated to Prof. Dr. Manfred T. Reetz on the occasion of his 75th birthday.

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