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Tuning the Electrical and Optical Properties of Dinuclear Ruthenium Complexes for Near Infrared Optical Sensing

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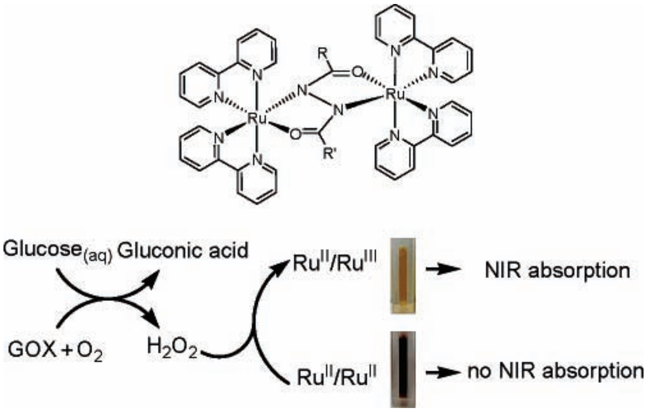
ABSTRACT



Redox-active dinuclear ruthenium complexes with various 1,2-dicarbonylhydrazido (DCH) ligands are designed and prepared to have intense absorption in the near-infrared region for potential optical sensing in aqueous media, as demonstrated for sensing hydrogen peroxide in this study.

Research on new sensors for detecting biologically important organic substances continues to advance, in part because of a need for better environmental monitoring and a vast potential in clinical applications and personal medical devices. Such a sensor mainly utilizes the electrochemical or optical properties of redox-active materials. One is an amperometric sensor, in which ruthenium complexes are used as electron mediators,[1] and is complicated to design and fabricate because of the electric and magnetic interferences. Another is an optical sensor,[2] which is simple in design, easy to operate, and free from electric and magnetic interference. Ruthenium complexes used so far in this type of sensor are only active, either absorbing or fluorescent, in the visible region (e.g., 400−750 nm). However, in this spectral window, endogenous chromophores either absorb light or

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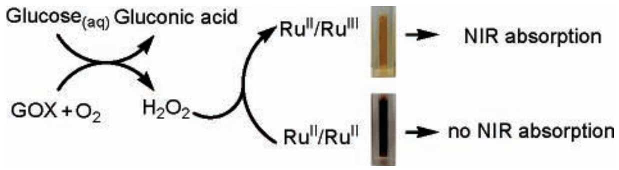
autofluoresce.[3] Thus, near-infrared (NIR) chromophores are desirable in biomedical studies because tissue autofluorescence and light absorption by tissue and water are low between 900 and 1300 nm.[4] Accordingly, we intend to demonstrate the use of redox-active, NIR-absorbing ruthenium complexes for sensing chemically and biologically important substances (e.g., hydrogen peroxide or glucose) in water or under physiological conditions.

It is known that dinuclear ruthenium complexes display intense and broad absorption in the NIR spectral region when in the mixed-valence state (Ru^{II}/Ru^{III}) because of intervalence charge-transfer transitions between the two metal nuclei or metal to metal charge transfer (MMCT). Oxidation to the mixed-valence state can be done by electrochemical means or with various oxidizing agents including hydrogen peroxide (H_2O_2). Therefore, in this study, we will demonstrate NIR optical sensing in water with H_2O_2. Because H_2O_2 is also an intermediate product from enzymatic glucose oxidation, it is conceivable that glucose can be detected and quantified as well by a NIR optical means under physiological conditions (Scheme 1). The sensing principle is simple; glucose is oxidized by glucose oxidase (GOX) and produces H_2O_2 as a byproduct, which then oxidizes the ruthenium complex to its Ru^{II}/Ru^{III} state, and NIR absorbance of the complex is monitored. Furthermore, the complex changes color from purple to yellow, although this visual effect is slow to appear to the naked eye.

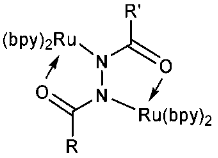
Scheme 1. Detection of Glucose on the Basis of the Redox Reaction of the Dinuclear Ruthenium Complex with Hydrogen Peroxide[a]



[a] Cuvettes shown are acetonitrile solutions of the complex in their respective oxidation states.

The basic requirements for the materials used in such a NIR optical sensor include: (1) intense absorption upon action with the analyte (e.g., H_2O_2) within the 900−1300 nm region, (2) adequate redox potentials, and (3) an ability to form transparent thin films on an electrode. In this paper, four ruthenium complexes with the 1,2-dicarbonylhydrazido (DCH) ligand are presented and their band-gap energies are systematically tuned by varying the electron-withdrawing or electron-donating ability of the substituents on the DCH ligand. Among them, one was selected and used for sensing H_2O_2 in aqueous solution and as a thin film.

As shown in Figure 1, four DCH−Ru complexes are designed to have different substituting R and R′ groups that can affect the electronic states of the coordinating sites (N and O atoms), which in turn influences the optical and electrochemical properties of the complexes. All four DCH ligands were synthesized by reaction of an acyl chloride, chloroformate, or isocyanate with the corresponding hydrazide or hydrazine by a similar reported method.[5] The ruthenium complexes were prepared by exchange with Ru(bpy)$_2$Cl$_2$ as previously reported.[6] These complexes were fully characterized by spectroscopic means (see Supporting Information).



DCH-Ru	R	R'
1	NHPr	NHPr
2	NHPr	OEt
3	OEt	OEt
4	Ph	Ph

Figure 1. Structure of dinuclear DCH−Ru complexes.

To correlate the substituent effect with the spectroscopic and electrochemical data, the Hammett parameters as a direct measure of electron-donor potentials were used.[7] The electrochemical and optical data for the DCH−Ru complexes are given in Table 1, and the cyclic voltammogram of complex **1** is shown in Figure 2. There is a linear dependence of electrochemical properties of DCH−Ru complexes on the Hammett parameters. As the donor strength of the substituent increases, there is a shift of both the first ($^1E_{1/2}$) and second oxidation potentials ($^2E_{1/2}$) to lower values, which can be

Table 1. Electrochemical Data, Hammett Substituent Parameters, and MMCT Band Energies for DCH−Ru Complexes

complex	$^1E_{1/2}{}^a$	$^2E_{1/2}{}^a$	ΔE^b	σ^*	$\lambda_{max}{}^c$	MMCT^d
1	50	580	530	−1.10	1150	0.8352
2	160	700	540	−0.79	1270	0.7133
3	240	800	560	−0.48	1410	0.6889
4	500	1100	600	−0.02	1600	0.6448

[a] Cyclic voltammetry performed at a 100 mV/s scan rate in acetonitrile/0.1 M tetraethylammonium perchlorate. Potentials E in millivolts vs NHE. [b] $\Delta E = {}^2E_{1/2} - {}^1E_{1/2}$ in millivolts. [c] For the Ru^{II}/Ru^{III} state of complexes in nanometers. [d] MMCT band energies in electronvolts.

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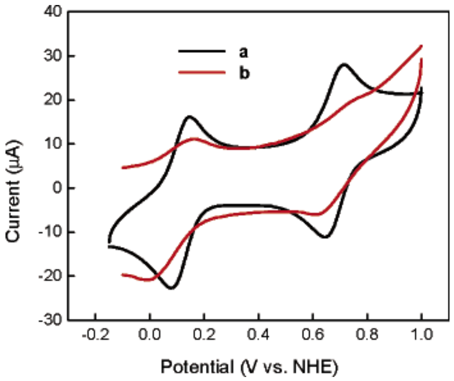

Figure 2. Cyclic voltammogram of complex **1** in acetonitrile/0.1 M tetraethylammonium perchlorate (trace a) and a film containing complex **1** on indium tin oxide coated glass (trace b) at a scan rate of 100 mV s^{-1}.

attributed to the improvement of the stability of the ruthenium d-orbitals when the ligand has poor σ-donor properties.[6] Compared with complex **4**, $^{1}E_{1/2}$ and $^{2}E_{1/2}$ of complex **1** with the strong electron-donating NHPr group decreased by 450 and 520 mV, respectively, and **1** has a $^{1}E_{1/2}$ as low as 50 mV, which implies ease in oxidation by H_2O_2 only to its NIR-absorbing Ru^{II}/Ru^{III} state rather than to the NIR-inactive Ru^{III}/Ru^{III} state, and thus a better sensitivity in sensing. The substituents also affect the optical properties of these complexes significantly. Figure 3 shows intense NIR absorption bands of four DCH−Ru complexes in their Ru^{II}/Ru^{III} states. The MMCT band is blue-shifted upon increasing the donor strength of the substituents. With a strong electron-donating NHPr group, complex **1** has a maximum MMCT absorption at 1150 nm, which falls in an ideal biowindow for sensing in an aqueous medium. Because H_2O_2 should readily oxidize complex **1** from the Ru^{II}/Ru^{II} state to the Ru^{II}/Ru^{III} state, by monitoring the change in absorbance in the NIR region or at 1150 nm, one can detect and quantify H_2O_2 directly or glucose indirectly.

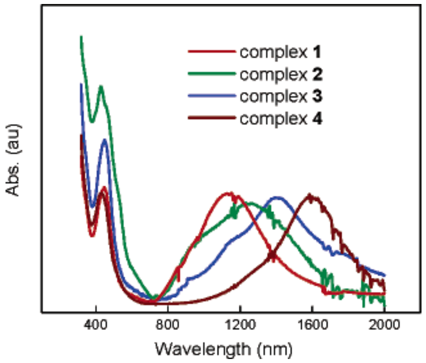

Figure 3. Absorption spectra of complexes in the Ru^{II}/Ru^{III} state in acetonitrile/0.1 M tetraethylammonium perchlorate obtained with an optically transparent thin-layer electrochemical cell.

A feasibility test was first carried out in solution using H_2O_2 directly. To complex **1** in acetonitrile (ACN) (1×10^{-4} M) in a cuvette was introduced H_2O_2 with the desired concentration up to 10 mM. The absorbance was monitored at 1150 nm and recorded at different times up to 10 min (Figure 4). For the glucose detection, because there is a 1:1 molar equivalent correlation between glucose and H_2O_2 in the enzymatic oxidation of glucose,[8] we can regard the H_2O_2 concentration as the same as that of glucose.

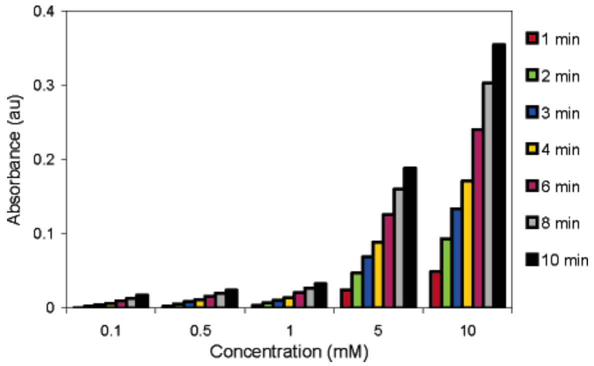

Figure 4. Absorbance (1150 nm) of **1** (1×10^{-4} M in 1:1 acetonitrile/Tris buffer) in the Ru^{II}/Ru^{II} state by oxidation with different concentrations of H_2O_2 recorded at different times.

Figure 4 shows clearly that complex **1** is sensitive enough to detect H_2O_2 at concentrations as low as 0.1 mM, which is much lower than the normal glucose levels in blood (typically in a range of 6−11 mM). There is a linear response of absorbance with increasing peroxide concentration after 2 and 7 min of reaction time. The response is also linear at other times, even after 30 s. Our spectrometer is not equipped with a stirring system; therefore, the rate of oxidation depends on diffusion. These conditions were not optimized, and addition of a stirring mechanism or flow cell should increase response time. Even in unoptimized conditions, **1** can be used to monitor the presence of H_2O_2.

To demonstrate the usefulness of complex **1** further as a sensoring material in a sensor device, a similar experiment was done using a cross-linked polyurethane film doped with **1**.[9] A thin film (0.58 μm) coated on a slide of indium tin oxide (ITO) glass, to act as an electrode, exhibited the two broad redox couples at potentials similar to those of complex **1** in solution (Figure 2). The film-coated ITO plate was placed in a Tris buffer solution (pH = 7.4) (2 mL), which had the same pH as human blood, in a cuvette, and 50 μL of H_2O_2 (35 wt % solution in water) was introduced to

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(9) Complex **1** (7.4 wt %), trimethylolpropane, carbamate with xylylene diisocyanate (available from Aldrich Chemicals Inc., catalog number 408778), trimethylolpropane (available from Aldrich Chemicals Inc., catalog number 239747), and tetraethylammonium hexafluorophosphate (9.2 wt %) were mixed in acetonitrile (1 mL) and sonicated for 1 h and then spin coated on an ITO plate (0.8 × 2.5 cm). After thermal curing at 50 °C under vacuum for 1 h, a film with a thickness of 0.58 μm was formed.

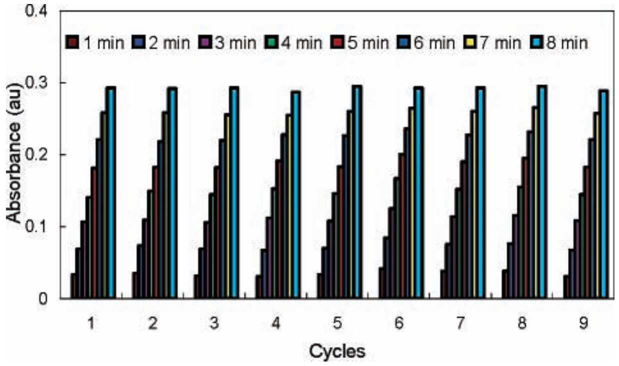

Figure 5. Normalized absorbance (1150 nm), recorded in real time, of a film containing **1** in the Ru^{II}/Ru^{II} state oxidized with H_2O_2 (0.3 M) in Tris buffer solution. The film was reduced electrochemically (−0.5 V). The cycle was repeated nine times.

oxidize complex **1** doped in the film to its Ru^{II}/Ru^{III} state, while monitoring the increase in absorbance at 1150 nm simultaneously. To prove the reusability of the device, we used a much higher concentration of H_2O_2 (0.3 M) in this experiment and did not wait for the absorbance to peak. After 8 min, a bias (−500 mV) was applied to the ITO plate after placing it in a tetraethylammonium perchlorate/ acetonitrile solution (0.1 M) to reduce the complex to its Ru^{II}/Ru^{II} state. These cycling experiments were repeated nine times with excellent reproducibility (Figure 5). The slight variation of the absorbance change most probably arose from the unoptimized test technique. The cross-linked film tightly adhered to the ITO electrode and was stable to prolonged soaking in acetonitrile and Tris buffer solution. There was no noticeable damage to the film on the ITO plate after many cycles of treatment of H_2O_2 and electrical reduction, demonstrating a potentially robust sensor device.

In conclusion, we have demonstrated the working principle of a new NIR optical sensor, based on the NIR-absorbing ruthenium complexes, for chemically and biologically important substances in aqueous media under physiological conditions.

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Supporting Information Available: Synthesis and characterization (including NMR and ESI-MS spectra) of DCH−Ru ligands and complexes **1**−**4**. This material is available free of charge via the Internet at http://pubs.acs.org.

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