The first enantioselective total synthesis of (−)-asperdiol has been accomplished in 15 steps from epoxygeranyl bromide. It is noteworthy that the trisubstituted epoxide was robust enough to survive the conditions for the nucleophilic displacement reactions which were used to form the C-12, C-13 and the C-3, C-4 bonds. The epoxide also survived the reductive desulfonylation and the intramolecular Horner–Emmons reaction. Our assumption that the cyclization to the 14-membered ring in the desepoxy series would be more straightfoward than in the epoxy series, which provided the impetus for the synthesis of (+)-desepoxyasperdiol, was shown to be false. A number of the optically pure fragments which were used for the total synthesis of **1**, particularly **4** and **7**, will be useful for the synthesis of other cembranoids.

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Supplementary Material Available: Spectroscopic data for compounds **4**, **5**, **7**, **9**, **12**, and **13** and experimental procedure for the intramolecular Horner–Emmons reaction (2 pages). Ordering information is given on any current masthead page.

(18) ^{1}H NMR ($CDCl_3$, 300 MHz) δ 5.43 (d, J = 7.8 Hz, 1 H), 5.11 (t, J = 6.8 Hz, 1 H), 4.94 (br s, 1 H), 4.75 (br s, 1 H), 4.47 (dd, J = 7.7, 5.8 Hz, 1 H), 4.05 (br s, 2 H), 2.66 (dd, J = 5.9, 4.4 Hz, 1 H), 2.45–1.2 (m, 13 H), 1.74 (br s, 3 H), 1.59 (br s, 3 H), 1.17 (s, 3 H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ 145.78, 139.55, 135.48, 128.76, 124.72, 113.77, 66.40, 65.87, 64.77, 60.25, 50.66, 37.55, 36.16, 28.11, 26.67, 25.94, 24.07, 22.45, 16.67, 15.86. IR (CH_3Cl_2) 3593, 3063, 2924, 1641, 1603, 1452, 1385 cm^{-1}. Mass spectrum, m/e 320 (M^+, weak) 302 ($M^+ - H_2O$), 177, 135, 108, 95, 81. Exact mass calcd for $C_{20}H_{32}O_3$ 320.2351, found 320.2357. $[\alpha]^{23}_D$ −79° (c 0.000 55, $CHCl_3$).

DNA-Mediated Photoelectron Transfer Reactions

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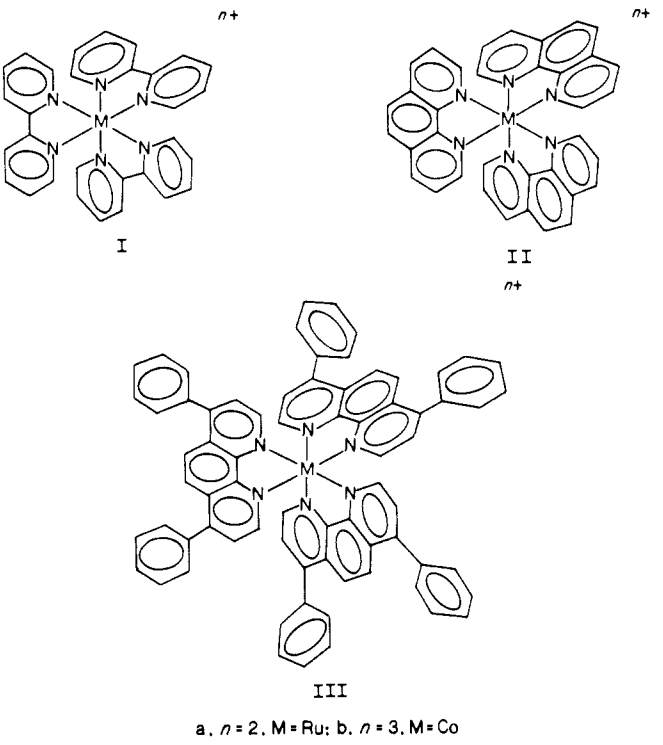
Various aspects of electron transfer involving metal centers have received intense scrutiny during the past two decades. Marcus theory[1] has provided an important theoretical framework to drive experiments.[2] Thermal and photochemical systems[3] have been developed to explore the validity of the theory and the relevance of electron transfer to biological systems.[4] For example, the efficiency of electron transfer was suggested to be attenuated by proteins, membranes, and other biological structures.[5] We report here an investigation of several donor–acceptor systems which undergo photoinduced electron transfer to examine the role of the DNA double helix in mediating electron transfer and to probe the various aspects of the DNA environment, such as local electrostatic fields, hydrophobic patches, lipophilic interactions and the dimensionality of space surrounding the double helix. A reduced dimensionality in diffusion of DNA-binding proteins was suggested as a major factor contributing to their ability to rapidly locate sequences along the DNA.[6] Another consideration of interest is whether the π-frame of the nucleic acid bases would assist the transfer of an electron across the strand in a manner similar to conductors.

The donors and acceptors employed are the polypyridyl complexes of Ru(II) and Co(III) as shown in Chart I. Several structural features prompted us to use these molecular probes, including their chirality. Binding of these complexes to DNA has been extensively studied and shows striking enantiomeric selec-

Chart I



a, n = 2, M = Ru; b, n = 3, M = Co

Table I. Electron-Transfer Rates for Various Donor–Acceptor Pairs in the Presence of DNA[a,b]

donor	acceptor	[DNA/Ru]	$K_{SV} \times 10^{-4}$, M^{-1}
$Ru(phen)_3^{2+}$	$Co(phen)_3^{3+}$	14	4.9
$Ru(phen)_3^{2+}$	$Co(phen)_3^{3+}$	18	6.0
$Ru(phen)_3^{2+}$	$Co(phen)_3^{3+}$	27	7.3
$Ru(phen)_3^{2+}$	$Co(phen)_3^{3+}$	55	8.6
$Ru(phen)_3^{2+}$	$Co(phen)_3^{3+}$	110	9.6
$Ru(bpy)_3^{2+}$	$Co(bpy)_3^{3+}$	8[c]	0.19
$Ru(bpy)_3^{2+}$	$Co(phen)_3^{3+}$	8[c]	0.35
$Ru(bpy)_3^{2+}$	$Co(DIP)_3^{3+}$	8[c]	0.83

[a] 20 mM NaCl, 110 μM calf thymus DNA, 5 mM Tris buffer, pH 7.2, typical errors are ±10%. [b] Suitable filters were placed on the excitation and emission sides to minimize any scattered and shorter wavelength light. Samples were excited at 450 nm and monitored at 600 nm. [c] These runs were made with 2 μM ruthenium, 80 μM calf thymus DNA, 50 mM NaCl, 5 mM Tris buffer, pH 7.2.

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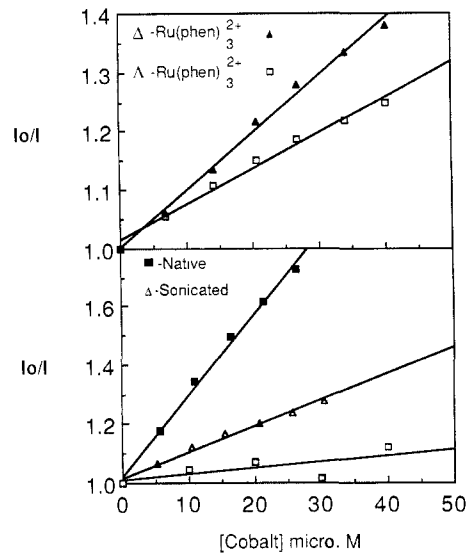

Figure 1. (Top) Quenching of Δ-$Ru(phen)_3^{2+}$ (▲) and Λ-$Ru(phen)_3^{2+}$ (□) (2 μM) by $Co(bpy)_3^{3+}$, in the presence of B-form poly(dG-dC) (90 μM DNA phosphate, 50 mM NaCl, 5 mM Tris buffer pH 7.2). (Bottom) Quenching of $Ru(phen)_3^{2+}$ (2 μM) by $Co(bpy)_3^{3+}$ in the presence of native (■) and sonicated (Δ) calf thymus DNA (80 μM DNA phosphate, 50 mM NaCl, 5 mM Tris buffer, pH 7.2). The squares represent a control experiment in the absence of DNA.

tivities.[7] Furthermore, the excited states of the ruthenium complexes are quenched by the cobalt complexes by electron transfer at significant rates.[8] In addition the excited states of ruthenium complexes are long lived enough for the quencher molecules to diffuse over long distances.

In homogeneous aqueous solution (5 mM Tris buffer, pH 7.2 and 50 mM NaCl), the electron transfer rates are close to $\sim 1.5 \times 10^9$ M^{-1} s^{-1} for most of the donor–acceptor pairs studied, evaluated by laser flash photolysis experiments. These rates are enhanced appreciably by the addition of calf thymus DNA[9] (110 μM nucleotides) as measured from Stern–Volmer quenching of donor emission by the Co(III) quenchers. Some of the quenching data are summarized in Table I. The key observations are (i) the Stern–Volmer quenching slopes for $Ru(phen)_3^{2+}$ as donor and $Co(phen)_3^{3+}$ as acceptor increase with increased DNA phosphate to ruthenium ratio and are curved downward and reach a plateau at higher quencher concentration; (ii) the quenching slopes for Ia as donor and various Co(III) complexes as quenchers in the presence of calf thymus DNA are in the order IIIb >> IIb > Ib, a profile which follows the expected binding constants for these complexes;[10] (iii) the Δ isomer of $Ru(phen)_3^{2+}$ is quenched more efficiently than the Λ isomer in the presence of B-form poly-(dG-dC) (Figure 1), consistent with the observed enantiomeric selectivity in binding;[11] and importantly (iv) the quenching slopes are larger for native calf thymus DNA than for sonicated calf thymus DNA[12] (Figure 1).

The increase in the rate of electron transfer upon binding to DNA, the correlation of this rate with binding constants, and the enantiomeric selectivity need first to be explained. These metal complexes bind to DNA by intercalation, surface binding, and electrostatic interactions.[13] An increase in Stern–Volmer quenching slope with increasing DNA/metal is seen because with higher DNA concentration a higher percent of ruthenium is in the bound form ($K(0) = 6 \times 10^3$ M^{-1}). At higher concentrations of quencher, especially for $Co(phen)_3^{3+}$, the plots are nonlinear and reach a plateau region, indicating that at least two components are involved. At low cobalt concentrations, the bound ruthenium is quenched very efficiently and at higher concentrations inefficient quenching of the free form is observed. The donor and acceptor ions are therefore being held at the DNA surface. The local concentrations of these species will scale as their binding constants. The observed quenching slopes with Ia as donor are in the order IIIb >> IIb > Ib, an order consistent with their binding affinities. With an appropriate donor, then, the relative binding abilities of the acceptors can be estimated from the initial quenching slopes.[14] The importance of local concentration to quenching rate is strikingly demonstrated in Figure 1, where the better binding Δ isomer is quenched more efficiently than the Λ isomer along B-form poly(dG-dC).[15] On this basis, *stereoselective electron transfer can be achieved in the presence of DNA.*

The local concentrations alone, however, cannot account for the enhancements in quenching slopes, since a significant increase in quenching is observed in comparing experiments conducted in the presence of long vs. short DNA strands, despite the fact that total nucleotide concentrations are the same. Since the excited states involved are fairly long lived (~500–1000 ns), the quencher molecules have sufficient time to diffuse over long distances (1500–3000 Å).[16] On longer pieces of DNA, long-range diffusion lengths are limited by the strand lengths; jumps from strand to strand are expected to be much slower than motion along the same strand. We suggest that such a reduced dimensionality is at least partially responsible for the enhanced quenching rates, since the observed rates are at least 2 orders of magnitude faster than in homogeneous phase. On long DNA strands, due to the long range of movement and decreased dimensionality, the electron-transfer rates are enhanced tremendously. A conservative estimate, based on single photon counting experiments, for the rate of electron transfer between IIa and IIb in presence of DNA is $\sim 2 \times 10^{11}$ M^{-1} s^{-1}.[17] *The DNA essentially catalyzes the electron transfer.* These results open the exciting possibility of investigating diffusion

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(9) Using single photon counting technique the nonexponential decay of Ru(II) excited states in the presence of DNA was followed at various quencher concentrations. The lifetimes decrease and the rate constants thus obtained are in close agreement with the steady-state experiments.

(10) The hydrophobic ligands favor binding to DNA and the hydrophobicity increases in the order I < II << III. Thus, the binding constants are expected to follow the order III >> II > I.

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(12) The native DNA was sonicated and the fraction isolated had a distribution with an average length of 290 bp compared to the native form distributed about a length of about 11 kb. Identical concentrations of nucleotides were employed in these experiments.

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(14) If both the redox partners have high binding affinity the DNA precipitates from the solution. In these experiments it is convenient to keep one of the partners to be Ia or Ib to monitor the binding abilities of the other redox partner.

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(17) The Stern–Volmer slopes in the presence of DNA for the phenanthroline complexes are nearly 2 orders of magnitude higher than in bulk aqueous phase. Preliminary experiments with single photon counting show that one of the components is quenched at $\sim 2 \times 10^{11}$ M^{-1} s^{-1}, assuming bulk concentrations. Since these rates depend upon DNA concentration, it is an approximation to consider them as bimolecular.

in a reduced dimensional space around the double helix. It is notable here that, based on the ΔG values for these reactions, the calculated rates from Marcus theory indicate that the electron transfer between these pairs should be diffusion-controlled.[9] An additional explanation that may account at least in part for our findings lies in the involvement of the π-framework of the nucleotides in mediating long-range electron transfer through the extended range of donor-acceptor electronic coupling. Some combination of long-range electron transfer and diffusion is possible.

In conclusion, binding to DNA assists the electron transfer between the metal-centered donor-acceptor pairs. The increases in rate in the presence of DNA illustrate that reactions at macromolecular surfaces may be faster than those in the bulk homogeneous phase. These systems can provide models for the diffusion of molecules bound on biological macromolecular surfaces, for protein diffusion along DNA helices, and in considering effects of medium, orientation and diffusion on electron transfer on macromolecular surfaces. Detailed experiments are in progress to sort out the different mechanisms possible and also to determine the effective diffusion rates small molecules experience in the vicinity of DNA.

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Catecholate Complexes of High Oxidation State Metal Ions. Synthesis and Characterization of Tris(3,5-di-*tert*-butylcatecholato)rhenium(VI)

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Catecholate ligands bond with transition-metal ions as strong π-donors and stabilize metal ions in high oxidation states.[1] Complexes of high oxidation state rhenium ions usually contain oxo or nitrido ligands, and examples of rhenium(VI) compounds without strong π-donor ligands are limited to the reactive fluoride and methyl complexes ReL_6 and ReL_8^{2-}, L = F, CH_3.[2] Neutral, trigonal-prismatic tris(1,2-dithiolene) and tris(1,2-thioamido) complexes of rhenium are known but metal-ligand delocalization complicates assignment of formal charge.[3,4] In this paper we describe the synthesis and characterization of a neutral tris(catecholato)rhenium(VI) complex which is isoelectronic with the 1,2-dithiolene complexes but exists with a charge-localized electronic structure.

Reactions between metal carbonyl complexes and *o*-benzoquinones under either thermal or photochemical conditions serve as convenient synthetic routes to simple binary metal-quinone complexes.[5] Metal-carbonyl complexes containing semiquinone ligands which may appear as intermediates in these reactions have been formed by using a monochromatic light source. Wan has reported formation of substituted semiquinone carbonyl complexes of manganese and rhenium by irradiation at 310 nm to form the metal tetracarbonyl radical, (1).[6,7] In a similar reaction carried out by using a polychromatic light source, we observed that the tetrameric 3,5-di-*tert*-butylsemiquinone complex of manganese(II) could be formed, (2).[8] Apparently, this results from photoexcitation of both the metal carbonyl and the semiquinone carbonyl complex products formed during the reaction. In similar chemistry, irradiation of a solution containing $Re_2(CO)_{10}$ and 3,5-di-*tert*-butyl-1,2-benzoquinone in toluene or anisole produces $Re(DBCat)_3$ as a dark purple crystalline product in nearly quantitative yield. The product obtained by using a polychromatic light source shows no carbonyl bands in the infrared, and a parent ion in the mass spectrum consistent with the monomeric tris(quinone)rhenium formulation.[9] The results of a crystallographic molecular structure determination confirm the monomeric structure of the complex (Figure 1)[10] and show that the molecule

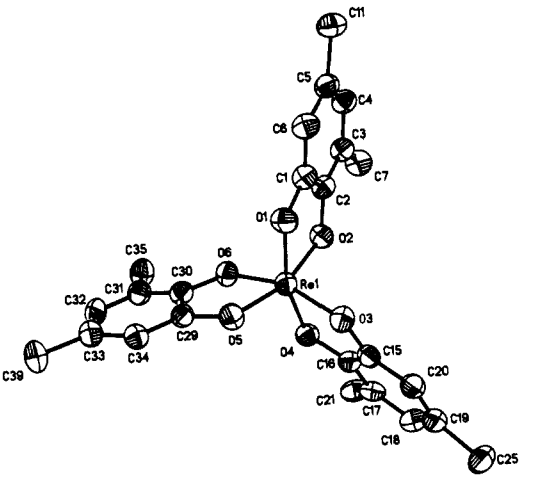


Figure 1. ORTEP plot of $Re(DBCat)_3$. Methyl carbon atoms of the *tert*-butyl groups have been omitted for clarity. The "twist angle" between triangular faces defined by chelating oxygen atoms is 37.9°.

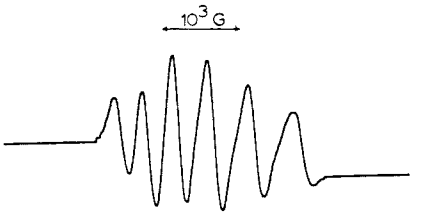
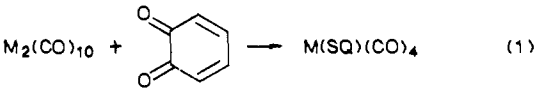
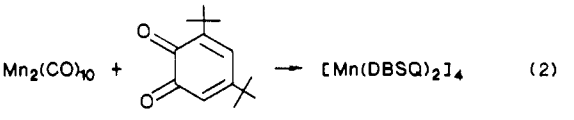


Figure 2. Isotropic EPR spectrum of $Re(DBCat)_3$ recorded in CH_2Cl_2 solution at room temperature. The horizontal coordinate of the figure is in units of gauss.





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(9) Mass spectrum: parent ions at m/z of 848 (^{187}Re) and 846 (^{185}Re). UV-visible: 273 (16 000 M^{-1} cm^{-1}), 492 (20 000 M^{-1} cm^{-1}), shoulder 590 nm.

(10) Monoclinic, $P2_1/n$, a = 15.880 (3) Å, b = 15.897 (3) Å, c = 16.450 (3) Å, β = 93.53 (2)°, V = 4145 (1) Å^3 at 296 K D_{calcd} = 1.358 g cm^{-3}, D_{expt} = 1.34 (2) g cm^{-3}, Z = 4, R = 0.039, R_w = 0.042 for 5711 observed reflections ($F > 6\sigma(F)$).

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