The mechanism by which **1** is formed may parallel the reaction of alkali metals with AlR_3 to form AlR_4^- salts (eq 2; M = alkali metal).[21] Parallels between the alkali metals and $(C_5Me_5)_2Sm$

$$3M + AlR_3 \rightarrow Al + 3RM \xrightarrow{3R_3Al} 3MAlR_4 + Al \quad (2)$$

and its solvated analogue $(C_5Me_5)_2Sm(THF)_2$ have been noted previously.[22] If the formation of **1** follows the sequence in eq 2, the intermediate analogous to RM would be $(C_5Me_5)_2SmC_2H_5$. This complex would be expected to be highly reactive and could readily decompose via β-hydrogen elimination. The less than quantitative yield of **1** from reaction 1 may be the result of decomposition of a $(C_5Me_5)_2SmEt$ intermediate. Consistent with this is the fact that when the reaction was run on a vacuum line attached to a Toepler pump, small amounts of ethene were obtained (0.2 equiv per equivalent of $(C_5Me_5)_2Sm$).

The synthesis of **1** provides an opportunity to study the chemistry of a fully characterized ethyl bridged organoaluminum complex. The reactivity of **1**, which includes polymerization of ethylene and interaction with CO, is under study.

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Supplementary Material Available: Tables of crystal data, bond distances, angles, final fractional coordinates, thermal parameters, fully numbered plots of molecules 1–3 (12 pages); listing of observed and calculated structure factor amplitudes (56 pages). Ordering information is given on any current masthead page.

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Fast Interfacial Electron Transfer between Cytochrome *c* Peroxidase and Graphite Electrodes Promoted by Aminoglycosides: Novel Electroenzymic Catalysis of H_2O_2 Reduction

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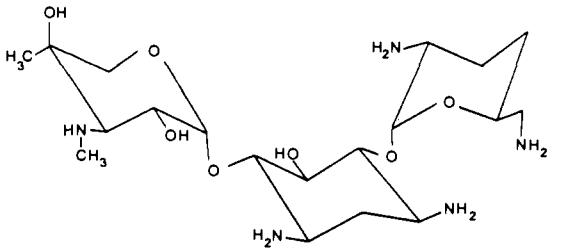
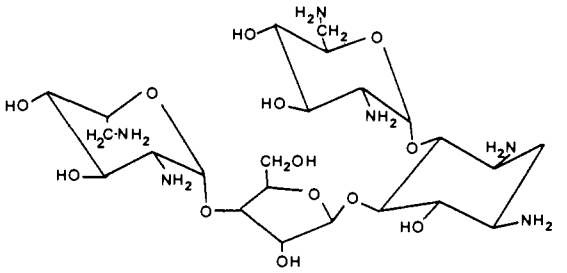
We have achieved fast interfacial electron transfer between cytochrome *c* peroxidase (CCP) and an electrode, thus establishing a fully operational *electrochemical* analogue of the archetypal biological redox system. In the latter,[1-3] CCP reacts rapidly with H_2O_2 to give a two-equivalent oxidized form (compound I) containing oxyferryl heme (Fe^{IV}=O) and a protein-bound radical; two rapid reactions with cytochrome *c* (II) then regenerate the Fe(III) form via an oxyferryl intermediate, compound II. Long-range electron transfer occurs across specific 1:1 complexes[4-6] stabilized by complementary polar interactions between lysines ($-NH_3^+$) located around the partly exposed heme edge region of cytochrome *c* and a ring of acidic ($-CO_2^-$) residues on CCP. In our electrochemical system we use aminoglycosides, gentamycin or neomycin, which contain spatial arrangements of $-NH_3^+$ groups



gentamycin C_{1a} base



neomycin B base

on a quasi-rigid framework, to promote the docking of CCP at a pyrolytic graphite edge (PGE) surface. As demonstrated by DC voltammetry (Figure 1), the system reductively exhausts H_2O_2 at high potentials.

A. In electrolyte alone (0.1 M KCl, 5 mM HEPES, pH 7.0) H_2O_2 shows no faradaic activity at a polished PGE between +850 and +250 mV vs NHE.[7] Upon addition of CCP[8] (0.2 μM) and gentamycin (5 mM) at 0 °C, a cathodic wave develops, ultimately (with 56 μM H_2O_2) to peak sharply at +575 mV.[9] Times required to achieve optimal peak potential vary with [CCP], being typically >15 min (0.1 μM) to <3 min (1.0 μM). Corresponding peak currents, corrected for background, are remarkably invariant. No response occurs without gentamycin, and 1 or 5 mM levels yield the same result, indicating saturation. Neomycin acts similarly but $Cr(NH_3)_6^{3+}$, a potent promoter of the electrochemistry of small electron-transfer proteins,[10] is much less effective.[11] Free protoporphyrin IX, substituted for CCP, is inactive. Alone, neither aminoglycoside responds or catalyzes H_2O_2 reduction between −800 and +950 mV.

B. Peak currents are proportional to $[H_2O_2]$ up to at least 70 μM. Peak potentials *increase* with decreasing $[H_2O_2]$, reaching typically ca. +750 mV at 11 μM (scan rate = 10 mV s^{-1}, [CCP] = 0.2 μM).

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(9) Between sweeps the diffusion layer was replenished by brief "microflea" stirring at open circuit potential. The electrochemistry is stable for at least 1 h at 0 °C, but instability is a problem at 25 °C. This may be due to thermal denaturation at the electrode surface or perhaps formation of excessive enzyme coverage which restricts efficient movement of electrons and substrate.

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(11) A broad ill-defined response developed during incubation times of 15–60 min with use of $Cr(NH_3)_6^{3+}$ in the concentration range 1–15 mM.

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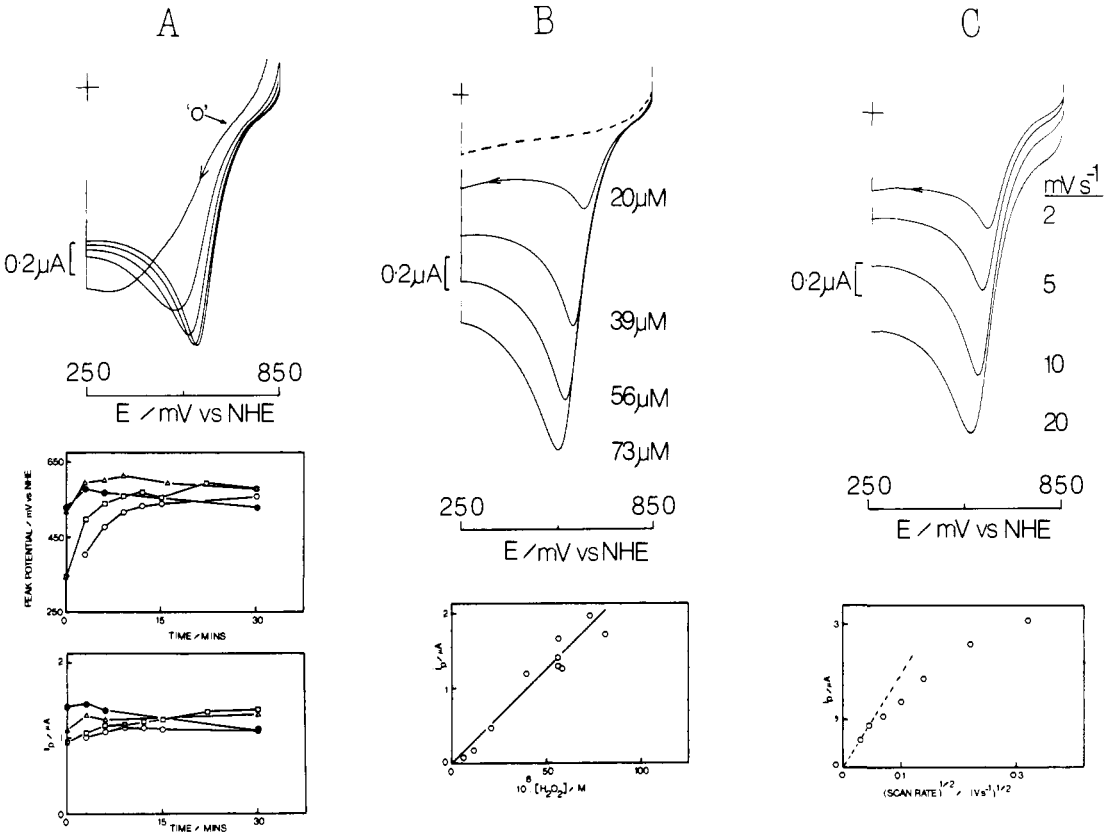

Figure 1. A. DC voltammograms showing the development of faradaic activity due to H_2O_2 reduction following addition of CCP (0.2 μM) to a solution of H_2O_2 (56 μM) and gentamycin C_{1a} (5 mM) in electrolyte (0.1 M KCl, 5 mM HEPES, pH 7.0). Temperature = 0 °C, scan rate = 10 mV s^{-1}, area of PGE electrode = 0.17 cm^2. Scans are at 3-min intervals following the "zero-time" ("0") scan. Under this set of conditions we observe, consistently, a broad feature at around +550 mV on the "0" scan. We believe that this reflects enhanced catalytic activity stemming from CCP molecules which have already undergone specific adsorption. Insets show the variation of peak potential and peak current with concentration of CCP: (○), 0.1 μM; (□), 0.2 μM; (△), 0.5 μM; (●), 1.0 μM. Adjoining lines indicate connectivity. All other conditions are as for above. B. The effect of varying $[H_2O_2]$ on the appearance of DC voltammograms and peak current magnitudes. System was preincubated with 0.2 μM CCP; other conditions are as for A. The base line voltammogram (– – –) was obtained in the absence of H_2O_2; it is identical with voltammograms obtained in the absence of any one of the reagents CCP or gentamycin. C. Appearance of DC voltammograms and variation of peak current with increasing scan rate. Inset shows plot of peak current vs (scan rate)$^{1/2}$; dotted line indicates limiting slope. System was preincubated with 0.2 μM CCP; other conditions are as for A.

C. Plots of peak current vs (scan rate)$^{1/2}$ are curved. The initial gradient yields $D_{H_2O_2} = 7 \times 10^{-6}$ cm^2 s^{-1} in broad agreement with the published values.[12]

These results show that compounds I and II are reduced rapidly and directly at PGE and regenerated continuously by H_2O_2 until depletion. The estimated reduction potential for compound II/Fe(III) is +1.09 V,[13] and a similar or higher value is likely for compound I/II.[14] The physiological reaction with cytochrome *c* (+0.26 V) thus occurs with a formidable driving force (ΔE = 0.8 – 0.9 V). The electrochemical analogue compares very favorably; H_2O_2 depletion at +750 mV demonstrates that the reaction is driven comfortably at $\Delta E \sim 0.4$ V.

We conclude that gentamycin and neomycin induce a stable enzyme-electrode interaction permitting facile electron transfer to the active site without restricting access for H_2O_2. Such features are embodied within the hypothetical model for the CCP–cytochrome *c* complex[6] in which the channel from the molecular surface to the heme crevice is unobscured by bound cytochrome *c*. We propose that an analogous configuration is assembled at the electrode interface. At pH 7, PGE is negatively charged through deprotonation (pK = 5.6) of acidic (C–O) functionalities.[10] For promotion of electrochemistry of small negatively charged electron-transfer proteins by Mg^{2+} or $Cr(NH_3)_6^{3+}$, we proposed[10] involvement of composite electrostatic interactions. The CCP/aminoglycoside system now extends this theme, whereby the larger enzyme molecule places greater demands upon the spatial charge distribution of promoters.[15] The resulting interaction is long-lived and produces a saturation coverage of oriented enzyme molecules. Gentamycin and neomycin are broad-specificity antibiotics[16] with charges of >+3.5 and >+4, respectively, at pH 7.4.[17] This is distributed among discrete $-NH_3^+$ groups, separated by up to 14 and 17 Å, to give a flattened "patch" of charge that is broadly complementary to the enzyme interaction domain. We thus witness the emergence of macromolecular recognition at an electrode interface.

This system represents a novel H_2O_2 biosensor, a composite "magic carpet" interface with possibilities for exploitation, including integration with biosystems that *generate* H_2O_2. With further investigations, including surface spectroscopy studies, we expect soon to characterize, in detail, the structure and dynamics of an operational enzyme–electrode interface.

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