Design And Characterization Of A Synthetic Electron-transfer Protein

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Abstract: A 30-residue polypeptide [H21(30-mer)] with the sequence Ac-KIEALEGK21IEALEHK-(IEALEGK)G-NH3 was synthesized. The circular dichroism (CD) spectrum of the peptide shows minima at 208 and 222 nm and \( \theta_{222}/\theta_{208} = 1.06 \), which indicates the formation of a self-assembled coiled-coil when dissolved in aqueous solution. The concentration dependence of the CD data can be fit to an expression that describes a two-state monomer–dimer equilibrium for the apoapetide \( (K_d = 1.5 \pm 0.4 \, \mu M) \) and \( \theta_{\text{max}} = -23800 \pm 130 \, \text{deg cm}^2 \, \text{dmol}^{-1} \), showing that it has a maximum helicity of 69%. A [MTSL-C21(30-mer)] dimer was also prepared in which MTSL is the thiol-specific nitroxide spin label 1-oxyl-2,2,5,5-tetramethyl-3-methyl-methanethiosulfonate attached to C21 of the 30-mer. Fourier deconvolution analysis of the dipolar line broadening of the electron paramagnetic resonance (EPR) spectrum yields a measure of the interchain Cα-Cα distance of 13.5 ± 0.9 Å at position 21 of the coiled-coil, which is nearly identical to those distances observed for the isostructural family of bZip proteins. Two metallolomodimers, [Ru(trpy)/(bpy)-H21(30-mer)]2 and [Ru(NH3)2-H21(30-mer)], in which the ruthenium complexes were coordinated with the H21 site of the 30-mer, were prepared. Sodium dodecyl sulfate–polyacrylamide gel electrophoresis (SDS-PAGE), chemical cross-linking studies, and analytical ultracentrifugation show that the peptides exist as a dimeric coiled-coil with a molecular weight of \( \sim 7.5 \, \text{kDa} \). The electron transfer (ET) heterodimer, [Ru(trpy)/(bpy)-H21(30-mer)]/[Ru(NH3)2-H21(30-mer)], was prepared, and molecular modeling shows that the two metal complexes are separated by a metal-to-metal distance of \( \sim 24 \, \text{Å} \) across the noncovalent peptide interface. Pulse radiolysis was used to measure an ET rate constant of \( k_{\text{et}} = 380 \pm 80 \, \text{s}^{-1} \) for the intracomplex electron transfer \( \Delta G^\circ = -1.11 \, \text{eV} \) from the Ru\(^{II}\)(NH3)2-H21 donor to the Ru\(^{II}\)(trpy)/(bpy)-H21 acceptor. The value for \( k_{\text{et}} \) falls within the range reported for modified proteins over comparable distances and supersedes the one reported in an earlier communication.

Introduction

Protein-based electron-transfer (ET) reactions have been the focus of considerable interest because of their important role in biological energy conversion.1,4 A central goal of this research is to identify the role, if any, of the intervening protein matrix in propagating long-range donor/acceptor interactions. To this end, much work has been done to investigate the ET properties of photosynthetic reaction centers,3,5 surface-derivatized proteins,4,6 protein–protein complexes,7–10 and peptide-based model compounds.7 The last approach to this problem includes the study of intramolecular ET reactions that occur

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models suffers from the following limitation: whereas many in vivo ET reactions occur across the noncovalent interface of a protein—protein complex, the early model compounds all used peptide bridges to form a covalent link between their donor and acceptor sites. The structural features of these model systems are thus inherently different from those often found in the native biological environment. We describe here a new approach toward the design of more nativelike ET models in which self-organized peptide assemblies are used to separate metal-based redox sites across a well-defined, yet noncovalent, peptide—peptide interface. Future study of these synthetic redox proteins should produce valuable insight into the mechanisms of biological ETs.

The synthesis of the self-assembled peptide—peptide ET complex is derived from recent advances in the rational design of artificial peptide assemblies that retain nativelike structures. A notable example of de novo designed proteins can be seen within the family of synthetic, two-stranded α-helical coiled-coils.25,26 This ubiquitous protein structure results from the coiled-coil (Figure 1a). This design creates a hydrophobic face of an α-helix to serve as a noncovalent dimerization site for the coiled-coil (Figure 1b). The current study utilizes this motif to prepare a unique, coiled-coil protein designated H21(30-mer) on which metal-based redox sites are positioned to create a synthetic metalloprotein that can exhibit long-range ET. The physico-chemical characterization of this protein is presented, along with the results of electron-pulse radiolysis experiments that demonstrate the occurrence of a unimolecular ET reaction (k0 = 380 ± 80 s⁻¹) occurring over a metal-to-metal distance of ca. 24 Å across the noncovalent interface.

Experimental

Materials. The Fmoc-protected L-amino acids, diisopropylcarbodiimide, and 1-hydroxybenzotriazole were purchased from Peptides International. N,N’-Dicyclohexylcarbodiimide, dicyclohexylamine, ethylene glycol, and trifluoracetic acid were obtained from Fisher Scientific. Piperidine, anisole, and [Ru(NH3)6Cl2]Cl2 were purchased from Aldrich Chemical Company. The thiol-specific MTSL (4-(2-mercaptoethyl)piperidine-1-oxyl-2,2,5,5-tetramethyl-3-pyrroline-3-methylhydroxysulfonate) was purchased from Toronto Research Chemicals Inc. All chemicals and solvents were used as received without further purification.

General Methods. Reversed-phase high-performance liquid chromatography (HPLC) analyses were performed on a Whatman Magnum 9 (300 × 9.4 mm) semi-preparative Partisil ODS-3 column. A single-pump system was used (Waters model 510) equipped with a binary gradient controller (Autochrm. Inc.) and a Waters model 994 diode array detector/spectrophotometer with a 1-cm cell path length. For preparative separations, the monitoring wavelengths were set to the tails of the absorption bands of the desired compounds. The purity of the resulting samples was subsequently verified by analytical HPLC runs from which the full ultraviolet-visible (UV–vis) spectra could be obtained. Gel filtration was carried out on columns packed with Bio-Gel P-2 resin (Bio-Rad). The UV–vis spectra of the purified compounds were recorded on a Hewlett-Packard model 8452A diode array spectrophotometer. The molar extinction coefficient, ε(478 nm) = 8800 M⁻¹ cm⁻¹, was used to determine the concentration of the Ru(terpy)(bpy)-H21(30-mer) peptide.27 Mass spectral (MS) data were obtained by the Core Protein Facilities of the University of Michigan (Ann Arbor, MI) and the Mass Spectrometry Center of the University of Maryland (College Park, MD). Cyclic voltammetry (CV) was conducted on a BAS 100W Electrochemical Analyzer using a small-volume (200 μL) sample cell equipped with a platinum working electrode, a platinum wire auxiliary electrode, and an Ag/AgNO3 reference electrode. The samples were dissolved in 50 mM phosphate buffer (pH 7.0).

Synthesis of the H21(30-mer) Peptide. The 30-residue polypeptide, with the sequence Ac-K(IEALEGK)₉(IEALEHKG)₉-G-NH₂, was synthesized on a Perceptive Biosystems model 9050 Plus Pep-Synthesizer (Framingham, MA) using the fluorenylmethoxycarbonyl N-terminal protection strategy and the manufacturer’s PAL PEG-PS resin. Activation was achieved using diisopropylcarbodiimide (DIPCDD) and 1-hydroxybenzotriazole (HOBt) with a 60-min cycle time. This polypeptide is designated H21(30-mer).

Prior to cleavage from the resin, the peptide was N-acetylated with a capping solution containing 0.5 M acetic anhydride, 0.125 M N,N-diisopropylethyamine (DIEA), and 0.015 M HOBt in dimethylformamide (DMF). Cleavage of the H21(30-mer) from the resin and obtained from Aldrich Chemical Company. The thiol-specific MTSL spin-label (MTSL = 1-oxyl-2,2,5,5-tetramethyl-1A-pyrrrole-3-methylmethanethiosulfonate) was purchased from Toronto Research Chemicals Inc. All chemicals and solvents were used as received without further purification.

(a) Wheel representation showing the sequence of the H21-(30-mer) protein. (b) Schematic representation of the third heptad repeat of the ET metalloheterodimer.

References


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deprotection of the amino acid side chains were achieved by gently stirring the resin in a mixture of 88% (v/v) trifluoroacetic acid, 5% (v/v) phenol, 2% (v/v), trisopropylamine and 5% (v/v) water for 2 h. The crude peptide was then precipitated in cold diethyl ether, collected by vacuum filtration, and dried under vacuum. Final purification was achieved by semipreparative reversed-phase C18 HPLC with a linear AB gradient of 1% (v/v) A/min, at a flow rate of 2 mL/min, in which solvent A was 0.1% (v/v) trifluoroacetic acid in acetonitrile and solvent B was 0.1% (v/v) trifluoroacetic acid in water. The collected peptide was then lyophilized and analyzed by MALDI-TOF MS (m/z obsd: 3287.8, calcld for [M + H]+: 3287.8).

Synthesis of the Spin-Labeled Peptide. The 30-residue polypeptide, C21(30-mer), with the sequence Ac-K(IEALEGK)2-(IEALECK)-(IEAL- 

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mer). After the reaction was complete, the solution was concentrated to near dryness and lyophilized. HPLC analysis showed the existence of a small amount (<5%) of free metal complex in the presence of the desired metallopeptide.

Synthesis of Ru(trpy)(bpy)-H21(30-mer). A 15-mg (34-μmol) sample of [Ru(NH3)5-H21(30-mer)] was then lyophilized and analyzed by MS (m/z obsd: 3399.9, calcld for [M + H]+: 3399.3). The collected peptide was then lyophilized and analyzed by HPLC. The reaction mixture was stirred at room temperature for 3 h after which it was purified by semipreparative reversed-phase C18 HPLC as already described. The collected peptide was then lyophilized and analyzed by M.S. (m/z obsd: 3399.9, calcld for [M + H]+: 3399.3).

Synthesis of Ru(trpy)(bpy)-H21(30-mer). To a 10-mg (3-μmol) sample of H21(30-mer) dissolved in 2 mL of argon-purged 50 mM phosphate buffer (pH 7.0) was added a concentrated (8–10 mM) solution of [Ru(trpy)(bpy)Cl2]+ dissolved in either water or phosphate buffer. The solution was then adjusted to pH 7.7–7.8 and stirred under reduced light for 3 days at 30 °C. The progress of the reaction was monitored by HPLC, which showed the growth of an absorption band centered at 478 nm for the HPLC peak corresponding to the H21(30- 

mer). After the reaction was complete, the solution was concentrated to a small volume by rotary evaporation and passed through a size-exclusion column equilibrated with water. The metallopeptide solution was then concentrated to near dryness and lyophilized. HPLC analysis showed the existence of a small amount (<5%) of free metal complex in the presence of the desired metallopeptide.
min, and then allowed to cool back to room temperature before the addition of glutaraldehyde (final concentrations ranged from 2 to 100 mM). The samples were incubated at 37 °C for 20 min before being quenched by adding glycine to a final concentration of 100 mM. These samples were then run on an 18% SDS-PAGE gel. Two different polypeptide standards were run in parallel (3.4, 5.5, 8.7, and ≥15.3 kDa; 3.0, 5.0, 9, and ≥14 kDa) for comparison.

Analytical Ultracentrifugation. Sedimentation equilibria were determined for samples of the [Ru(bpy)2Im-H21(31-mer)]/[Ru(NH3)5-]
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Electron Paramagnetic Resonance (EPR) Spectroscopy and Spectral Analysis. EPR spectra were collected with a Bruker ESP 300E spectrometer (Bruker, Germany) equipped with a loop-gap resonator (Medical Advances, Milwaukee, WI) and a low-noise microwave amplifier (Miteq, Hauppauge, NY). Spin concentrations were determined by comparing doubly integrated room-temperature spectra with that of a TEMPO standard solution. Low-temperature spectra were collected at 125 K and 8-microwatt microwave power and a modulation amplitude of 1 G, and spin concentration was ~300 μM. The EPR spectra were independent of concentration up to 2 mM.

Electron dipolar interactions between two interacting nitroxide spin labels lead to overall EPR spectral broadening. Quantitative analysis of EPR-temperature spectra is nontrivial because of the motional line broadening in addition to the dipolar line broadening. Low-temperature spectra of motionally frozen samples permits extraction of the dipolar broadening function directly from Fourier deconvolution analysis of the interacting double-label spectra with respect to noninteracting monoradical spectra. The motionally frozen state is readily achieved by freezing the EPR samples near the liquid nitrogen temperature. This method provides an accurate estimation for interspin distances in the range 8–25 Å, and its applications to peptides and proteins have been described previously. Because these experiments were designed to detect the relatively weak dipolar interactions between two spin labels at the f positions of the peptide dimer, which are >20 Å apart, special efforts were made to minimize the experimental error. The average of five independently obtained low-temperature spectra was used in the final analysis. The noninteracting monoradical reference spectra were taken both from the sample prepared by mixing the spin-labeled peptide with the unlabeled peptide at a 1:10 molar ratio and from a sample of the spin-labeled peptide sample denatured in 6 M GuHCl.

Molecular Modeling. Computational results were obtained using software programs from Biosym/MSI (San Diego, CA). Energy minimization calculations were performed with the Discover® program using the ESFF force field and the conjugate gradient method, setting a final convergence criterion of 0.001 kcal/(mol Å) rms force. Molecular dynamics simulations were performed by the Nose temperature control method. All structures were solvated with a water box prior to performing the calculations. Graphical displays were obtained from the Insight®II molecular modeling program.

Results

Synthesis and Characterization of Peptides. Solid-phase methods were used to prepare a 30-residue polypeptide called H21(30-mer). The sequence (Ac−K(IEALEGK)2I(IEALEHK)-G-NH2) was based on a seven-residue repeat developed by Hodges and co-workers to prepare artificial coiled-coils. In the sequence, positions a, d, e, and g are occupied by isoleucine, leucine, glutamic acid, and lysine, respectively, as these substitutions have been shown to encourage the formation of two-stranded coiled-coils in solution. In particular, it has been found that dimeric coiled-coils are favored by the incorporation of β-branched amino acids into position a of the heptad. An additional feature of the sequence is that it places a single histidine residue at position 21 to provide a metal-binding site on the most highly solvent-exposed position of the third heptad repeat.

The two metallopeptides, [Ru(trpy)(bpy)-H21(30-mer)] and [Ru(NH3)5-Cu21(30-mer)], were prepared by appropriate modification of methods previously described for the attachment of ruthenium complexes to the surface of cytochrome c. In each case, purification was achieved by a combination of semipreparative reversed-phase HPLC and size-exclusion chromatography. The UV absorption spectrum of the [Ru(trpy)(bpy)-H21(30-mer)] peptide exhibits maxima at λ = 206 (log ε = 5.0), 274 (log ε = 4.5), 288 (log ε = 4.5), 314 (log ε = 4.50), and 476 nm (log ε = 3.9), and is quite similar to the spectrum previously reported for the related model compound, [Ru(trpy)-(bpy)]Im2+. When dissolved in water, the metallopeptide has a short-lived emission at 650 nm (τ = 23 ns) that is nearly the same as that reported for the related ruthenated plastocyanin, Diff. pulse polargraphy and CV show a reversible redox couple for the metallopeptide at E1/2 = +1.17 V versus NHE that is similar to the value reported for the model compound, (Ru(trpy)(bpy)]Im2+. Characterization of the [Ru(NH3)5-Cu21(30-mer)] peptide was accomplished by CV, which showed nearly identical behavior to that of Ru(NH3)5-modified cytochrome c. A reversible one-electron reduction at E1/2 = +0.065 V versus NHE was observed.

Circular Dichroism Spectroscopy. Figure 2 shows the circular dichroism (CD) spectrum of a 76 μM solution of H21(30-mer) peptide in 50 mM phosphate buffer (pH 7, 298 K). Inset: The concentration dependence of θ222 for H21(30-mer). The solid line shows the fit to a two-state monomer—dimer equilibrium model (eq 6) as described in the text.

H21(30-mer). The sequence (Ac−K(IEALEGK)2I(IEALEHK)-G-NH2) was based on a seven-residue repeat developed by Hodges and co-workers to prepare artificial coiled-coils.

Figure 2. The circular dichroism spectrum of a 76 μM solution of H21(30-mer) peptide in 50 mM phosphate buffer (pH 7, 298 K). Inset: The concentration dependence of θ222 for H21(30-mer). The solid line shows the fit to a two-state monomer—dimer equilibrium model (eq 6) as described in the text.

(37) A second reversible wave seen at 0.87 V versus NHE is assigned to the presence of [Ru(trpy)(bpy)]Im2+ which is observed as a minor component (~5%) by HPLC in the peptide sample.
an ellipticity ratio of \( \theta_{222}/\theta_{208} = 1.06 \) was observed, which indicates the existence of an \( \alpha \)-helical coiled-coil.\(^{25}\) In contrast, single-stranded \( \alpha \)-helices are expected to display values of \( \theta_{222}/\theta_{208} \approx 0.86 \), as theoretical calculations have shown that the CD band located at 208 nm is polarized parallel to the helical axis and its magnitude is therefore sensitive to whether the helical structure is comprised of a single peptide chain or interacting \( \alpha \)-helices.\(^{38}\) It is interesting to note that when H21(30-mer) is dissolved in methanol, \( \theta_{222}/\theta_{208} = 0.9 \), indicating that the coiled-coil structure has unfolded into noninteracting helical monomers.

Thermal denaturation studies performed in aqueous solution (not shown) indicate that the self-assembled peptide structure is very stable, producing a melting curve in which \( T_m = 65 \, ^\circ\text{C} \).

The ellipticity value at 222 nm can be used to estimate the helical content of the peptide by comparison to the maximum molar ellipticity \( (X_H^\text{max}) \) calculated for a 30-residue polypeptide:

\[
X_H^\text{max} = (-37 \times 400 \text{ deg cm}^2 \text{ dmol}^{-1})(1 - k/n) = -34 \times 283 \text{ deg cm}^2 \text{ dmol}^{-1} \quad (5)
\]

where \( k \) is a wavelength-dependent constant equal to 2.5 for 222 nm, and \( n \) is the number of residues per helix.\(^{39}\) Significantly, the observed helicity of the H21(30-mer) peptides increases with increasing peptide concentration, which is consistent with the formation of a self-assembled coiled-coil structure. Recent studies\(^{40}\) of some coiled-coil peptides have analyzed the concentration dependence of \( \theta_{222} \) in terms of a two-state monomer-dimer equilibrium for which the dissociation constant, \( K_d \), can be calculated from eq 6:

\[
K_d = 2[M_0] \frac{(1 - \Delta \theta/\Delta \theta_{\text{max}})^2}{(\Delta \theta/\Delta \theta_{\text{max}})} \quad (6)
\]

where \([M_0]\) is the total peptide concentration, \( \Delta \theta = (\theta_{\text{obs}} - \theta_0) \), \( \Delta \theta_{\text{max}} = (\theta_{\text{max}} - \theta_0) \), \( \theta_0 \) is the ellipticity of the folded dimer, and \( \theta_{\text{max}} \) is the ellipticity of the unfolded monomer, which is usually taken to be 2500 deg cm\(^2\) dmol\(^{-1}\). All ellipticities are at 222 nm. The inset in Figure 2 shows the results of a nonlinear least-squares fit of the concentration dependence of \( \theta_{222} \) to eq 6, which yields values of \( K_d = 1.5 \pm 0.4 \) \( \mu \)M and \( \theta_{\text{max}} = -23 \pm 800 \pm 130 \) deg cm\(^2\) dmol\(^{-1}\), showing that the peptide has a maximum helicity of 69%. These results are consistent with those reported for studies\(^{25}\) of synthetic coiled-coils with similar amino acid sequences to that of H21(30-mer) in which the deviations from ideality are likely due to endgroup fraying.

The CD properties of the \([\text{Ru(trpy)(bpy)}-\text{H}21(30\text{-mer})]\) and \([\text{Ru(NH}_3\text{)}_5\text{-H}21(30\text{-mer})]\) metallopeptides are qualitatively similar to those of the apoprotein. Both show a positive CD band at <195 nm and two minima at 208 and 222 nm. In addition, both peptides display values of \( \theta_{222}/\theta_{208} \approx 1.05 \), indicating that they adopt the coiled-coil structure when dissolved in aqueous solution. The concentration dependence of \( \theta_{222} \) for the two metallopeptides can be fit to eq 6 to give \( K_d = 0.27 \pm 0.1 \) \( \mu \)M and \( \theta_{\text{max}} = -19 \pm 0.3 \) deg cm\(^2\) dmol\(^{-1}\) for the \([\text{Ru(NH}_3\text{)}_5\text{-H}21(30\text{-mer})]\) and \( K_d = 0.24 \pm 0.1 \) \( \mu \)M and \( \theta_{\text{max}} = -26 \pm 176 \pm 114 \) deg cm\(^2\) dmol\(^{-1}\) for the \([\text{Ru(trpy)(bpy)}-\text{H}21(30\text{-mer})]\).

**Gel Electrophoresis, Chemical Cross-Linking Experiments, and Analytical Ultracentrifugation.** SDS-PAGE experiments (not shown) were used to determine the oligomerization state of the H21(30-mer) and showed the presence of monomers and dimers in solution. Subsequent intersubunit cross-linking experiments using glutaaldehyde also produced bands at positions corresponding to the monomer and dimer species (MW < 8.7 kDa). Higher concentrations of glutaraldehyde produced more intense dimer bands. However, no evidence for higher cross-linked oligomers was observed, even under saturating conditions of glutaraldehyde. To directly determine the molecular weight of the peptide in solution, the sedimentation equilibrium of equimolar samples of the \([\text{Ru(trpy)(bpy)}-\text{H}21(31\text{-mer})]\) and \([\text{Ru(NH}_3\text{)}_5\text{-H}21(31\text{-mer})]\) metallopeptides were studied by analytical ultracentrifugation. Figure 3 shows that the results obtained within the concentration range 20–80 \( \mu \)M can be accurately fit to a dimer model using the averaged molecular weight of 7.5 kDa for the dimer. Metal derivatization of the peptide does not seem to perturb its overall aggregation state as was sometimes observed in the case of organic fluorophores attached to coiled-coil peptides.\(^{41}\)

**Preparation of the ET Metallo-heterodimer.** The results just discussed show that the two noncovalent metallohomodimers, \([\text{Ru(trpy)(bpy)}-\text{H}21(30\text{-mer})]\)_2 and \([\text{Ru(NH}_3\text{)}_5\text{-H}21(30\text{-mer})]\)_2, can be readily prepared. In a recent study of a related peptide, stopped-flow CD spectroscopy was used to examine the unfolding kinetics of a dimeric coiled-coil peptide to yield a half-life of several minutes.\(^{42}\) Thus, the desired ET heterodimer (Figure 4) was generated in situ by mixing an approximately equimolar solution of the two homodimers and allowing the sample to stand under ambient conditions for at least 25 min. This procedure yields a statistical mixture of the peptide homodimers and heterodimers that cannot be separated from one another. However, we note that within this statistical distribution of metallopeptides, the \([\text{Ru(trpy)(bpy)}-\text{H}21(30\text{-mer})]/[\text{Ru(NH}_3\text{)}_5\text{-H}21(30\text{-mer})]\) heterodimer is the only species that can display intracomplex ET.

**EPR Measurements.** The nitroxide–nitroxide distance measured by EPR was used to estimate the distance between the two \( \alpha \)-carbons at positions 21 and 21’ within the peptide dimer. These positions are the sites of ruthenium attachment in the ET metalloprotein already described. The identity of the spin-labeled variant was verified by ESI-MS and its dimeric aggregation state was confirmed by analytical ultracentrifugation.

Figure 5a shows a comparison of the average of five independently obtained spectra of the \([\text{MTSL-C}21(30\text{-mer})]\)_2.
dimer, with the noninteracting spectra obtained from a magnetically dilute sample of [MTSL-C21(30-mer)] dissolved in a stoichiometric excess of unmodified [C21(30-mer)], and a sample of [MTSL-C21(30-mer)] denatured in 6 M GuHCl. This comparison reveals a small but distinct spectral line broadening in the spin-labeled dimer due to electron-electron dipolar interactions. Importantly, no evidence for the presence of monomeric peptides was detected in these samples.

Fourier deconvolution analysis was performed to determine the interspin distance from these spectra. Previous studies have measured interspin distances in derivatized α-helices to show that the experimentally determined values were identical to those calculated from idealized models within a standard deviation of ±0.9 Å. The dipolar broadening function extracted from the analysis in the Fourier space is shown in Figure 5b. From this function, an average interspin distance of 22.5 Å was obtained. These results were invariant to the choice of reference sample used to compare the line shapes (i.e., the magnetically diluted, or chemically denatured samples).

An estimate of the intersubunit Cα(21)–Cα(21′) distance can be obtained from the spin-label distance using the following geometrical argument (Figure 5c). In several previous studies, it has been found that the average location of a nitroxide spin-label attached to an α-helix lies 7 Å away from the center of the helix on the line connecting the helical axis and the α-carbon of the cysteine residue. The Cα positions are located 2.5 Å away from the helical axis along this radius. Thus, the two Cα sites at the f positions of the dimer lie nearly on the straight line connecting the two helical axes. The distance between these sites is therefore measured to be 13.5 ± 0.9 Å, which is within experimental error to the average value of 14.2 Å seen in the 1.8 Å resolution crystal structure of GCN-4. The H21(30-mer) is therefore believed to exist within the nativelike structure of an α-helical coiled-coil. These results also indicate that the peptide dimer consists of a parallel arrangement of α-helices because an antiparallel arrangement would result in very large interspin distances giving rise to narrow EPR signals.

**Molecular Modeling.** As described later, the pulse radiolysis technique was used to determine the rates of a ground-state ET occurring from the Ru II (NH 3 ) 5 electron-donor (d 6 ) to the Ru III - (trpy)(bpy) acceptor (d 5 ). Because this reaction involves metal-based d-orbitals, an estimate of the metal-to-metal distance in the ET heterodimer was obtained by energy-minimization calculations based on the results previously obtained for the related metalloheterodimer [Ru(bpy) 2 Im-H21(31-mer)]/[Ru(NH 3 ) 5 -H21(31-mer)] whose synthesis has been described earlier. These calculations were initiated by coordinating the appropriate ruthenium complexes to the H21 positions of the 31-mer apopeptide using starting coordinates taken from the crystal structures of the GCN-4 dimerization domain, and the relevant model complexes, cis-[Ru(bpy) 3 ] 2+ , and [Ru(NH 3 ) 3 -Ru(His)]Cl 2 •H 2 O. Separate energy minimization calculations were then performed for 640 initial structures in which the side-
chain dihedral angles $\chi_1$ and $\chi_2$ for the H21 residue were systematically varied from $-180^\circ$ to $+180^\circ$ and in which the backbone structure of the peptide remained fixed. For the current study, the two lowest energy structures were identified, and their ruthenium polypyridyl sites were changed to [Ru(tpy)(bpy)]. Energy minimization calculations were subsequently performed followed by molecular dynamics simulations at 298 K to overcome local energy barriers. After a second round of energy minimization was performed an average metal-to-metal distance of 24.4 Å was found, which was within 0.2 Å of the value obtained from the original starting coordinates. From these final coordinates, the edge-to-edge distance is 18.4 Å as measured from the $C_{\alpha}$ positions of the histidine residues.

**Electron-Transfer Studies.** The monitoring wavelength for studying the ET kinetics was determined by examining the difference absorption spectra obtained after oxidizing the [Ru$^{II}$ (trpy)(bpy)-H$_2$(30-mer)] homodimer. The usable concentration range for these measurements was carried out on solutions having concentrations in the range of 1.2 to 20 μM for the heterodimer (total peptide concentrations of 2.4 to 40 μM). Control experiments were performed on similar solutions of the [Ru(tpy)(bpy)-H21(30-mer)] homodimer. The usable concentration range for these experiments was limited on the low end by the monomer–dimer equilibrium constant, and at the high end by the absorbance of the sample.

Figure 6a shows a typical transient absorption trace from a control experiment involving the pulse radiolysis of [Ru(tpy)-(bpy)H21(30-mer)] (total peptide concentration = 10 μM). A rapid bleach at 490 nm is observed that indicates formation of the oxidized [Ru$^{III}$(trpy)(bpy)H21(30-mer)] species. The second-order rate constant for this process is $k_{et} \approx 1.5 \times 10^9$ M$^{-1}$ s$^{-1}$, based on the pseudo-first-order rate constants measured at different peptide concentrations. As shown, the oxidized metallopeptide lives for $>70$ ms in the absence of a reductant. Observations at longer times show evidence for a partial (~20%) recovery of the MLCT bleach occurring within ~1000 ms.

Figure 6b shows the results of the radiolysis experiment performed on a 5.2-μM solution of the ET heterodimer preparation (total peptide concentration of 10.4 μM). A rapid bleach is observed at 490 nm that indicates that the ruthenium polypyridyl centers have been oxidized by the azide radical. This process proceeds with an estimated second-order rate constant of $\sim k_{et} = 2 \times 10^7$ M$^{-1}$ s$^{-1}$, which is similar to that already seen for the oxidation of the related homodimer. However, the absorption change observed for the ET heterodimer recovers by a process that can be fit to a sum of two exponentials within the 70-ms time scale of the experiment. The rate of the faster major component is independent of concentration, and is thus assigned to the intracomplex ET reaction. Measurements were performed on samples containing 1.2, 2.0, 4.0, 5.2, 10, and 20 μM solutions of the ET heterodimer to give first-order rate constants of $k_{et} = 290 \pm 60$ (12), 410 $\pm$ 50 (11), 400 $\pm$ 35 (9), 400 $\pm$ 50 (12), 480 $\pm$ 40 (11), and 310 $\pm$ 50 s$^{-1}$ (9), respectively, where the number of independent observations made for each concentration are shown in parentheses. These data give an average value of $k_{et} = 380 \pm 80$ s$^{-1}$ for the intramolecular ET reaction occurring within the ET heterodimer. This value supersedes the one previously reported for a closely related peptide, in which the laser flash quench method was improperly used because of the incorrect choice of the exogenous quencher that allowed for the pre-flash oxidation of the donor site.

Examination of Figure 6b also shows the existence of a persistent bleach at 490 nm. This behavior is similar to that seen in Figure 6a and can be attributed to the radiolytic oxidation of the [Ru$^{III}$(trpy)(bpy)-H21(30-mer)] homodimers present in the solution (these account for half of the [Ru(tpy)(bpy)] species.
present), as well as to the accumulation of the ET-inert product, [Ru\(^{(bpy)}\)(trpy)-H\(_2\)]/[Ru\(^{(NH_3)}\)-H\(_2\)]. These oxidized ruthenium polypyridyl species can only decay by a bimolecular ET reaction with the [Ru\(^{(NH_3)}\)-H\(_2\)] species. However, only a small percentage can react in this way because the concentration of the ruthenium(II) pentammine sites has been lowered by repeated pulsing of the sample. The kinetic fits to the data show that the slower, minor component to the bleach recovery appears to occur with a concentration-independent rate of \(k_{\text{aparent}} = 32 \pm 9 \text{ s}^{-1}\). However, the small amplitude of this component and the 70-ms time domain of the experiment prevents an unambiguous analysis of these data to be made at this time.

Discussion

This work describes a new approach toward the preparation of self-assembled peptide complexes that are capable of displaying long-range ET reactions. In recent years, several examples have been reported in which the principles of de novo protein design have been used to prepare a new generation of synthetic ET proteins. However, a unique feature of the current system is that instead of using polypeptide chains to provide covalent bridges between the electron donor and acceptor sites, the ET event is now made to occur across a well-defined, yet noncovalent, peptide–peptide interface. Accordingly, this synthetic protein provides the first peptide-based model system that is amenable to mechanistic studies of interfacial ET reactions as they occur within native protein–protein complexes.

The results of CD, EPR, analytical ultracentrifugation, and molecular modeling studies show that both the apo and metalated derivatives of the [H\(_2\)(30-mer)] peptide form two-stranded α-helical coiled coils that remain essentially isostructural to the family of native leucine zipper proteins. In particular, the EPR spin-label experiments show that the interchain C21–C21\(^{\prime}\) distance (C\(_{\text{A}}\)–C\(_{\text{A}}\)) of the peptide dimer is nearly identical to that observed from the X-ray crystal structure of GCN-4. Based on these results, computer modeling studies suggest that the ET heterodimer, [Ru\(^{(bpy)}\)(trpy)-H\(_2\)]/[Ru\(^{(NH_3)}\)-Im-H\(_2\)], has an interhelical, metal-to-metal distance of \(\sim 24 \text{ Å}\).

Pulse radiolysis experiments were used to measure a concentration-independent value of \(k_{\text{et}} = 380 \pm 80 \text{ s}^{-1}\) for the interhelix ET reaction occurring between the [Ru\(^{(bpy)}\)(trpy)-H\(_2\)] electron-donor and the [Ru\(^{(bpy)}\)(trpy)-H\(_2\)] acceptor.

The electrochemistry measurements performed on the two metallo-homodimers show that the driving force for this reaction is \(AG^\circ = -1.11 \text{ eV}\), which is slightly higher than the magnitude of \(\lambda\) calculated for this system. The observed value of \(k_{\text{et}}\) is therefore believed to be close to that of \(k_{\text{max}}\) (i.e., the activationless ET rate constant) and can therefore be compared with those reported for related systems. Interestingly, the value falls

(49) Our studies have also found that the Ru\(^{(bpy)}\)(trpy)-H\(_2\)) homodimer used in the previous study is photobleachable in the absence of quencher. Photoexcitation of this species results in a transient bleach of the ruthenium MLCT peak, which does not fully recover to the original baseline on the millisecond time scale.

(50) An estimate of the reorganization energy for this system can be made using the Marcus cross-relation: \(\lambda_{11} = 1/2(\lambda_{11} + \lambda_{22})\) where \(\lambda_{11}\) and \(\lambda_{22}\) are the self-exchange reorganization energies for two metal complexes involved in the electron–transfer. Substitution of the values (ref 4c) of \(\lambda_{11} = 0.6 \text{ eV}\) for Ru\(^{(bpy)}\) and \(\lambda_{22} = 1.20 \text{ eV}\) for Ru\(^{(NH_3)}\)(pyr) yields a value of \(\lambda_{12} = 0.9 \text{ eV}\).

within the range of those reported for ET reactions that occur across comparable metal-to-metal distances in both native and surface-modified metalloproteins. For example, Farver and Pecht\(^{51}\) report a value of \(k_{\text{max}} = 3 \times 10^{2} \text{ s}^{-1}\) for the reaction between the [Cys3–S–S–Cys26]– disulfide radical and the Cu\(^{2+}\) center of wild-type azurin that are located 24.6 Å apart. In addition, Gray and co-workers\(^{46}\) report values of \(k_{\text{max}} = 3.1 \times 10^{4} \text{ s}^{-1}\) for His54-ruthenated cytochrome c (d\(_{\text{S-M}}\) = 22.5 Å), \(k_{\text{max}} = 2.4 \times 10^{2} \text{ s}^{-1}\) for His107-ruthenated azurin for (d\(_{\text{S-M}}\) = 25.7 Å), and \(k_{\text{max}} = 1.3 \times 10^{2} \text{ s}^{-1}\) for His126-ruthenated azurin (d\(_{\text{S-M}}\) = 26 Å). The behavior of the H\(_2\)(30-mer) metalloprotein clearly falls within this range of data and highlights the rich variability in the ET behavior of protein-based systems.

At this point, it should be acknowledged that relatively little is presently known about the conformational dynamics of the ET heterodimer. It is certainly possible that internal motions of the metalloprotein may play an important role in regulating the observed intracomplex ET rate. However, it appears likely that the gross dynamics of the monomer/dimer equilibrium do not gate the observed ET reaction because Zitzewitz et al.\(^{42}\) recently used stopped-flow CD to determine that the monomer/dimer equilibrium for the related GCN-4 coiled-coil peptide has an unfolding rate constant of \(3.3 \times 10^{-3} \text{ s}^{-1}\), which is significantly smaller than the ET rate constant measured in the present system. Nevertheless, future work will attempt to address this issue by examining the temperature and/or viscosity dependence of \(k_{\text{et}}\) for this and related systems. In the absence of such experiments, a pathway analysis of the H\(_2\)(30-mer) ET heterodimer identifies the primary coupling path (metal-to-metal) in this system to consist of 22 covalent bonds and a critical interhelix through-space jump of 3 Å between the C\(_{\text{D}}\) of Lys22 and C\(_{\text{F}}\) of Ile23′ of the next heptad repeat.\(^{52}\) Interestingly, a secondary pathway is also identified that has the same number of covalent interactions and only a 20% lower coupling strength than that of the primary path because of a slightly longer through-space jump occurring between the C\(_{\text{A}}\) of Glu20 and the C\(_{\text{D}}\) of Leu19′. Thus, ongoing work in our laboratory is attempting to chemically modify the nature of the peptide–peptide interface to probe the mechanisms of interfacial ET reactions.

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