mL, round-bottomed flask equipped with a reflux condenser and N_2 inlet was charged with $NaNH_2$ (5.0 g, 128 mmol, 12.6 equiv) and dry toluene (50 mL). The top of the condenser was connected to a dry ice–acetone-cooled cold-finger trap (packed loosely with glass wool) with a 2-cm section of Tygon tubing. A slow stream of dry N_2 was introduced into the reaction flask through the N_2 inlet and exited through the cold trap via a mineral oil bubbler. A solution of *exo*-5-benzoylbicyclo-[2.1.0]pentane-*endo*-5-*d* (1.75 g, 10.1 mmol) in toluene (10 mL) was added to the reaction flask via syringe, and the stirred suspension was heated at reflux. After 3 h, the heat was removed, and the cold trap was connected directly to the reaction flask by removal of the reflux condenser. When the reaction flask had cooled to room temperature, the cold finger was isolated from the apparatus, and the bicyclopentane was stored at −78 °C.

***endo*-4-Phenyl-2,4,6-triazatricyclo[5.2.1.0^{2,6}]decane-3,5-dione-*syn*-10-*d*.** This urazole was prepared by the method of Dougherty et al.[34] *N*-Phenyl-1,2,4-triazoline-3,5-dione[35] (1.77 g, 10.1 mmol) was placed in a 100-mL, round-bottomed flask equipped with a water-cooled spiral condenser. A dry ice–acetone-cooled Dewar condenser was placed on top of the spiral condenser and the reaction apparatus was purged with dry N_2. Bicyclo[2.1.0]pentane-*endo*-5-*d* was transferred from its chilled container to the reaction flask with five 10-mL portions of hexanes. The reaction mixture was heated for 3 h at reflux and was allowed to cool to room temperature. Purification was achieved by elution down a 45-mm silica gel column with 1:1 hexanes/ethyl acetate. Pure *endo*-4-phenyl-2,4,6-triazatricyclo[5.2.1.0^{2,6}]decane-3,5-dione-*syn*-10-*d* (250 mg, 1.02 mmol) was obtained in a combined 10% yield for the two steps from 5-benzoylbicyclo[2.1.0]pentane. Alternatively, conducting the reaction in isooctane solution in a sealed tube resulted in a 3% yield: ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.37–7.47 (m, 5 H), 4.67 (br s, 2 H), 1.78–2.00 (m, 5 H).

2,3-Diazabicyclo[2.2.1]hept-2-ene-*endo*-7-*d* (5). A 100-mL, round-bottomed flask equipped with a reflux condenser was charged with a 1:1 mixture of 2-propanol and methanol (35 mL). The solution was deoxygenated with a N_2 purge for 15 min. KOH (1.4 g, 25 mmol) and *endo*-4-phenyl-2,4,6-triazatricyclo[5.2.1.0^{2,6}]decane-3,5-dione-*syn*-10-*d* (300 mg, 1.23 mmol) were added successively. The stirred solution was heated for 18 h at reflux under a N_2 atmosphere. After cooling to room temperature, the solution was acidified to pH 2 with concentrated HCl and then heated at 70 °C for 5 min to effect decarboxylation. After neutralization to pH 7 with 6 N aqueous ammonia and cooling to 0 °C in an ice bath, 2 mL of a 1 M aqueous $CuCl_2$ solution was added. The solution was readjusted to pH 7 with additional ammonia, resulting in the precipitation of the brick-red copper–azo complex. Stirring was continued for 15 min, and the complex was collected in a Büchner funnel. The complex was washed with two 1-mL portions of ice-cold saturated aqueous NaCl solution and was transferred to a 60-mL separatory funnel. The complex was decomposed by the addition of 10 mL of a 6 N aqueous NH_3 solution. The blue solution was extracted with four 10-mL portions of ether. The combined extracts were washed successively with H_2O (10 mL) and saturated aqueous NaCl (10 mL) and were dried over Na_2SO_4. After decantation from the drying agent, the solution was heated to 70 °C in an oil bath and the ether was removed by distillation through a 10-cm column packed with glass helices. When the volume had been reduced to approximately 1 mL, pentane (10 mL) was added, and the distillation was continued. When the volume had again been reduced to 1 mL, the distillation flask was removed, and its contents cooled to −78 °C under a N_2 atmosphere, resulting in precipitation of the azo compound. The supernatant was removed by decantation. Residual pentane was removed by warming the flask in an oil bath at 50 °C for 5 min. 2,3-Diazabicyclo[2.2.1]hept-2-ene-*endo*-7-*d* (**5**) (43 mg, 0.44 mmol) was obtained in 36% yield. Analysis by ^{1}H NMR showed the presence of a minor unidentified impurity. The impurity was chemically inert under pyrolysis conditions and contained no deuterium as was evident from the ^{2}H NMR spectrum of the azo compound: ^{1}H NMR (200 MHz, $CDCl_3$) δ 5.35 (br s, 2 H), 1.70–1.90 (m, 2 H), 1.40 (s, 1 H), 1.13–1.30 (m, 2 H).

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Acknowledgment. We thank Professor Gregory Ezra for bringing ref 24a and b to our attention. The theoretical work was conducted using the Cornell National Supercomputer Facility, a resource Center for Theory and Simulations in Science and Engineering (Cornell Theory Center), which receives major funding from the National Science Foundation and IBM Corporation, with additional support from New York State and members of the Corporate Research Institute.

Electron Transfer in Di(deoxy)nucleoside Phosphates in Aqueous Solution: Rapid Migration of Oxidative Damage (via Adenine) to Guanine

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Abstract: In aqueous solution, the one-electron loss centers created statistically by the oxidant $SO_4^{\bullet-}$ or by photoionization in di(2′-deoxy)nucleoside phosphates (DNPs) containing the base guanine (G) become localized at G, as concluded from pulse radiolysis and 193-nm laser photolysis experiments. From the latter it is evident that, in the case of adenylyl(3′→5′)guanosine (ApG), the charge-transfer process is complete in ≤50 ns. With DNPs containing a pyrimidine and the purine base adenine, the oxidative damage is collected by the adenine moiety ($k \geq 2 \times 10^5$ s^{-1}).

Introduction

It has long been known that the electron loss centers created in DNA[1,2] or DNA model compounds[3,4] by ionizing radiation or other oxidizing agents ultimately end up at guanine (G). Since with ionizing radiation the initial distribution of the electron loss centers is of statistical nature, it was proposed that the "positive holes" migrate along (or across)[5] the stacked bases of DNA until

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they are finally trapped at G. However, the results reported so far[1,3-5] are from stationary methods,[6] which means that very little can be discerned about the *rate* of the charge migration process. However, this is an important parameter since there may be competition by rapid reactions such as deprotonation[7-10] or hydration[7,10-12] of the radical cations involved.

We decided to approach this problem by studying the one-electron oxidation of 3′→5′ di(2-deoxy)nucleoside phosphates (DNPs) in aqueous solution. These molecules are ideal model compounds for the DNA macromolecule: on the one hand, their radical chemistry can be understood on the basis of the known[7-11,13-15] behavior of the *mono*nucleosides/-nucleotides;[16,17] on the other hand, the DNPs show a considerable degree of base stacking, even in aqueous solution at room temperature,[18] a property characteristic of the macromolecule.

Experimental Section

Aqueous solutions of the (2′-deoxy)nucleosides and nucleotides and (2′-deoxy)dinucleoside phosphates (from Sigma) were prepared using water purified with a Millipore Milli-Q system. Potassium peroxydisulfate, thallium(I) sulfate, *tert*-butyl alcohol, and sodium and potassium phosphates were purchased from Merck. The solutions were degassed with argon or saturated with N_2O or O_2 for ≥30 min before the experiment and the environment was maintained throughout. The solutions were flowed through 2- by 10-mm (in the pulse radiolysis experiments) or 2- by 4-mm (in the laser experiments) Suprasil quartz cells with rates of approximately 1–2 mL/min. The computer-controlled 3-MeV van de Graaff accelerator and ArF excimer laser systems have been described elsewhere.[19]

As oxidizing radicals we used $SO_4^{\bullet-}$ and[9,20] $TlOH^{\bullet+}$. $SO_4^{\bullet-}$ was generated by pulse radiolysis of deaerated aqueous solutions containing 5 mM $S_2O_8^{2-}$, 40–50 mM *tert*-butyl alcohol, and 0.1 mM DNP at pH 7 and room temperature. Under these conditions, the hydrated electrons (e^-_{aq}) react with $S_2O_8^{2-}$ to give $SO_4^{\bullet-}$, whereas the hydroxyl radicals ($OH^\bullet$) produced by the radiolytic decomposition of water are scavenged by the alcohol. In order to produce $TlOH^{\bullet+}$,[21] N_2O-saturated solutions with 2 mM Tl^+ and 0.1 mM substrate were irradiated.

Radiation chemical dosimetry was performed with the KSCN system by measuring the optical density at 480 nm due to $(SCN)_2^{\bullet-}$ formed on irradiation of N_2O-saturated aqueous solutions of 10 mM KSCN, assuming that $G((SCN)_2^{\bullet-}) = 6.0$ and $\epsilon((SCN)_2^{\bullet-}) = 7600\ M^{-1}\ cm^{-1}$.[22] In addition, argon-saturated solutions containing 5 mM $K_2S_2O_8$, 40–50 mM *tert*-butyl alcohol, and 0.1 mM 2′-deoxyguanosine 5′-monophosphate (2′-dG-5′-MP) were used under the same conditions as in the experiments with G-containing DNPs. The yields of the one-electron oxidized guanine moiety in the DNPs were then calculated by assuming that the product $G\epsilon$ is the same for the mono- and for the dinucleotide.

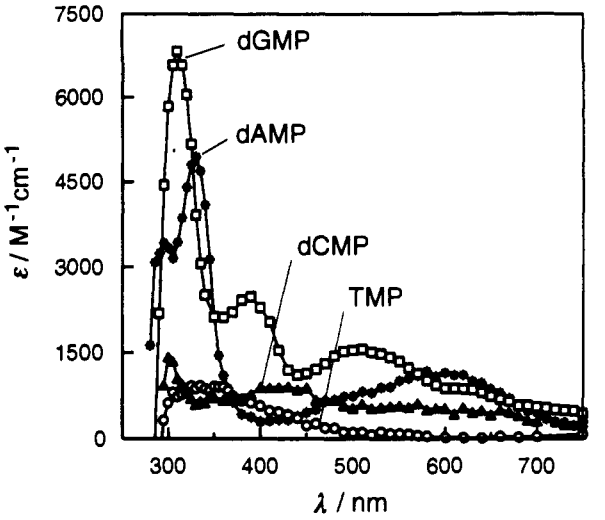

Figure 1. Absorption spectra recorded (at 10–20 μs after the pulse) on irradiation of Ar-saturated aqueous solutions at pH ≈ 7 containing 5 mM $K_2S_2O_8$, 40–50 mM *tert*-butyl alcohol, and 0.2 mM nucleotides 2′-dG-5′-MP (dGMP, □), 2′-dA-5′-MP (dAMP, *), 2′-dC-5′-MP (dCMP, ▲), and T-5′-MP (TMP, ○).

The deconvolution of the measured absorption spectra $S(\lambda)$ in terms of a set of N measured bench-mark spectra $B_i(\lambda)$ was performed by a computer program that finds the best set of coefficients c_i that yield the composite spectrum $R(\lambda)$

$$R(\lambda) = \sum_{i=1}^{N} c_i B_i(\lambda)$$

such that χ^2 (defined as the unweighted sum of the squares of the differences between the experimental and the composite spectra at each wavelength) is minimized.

$$\chi^2 = \sum_{\lambda} [R(\lambda) - S(\lambda)]^2$$

In order to obtain the bench-mark spectra, Ar-saturated aqueous solutions containing 5 mM $K_2S_2O_8$, 40–50 mM *tert*-butyl alcohol, and 0.2 mM of the nucleotides 2′-dG-5′-MP, 2′-dA-5′-MP, 2′-dC-5′-MP, and T-5′-MP were pulse irradiated. The spectra, recorded after the complete disappearance of $SO_4^{\bullet-}$, are shown in Figure 1. The spectra are similar to those obtained[7] by $SO_4^{\bullet-}$ reaction with the corresponding nucleosides. To obtain the ϵ-values, it was assumed that G(one-electron oxidized nucleotide) = $G(SO_4^{\bullet-})$ = 3.0, as calculated from the Balkas–Schuler equation.[23] The ϵ-values at λ_{max} are 6800 at 310, 4940 at 330, 1420 at 300, and 920 $M^{-1}\ cm^{-1}$ at 330 nm for the cases of 2′-dG-5′-MP, 2′-dA-5′-MP, 2′-dC-5′-MP, and T-5′-MP, respectively. From these numbers and inspection of Figure 1, it is obvious that the extinction coefficients of the pyrimidine-derived radicals are much smaller than those of the purine radicals.

Results and Discussion

In the presence of 0.1 mM DNPs ApG, TpdG, dCpdG, TpdA, and dApdC at pH 7, the $SO_4^{\bullet-}$ (produced by e_{aq}^- reaction with $S_2O_8^{2-}$ and monitored by its absorption at 450 nm) decayed by first-order kinetics with $k_{obsd} \approx 2 \times 10^5\ s^{-1}$, from which the rate constant for reaction of $SO_4^{\bullet-}$ with the DNPs results as $\approx 2 \times 10^9\ M^{-1}\ s^{-1}$. This rate constant is similar to those for reactions with the individual nucleotides.[24] The absorption spectra recorded after complete decay of $SO_4^{\bullet-}$ in the presence of the *guanine*-containing DNPs TpdG, dCpdG, and ApG were found to be all very similar (see Figure 2A for examples). The spectra of the

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(24) These rate constants, as determined by monitoring at pH ≈ 7 the rate of decay of $SO_4^{\bullet-}$ (produced by 248-nm photolysis of 70 mM $S_2O_8^{2-}$) as a function of [deoxynucleotide], are 2.3×10^9, 2.2×10^9, 1.6×10^9, and $1.6 \times 10^9\ M^{-1}\ s^{-1}$ for 5′dGMP, 5′-dAMP, 5′-dCMP, and 5′-TMP, respectively.

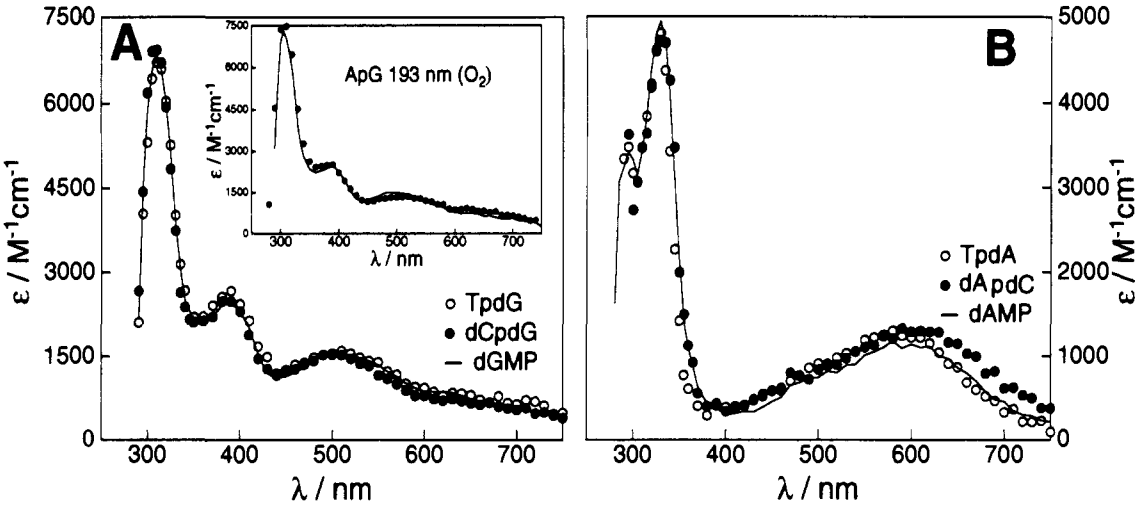

Figure 2. (A) Absorption spectra observed at ≈20 μs after pulsing deoxygenated 0.1 mM solutions of TpdG (○), dCpdG (●), or dGMP (line) containing 5 mM $S_2O_8^{2-}$ and 40 mM *tert*-butyl alcohol at pH ≈ 7. Inset: Spectrum measured at 2 μs after 193-nm laser photolysis[28] of an oxygen-saturated 80 μM solution of ApG at pH ≈ 7. The line is the calculated spectrum based on 95% GMP(-H)• and 5% AMP(-H)•. (B) Absorption spectra observed at ≈20 μs after pulsing deoxygenated 0.1 mM solutions of TpdA (○), dApdC (●), or dAMP (line) containing 5 mM $S_2O_8^{2-}$ and 40 mM *tert*-butyl alcohol at pH ≈ 7.

Table I. Rate Constants for Reaction of One-Electron Oxidized Nucleic Acid Bases with Other Bases in Aqueous Solution at 20 ± 1 °C

oxidizing radical from	identification in terms of	base	pH	$k/M^{-1}\ s^{-1}$
adenosine	radical cation	guanosine	2.3	6.0×10^8
	deprotonated radical cation		7.0	2.9×10^7
2′-deoxycytidine	radical cation	guanosine	3.0	8.3×10^8
	deprotonated radical cation		6.4	2.5×10^8
	deprotonated radical cation	2′-deoxyguanosine	7.0	2.9×10^8
2′-deoxycytidine 5′-phosphate	deprotonated radical cation	2′-deoxyguanosine 5′-phosphate	7.1	1.0×10^8
thymidine	deprotonated radical cation	guanosine	6.4	1.7×10^8

DNPs are dominated by that of the one-electron oxidized G moiety, as is evident by comparison with the spectrum from 2′-dG-5′-MP. The oxidized species is the deprotonated radical cation of G(G(-H)•).[9] An analogous situation exists in the case of TpdA and dApdC, where the resulting spectra (see Figure 2B) are characteristic of the one-electron oxidized A moiety (see later). Concerning the G-containing DNPs, the *yields* of G(-H)• were found to be 90–100%. That $SO_4^{\bullet-}$ reaction with the DNPs leads to oxidation of only G was confirmed by reacting the DNPs ApG and TpdG at pH ≈ 7 with $TlOH^{\bullet++}$ ($k = 5 \times 10^8\ M^{-1}\ s^{-1}$), an oxidant known to react predominantly with G[20] to give, at pH 7, G(-H)•.[9] The absorption spectra recorded after completion of the reaction of $TlOH^{\bullet++}$ with the DNPs were found to be identical to each other and to those obtained on reaction of $SO_4^{\bullet-}$ with the DNPs, from which it is concluded that the same transient (G(-H)•) is formed with the same yield. The spectra of the DNPs containing the one-electron oxidized and deprotonated G moiety remained unchanged until 1 ms after the pulse.

The exclusive formation of G(-H)• from reaction of the DNPs with $SO_4^{\bullet-}$ can be explained in two ways: (a) $SO_4^{\bullet-}$, which is usually *not* a particularly selective radical, reacts with the DNPs *selectively* by only attacking at the G part and (b) $SO_4^{\bullet-}$ reacts *unselectively*, i.e., it attacks *both* of the two bases in the dinucleotide, e.g., in the proportion of the rate constants for reaction with the component *mono*nucleotides.[24] One-electron oxidation of the non-G base is followed by repair by electron transfer (ET) (see eq 1) from G followed by deprotonation to yield G(-H)•. In this case, since the spectrum observed directly after reaction with $SO_4^{\bullet-}$ is that of G(-H)• ($k_{obsd} = 2 \times 10^5\ s^{-1}$), the rate constant for ET is greater than or equal to this number.

If ET from G to A occurs as an *intra*molecular process, it could also be possible *inter*molecularly. This was tested by reacting $SO_4^{\bullet-}$ with adenosine (Ado, 3 mM) and guanosine (Guo, 0.4–1 mM). The initial spectra were those of an ≈3:(0.4–1) mixture of the one-electron oxidation products[8,9] of the nucleosides. The spectra changed to give that[9] of the Guo radical with a rate increasing from pH ≈ 7 to 3 in a sigmoidal way with an inflection point at 3.4. At pH ≈ 7, the bimolecular rate constant for reaction of the Ado radical (identified as Ado(-H)•, resulting from *deprotonation* at N^6 of the radical cation)[8,16] with Guo is $2.9 \times 10^7\ M^{-1}\ s^{-1}$ (for this and related rate constants see Table I). However, at pH 2.3 the rate constant is $6.0 \times 10^8\ M^{-1}\ s^{-1}$. This higher value is assigned to reaction of the Ado radical *cation*.[25] On the basis of the redox potentials of adenosine and guanosine in aqueous solution at pH 7,[26] the thermodynamic driving force for reaction of Ado(-H)• with Guo at pH 7 is ≈5 kcal/mol.[20b]

After having established that *inter*molecular ET from G to $A^{\bullet+}$, to A(-H)•, or to the one-electron oxidized cytosine moiety is possible (see Table I), an attempt was made to measure the *rate* of the *intra*molecular ET process in the DNP ApG.[27] For this purpose, oxidation of the two bases in the DNP has to occur (i) rapidly and (ii) *un*selectively. This is possible using 193-nm laser photolysis by which the purine bases, nucleosides, and nucleotides in aqueous solution are ionized in a monophotonic process in ≤20 ns.[28]

(25) The previously given value for the pK_a of ≤1, which was based on assumed differences of absorption spectra,[16] is probably too low (Steenken, S., unpublished results). It is also possible that the radical cation of Ado [formed by reaction of $SO_4^{\bullet-}$ with *protonated* Ado (pK_a(Ado) = 3.5)] reacts very rapidly with water to give an OH adduct which oxidizes Guo. However, the OH adducts of Ado are either reducing or only weakly oxidizing, see ref 8. Therefore, the observed increase in reactivity with decreasing pH is considered not to be due to OH–adduct formation.

(26) See Jovanovic, S. V.; Simic, M. G. *J. Phys. Chem.* **1986**, *90*, 974 and ref 20b.

(27) In the DNPs, due to the possibility of base-stacking[18] resulting in overlap of the π-electron systems of the two bases, the activation barrier for ET from guanine to the radical of the neighboring base should be very low, and the rate constant for this reaction should thus be high. The rate of ET along the DNA helix has been estimated to be up to $10^{14}\ s^{-1}$, cf. Dee, D.; Baur, M. E. *J. Chem. Phys.* **1974**, *60*, 541. The rate between two intercalated dyes has been determined to be up to $10^9\ s^{-1}$: Brun, A. M.; Harriman, A. *J. Am. Chem. Soc.* **1992**, *114*, 3656. For information on parameters influencing ET rates, see Bolton, J. R.; Mataga, N.; McLendon, G., Eds. *Electron Transfer in Inorganic, Organic, and Biological Systems*; ACS Advances in Chemistry Series 228; American Chemical Society: Washington, DC, 1991.

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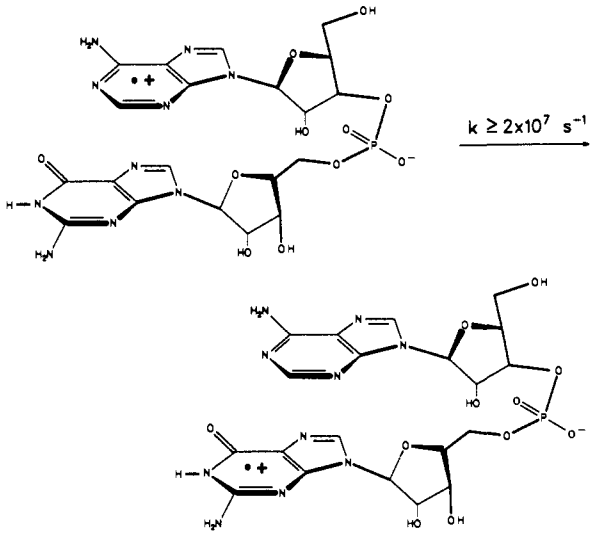
A deoxygenated 0.1 mM solution of ApG was photolyzed at pH 3.65 and 7.2. It was observed that the absorption spectrum, as measured between 280 and 400 nm and recorded 50 ns after the laser pulse, was identical to the spectrum of the guanosine radical cation $G^{\bullet+}$.[29] At pH ≈ 7, there were time-dependent changes of the spectrum on the microsecond time scale interpretable in terms of deprotonation of $G^{\bullet+}$ to yield G(-H)•. At >400 nm, the hydrated electron was visible whose absorption overlaps with the broad band[9] of $G^{\bullet+}$ or G(-H)•. The electron could be removed by saturating the solution with O_2.

On the basis of the quantum yields of photoionization and of the extinction coefficients of the bases at 193 nm,[28] the photoejected electrons originate to 70% from G and to 30% from A. The observed absorption spectrum, however, was found, using the deconvolution technique described in the Experimental Section, to correspond to 95% of G radicals (Figure 2A, inset). This result thus means intramolecular ET from G to $A^{\bullet+}$ in ≤50 ns, which corresponds to the rate constant $\geq 2 \times 10^7\ s^{-1}$ (eq 1).[30] The driving force for ET from G to a pyrimidine base$^{\bullet+}$ is likely to be higher than that from G to $A^{\bullet+}$, since the ionization potentials of the pyrimidines[31] are higher than that of the A moiety.



(1)

In order to see whether positive charge transfer also occurs from a pyrimidine base$^{\bullet+}$ to *adenine*, the other purine base of DNA, i.e., whether adenine can also act as a "sink" for positive charge (or function as an electron donor to a pyrimidine radical cation), the DNPs TpdA and dApdC were studied using oxidation by $SO_4^{\bullet-}$. From the results (Figure 2B) it is evident that at pH ≈ 7 $SO_4^{\bullet-}$ leads in all cases to the same species, the neutral radical formed by deprotonation from N^6 of the radical cation,[8] with yields ≥90%. If it assumed that $SO_4^{\bullet-}$ reacts with the two types of bases in the DNPs *un*selectively, i.e. with rates that correspond to the reactivity[24] with the *individual* nucleotides, the essentially quantitative formation of A(-H)• based on the initial yield of $SO_4^{\bullet-}$ means that electron transfer has occurred from A to the pyrimidine radical cations. From k_{obsd} for formation of A(-H)•, the rate constant for ET from A is $\geq 2 \times 10^5\ s^{-1}$.[32] Since $A^{\bullet+}$ (or A(-H)•) is able to be repaired by electron transfer from G, A can serve as a relay in the ET from G to a pyrimidine radical cation. This (indirect) path obviously makes ET over larger distances much more efficient than it would be in its absence.

Due to its highly damaging action, a very important oxidizing agent is the OH radical. On reaction of OH• with guanylyl-(3′→5′)adenosine (GpA) in neutral solution, time-dependent absorption spectra were observed which are interpreted in terms of the (unimolecular) transformation reactions (dehydration and ring opening) of the OH adducts at the adenine[8] and guanine[33] moiety. Since the rate constants are very similar to those of the OH adducts of the *mono*nucleoside phosphates GMP and AMP,[8,9] these reactions are apparently not affected by the neighboring base in the DNP.[34,35] Since dehydroxylation of the C4-OH adduct of A leads to $A^{\bullet+}$ (or A(-H)•),[16,17,36] this OH•-induced damage can be repaired by ET from G. In this reaction sequence, the rate-determining step is the dehydration reaction.

Summary

In conclusion, the results reported show the rapid and efficient "hole migration" toward adenine and from there on to guanine from the pyrimidine base radical cations or even their less strongly oxidizing *deprotonated* forms created in dinucleoside phosphates by one-electron oxidation, here effected by $SO_4^{\bullet-}$ and by photoionization and also by OH• addition to A followed by dehydration. The rate constant for ET was found to be $\geq 2 \times 10^7\ s^{-1}$ in the case of ApG and $\geq 2 \times 10^5\ s^{-1}$ in the other[32] cases. Values of this magnitude mean that there is only a low chance for competing reactions such as reaction with water or deprotonation.[37] However, on the basis of the results on the *inter*molecular ET, even if deprotonation of the radical cations occurs, this may not necessarily "protect" them against repair by ET from G.

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(29) At λ ≤ 400 nm, there is essentially no interference due to e^-_{aq}.

(30) Analogous 193-nm photoionization experiments with DNPs containing a *pyrimidine* base are not possible because the pyrimidine extinction coefficients and ionization yields at 193 nm are too low.[28]

(31) Hush, N. S.; Cheung, A. S. *Chem. Phys. Lett.* **1975**, *34*, 11. Peng, S.; Padva, A.; LeBreton, P. R. *Proc. Natl. Acad. Sci. USA* **1976**, *73*, 2966. McGlynn, S. P.; Dougherty, D.; Mathers, T.; Abdulner, S. In *Excited States in Organic Chemistry and Biochemistry*; Pullman, B.; Goldblum, N., Eds.; Reidel: Dordrecht, 1977; p 247. From ref 26 it can be concluded that the difference in aqueous-phase oxidation potential between adenosine and pyrimidine nucleosides is ≥0.8 V.

(32) This value for the lower limit merely reflects the fact that the *production* of the radical cation (by $SO_4^{\bullet-}$) is rate-limiting at 0.1 mM DNP.

(33) Candeias, L. P.; Steenken, S. In *The Early Effects of Radiation on DNA*; Fielden, E. M.; O'Neill, P., Ed.; NATO ARW Series H54; Springer: Berlin, 1991; p 265.

(34) An analogous observation has been made in the case of polyA (Hankiewicz, E.; Bothe, E.; Schulte-Frohlinde, D. *Free Radical Res. Commun.* In press.

(35) From the similarity of the kinetics and of the spectral properties of the changes with those of the component *mono*nucleotides it appears that the OH adducts are not involved in charge-transfer reactions.

(36) Fielden, E. M.; O'Neill, P.; Steenken, S. *In The Early Effects of Radiation on DNA*; Fielden, E. M.; O'Neill, P., Ed.; NATO ARW Series H54; Springer: Berlin, 1991; p 231.

(37) The ET process may, however, be reversible, in which case these competing reactions could still proceed under conditions of sufficiently long radical lifetime such as in DNA.[2b]