Electron Spin Resonance Study of Radicals derived from Cyclic Hydrazides

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Transient radicals derived from cyclic hydrazides (QH_2), generated by *in situ* photolysis of flowing aqueous solutions in the presence of either added oxidants or reductants, have been studied by e.s.r. The radicals obtained through one-electron oxidation at basic pH values have a semiquinone-type structure ($Q^{-\bullet}$) of the same type as certain intermediates in the chemiluminescence of luminol and other cyclic hydrazides. At acidic pH values, the conjugate acids ($QH^\bullet$) of the semiquinone radicals derived from cyclic hydrazides of both phthalic and naphthalene-2,3-dicarboxylic acids were identified as the corresponding *o*-formyl carboxylate radicals, produced through a mechanism involving loss of dinitrogen. Reduced radicals ($QH_2^{-\bullet}$ and $QH^{2-\bullet}$) generated in aqueous solution in the presence of propan-2-ol were detected only in the case of cyclic maleohydrazide. Reactions of hydrazides with the $OH^\bullet$ radical were also investigated; an OH-adduct to the C=C bond of the protonated maleohydrazide was identified in the pH range 2—3.

The chemistry of cyclic hydrazides has attracted considerable attention recently, with the aim of clarifying the mechanism of their chemiluminescence. Although pulse radiolysis[1—9] has revealed unambiguously the existence of transient radicals as intermediates in this mechanism, the proposed structures need confirmation by an independent method. An e.s.r. investigation of the radicals derived from cyclic hydrazides therefore seems appropriate.

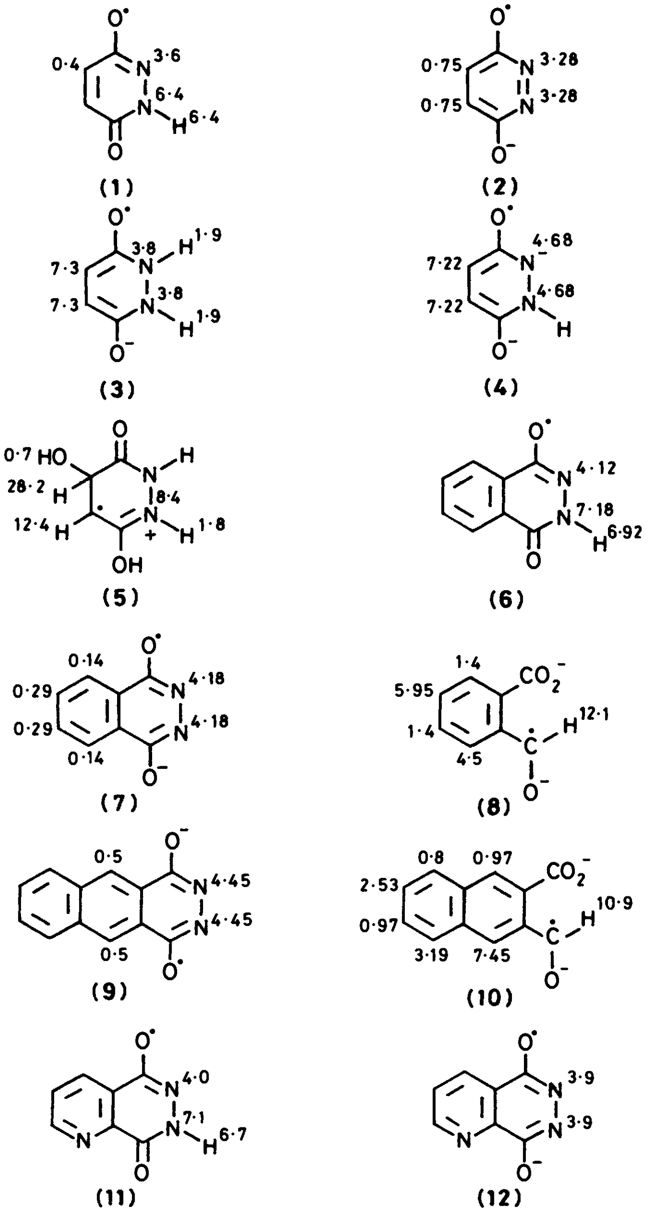
Experimental

Materials.—Pyridazine-3,6-diol (cyclic maleohydrazide) (Fluka) was used without further purification. 2,3-Dihydrophthalazine-1,4-dione (cyclic phthalohydrazide),[10] 6,7-dihydropyrido[2,3-*d*]pyridazine-5,8-dione,[11] and 2,3-dihydrobenzo[*g*]phthalazine-1,4-dione[12] were prepared as described in the literature. All other chemicals used were of reagent grade.

Generation of Radicals.—Typically aqueous 1—3mM solutions of hydrazides were oxidized by *in situ* photolysis of the flowing solutions in the presence of 30mM-potassium persulphate with acetone (1%) as photosensitizer. Reduction was accomplished in aqueous 1—3mM-solutions of hydrazides containing propan-2-ol (5%) and acetone (5%). The pH values of the solutions were adjusted by adding small amounts of either perchloric acid or sodium hydroxide. Photolysis was carried out with a previously described set-up.[13] The radiomimetic system $Ti^{3+} + H_2O_2$ was used to generate $OH^\bullet$, which was treated with the hydrazide in a special quartz cell with a mixing chamber, following the procedure described by Dixon and Norman.[14] E.s.r. spectra were recorded with a Bruker 200 D spectrometer.

Results and Discussion

Radicals derived from Cyclic Maleohydrazide.—Oxidation of an aqueous solution of the hydrazide at pH 2.5—6.0 with $SO_4^{-\bullet}$ (from photolysis of potassium persulphate) gave a solution with an e.s.r. spectrum showing the interaction of one unpaired electron with two nonequivalent protons and two nonequivalent nitrogen nuclei. This spectrum is identical with that reported[15] for the product of oxidation of the hydrazide with Ce^{IV}–H_2O_2. This was assigned[15] the structure (1) on the assumption that the coupling of a third proton is smaller than the linewidth.†



(1) (2) (3) (4) (5) (6) (7) (8) (9) (10) (11) (12)

Hyperfine coupling constants (× 10^4) in T

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† The assignment[15] is based on comparison with *N*-substituted homologous radicals.

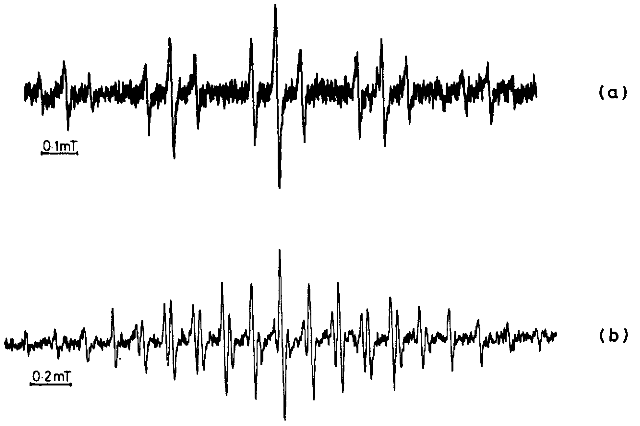
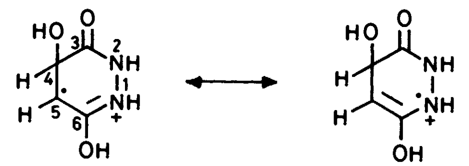


Figure 1. E.s.r. spectrum of the radicals derived from cyclic maleohydrazide: (a) by oxidation at pH 7 [radical (2)]; (b) by reduction at pH 10.0 [radical (3)]



(5a) (5b)

At pH $\geqslant$ 7 another, much stronger, e.s.r. spectrum appeared, which we assigned to the semiquinone-type radical (2) [the conjugate base of (1)], since it shows hyperfine coupling constants from a pair of equivalent protons and a pair of equivalent nitrogen nuclei [Figure 1(a)].

Cyclic maleohydrazide was reduced by electron transfer from either the $(CH_3)_2\dot{C}OH$ radical or its conjugate base. At pH 9.2—11 we obtained an e.s.r. spectrum which displayed splitting constants from two pairs of equivalent protons and from a pair of equivalent nitrogen nuclei [Figure 1(b)]. This spectrum is compatible with structure (3). The conjugate acid of the radical (3) was not detected at lower pH. At pH $\geqslant$ 12.5 we found another radical showing an e.s.r. spectrum with coupling constants from a pair of equivalent protons and a pair of equivalent nitrogen nuclei. This spectrum exhibits an alternating linewidth effect due to modulation of the hyperfine coupling constants which can arise from a fast intramolecular proton exchange. A radical dianion with structure (4) is compatible with these observations.

The reaction of cyclic maleohydrazide with OH$^\bullet$ was also investigated. At pH 2—3 we recorded a weak e.s.r. spectrum, which shows hyperfine couplings from four nonequivalent protons and only one nitrogen nucleus. At higher pH no e.s.r. spectrum could be recorded, although Eriksen, Lind, and Merényi[5] detected at pH 3.5, by pulse radiolysis of the hydrazide in aqueous solution, a transient species, which they assumed to be a neutral radical obtained by addition of OH$^\bullet$. Therefore we attribute the e.s.r. spectrum at pH 2—3 to the conjugate acid of this radical, *i.e.* the radical cation (5). The values of the two largest constants can be assigned to the protons in positions 4 and 5 [structure (**5a**)] according to the known values for hyperfine coupling constants of protons in similar positions of heterocyclic radicals.[16] The smallest splitting constant was assigned to the proton of the OH group in position 4.[16] The large nitrogen splitting assigned to position 1 may arise from the contribution of a mesomeric structure such as (**5b**).

We can now see that the e.s.r. spectrum is not compatible with any of the four tautomers of the neutral radical [deprotonated (5)] detected on pulse radiolysis,[5] because the remaining *N*-proton in position 2 could not be responsible for the proton coupling of 1.8×10^{-4} T: it would then be bonded to a nitrogen atom with no coupling. The only nitrogen coupling of 8.4×10^{-4} T in the e.s.r. spectrum would have to be assigned to position 1 in the neutral radical [deprotonated (5)] for the same reasons as in the radical cation (5).

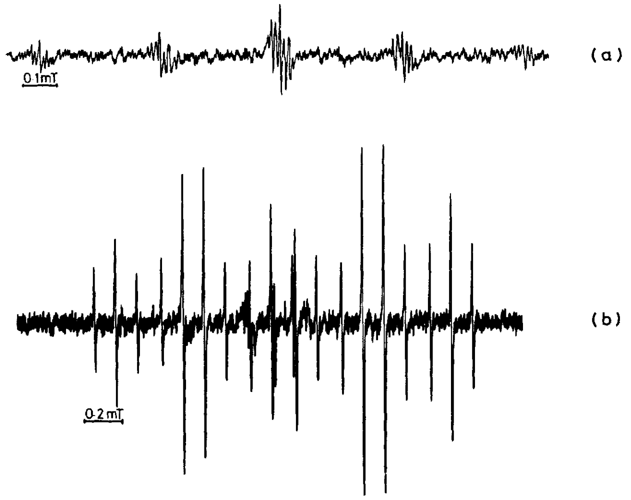


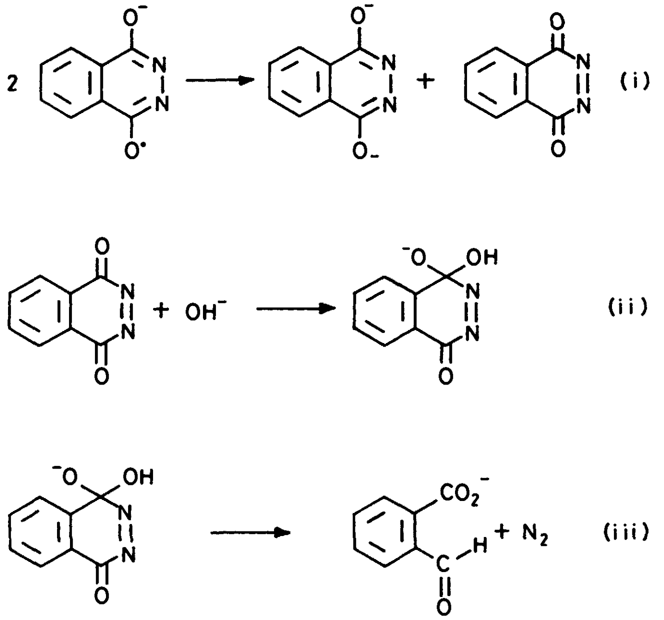
Figure 2. E.s.r. spectrum of radicals derived from cyclic phthalohydrazide: (a) by oxidation at pH 8.2 [radical (7)]; (b) by oxidation at pH 11 [radical (**8**)]

Radicals derived from Cyclic Phthalohydrazide.—By oxidizing this hydrazide at pH 4.2—6.8 we obtained the radical (6), identical with that reportedly[15] obtained by using the Ce^{IV}–H_2O_2 system. The spectrum obtained at pH 7—10 [Figure 2(a)] is clearly distinguishable from that observed at lower pH. It can be assigned to a semiquinone-type radical (7) by comparison with the hyperfine coupling constants of the 1,4-naphthosemiquinone radical.[17] Radicals of type (7) have been proposed as intermediates in the mechanism of chemiluminescence of cyclic hydrazides on the basis of pulse radiolysis experiments.[1,2,4,6–9] At pH $\geqslant$ 11 we observed a spectrum where nitrogen coupling constants were missing [Figure 2(b)]. This was assigned to a radical with structure (**8**), confirmed by the identical e.s.r. spectrum obtained by photolysing 2-formylbenzoic acid in aqueous propan-2-ol in the same pH range.

The assignment of the hyperfine coupling constants can be made by comparison with the values reported for the same radical in dimethyl sulphoxide.[18]

The formation of the radical (**8**) from cyclic phthalohydrazide involves the loss of a nitrogen molecule. This process takes place only after photolysis, since unchanged hydrazide was recovered after treatment with alkali. As recently proposed in a study of luminol chemiluminescence,[9] such a mechanism involves a disproportionation of the radical (7) [reaction (i)] followed by the addition of hydroxide ion to the carbonyl group of the diazoquinone obtained [reaction (ii)]. The resulting adduct, by loss of dinitrogen, gives the 2-formylbenzoate [reaction (iii)], which is eventually reduced to its radical anion by the $(CH_3)_2C^\bullet$–O^- radical.

The analogous radical formed from cyclic maleohydrazide by loss of dinitrogen was not observed. This result is in agreement with the conclusions of Eriksen *et al.*,[5] who studied this hydrazide by pulse radiolysis and found no reaction similar to (ii) between its diazoquinone and hydroxide ion.



Radicals derived from Other Cyclic Hydrazides.—Radicals derived from 6,7-dihydropyrido[2,3-*d*]pyridazine-5,8-dione and 2,3-dihydrobenzo[*g*]phthalazine-1,4-dione were also investigated. By oxidizing the latter we obtained a semiquinone-type radical (**9**) (at pH 9—11) and a radical (**10**) (at pH ⩾ 11.8) resulting from loss of dinitrogen. The assignment of the hyperfine coupling constants of the radical (**9**) can be made by comparison with the 1,4-anthrasemiquinone radical[19] and those of the radical (**10**) by comparison with the radical anion of 2-nitronaphthalene.[20]

From 6,7-dihydropyrido[2,3-*d*]pyridazine-5,8-dione we generated the radicals (**11**) (at pH 3—5) and (**12**) (at pH ⩾ 9) through oxidation. The assignment of the coupling constants can be made straightforwardly by comparison with the radicals (**6**) and (**7**).

Acknowledgements

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