Reversibility in the Reaction of Cyclohexadienyl Radicals with Oxygen in Aqueous Solution

Xingwang Fang, Xianming Pan, Anja Rahmann, Heinz-Peter Schuchmann, and Clemens von Sonntag*

Abstract: Hydroxyl radicals were generated radiolytically and reacted with a number of benzene derivatives (PhH). In the presence of oxygen, the hydroxycyclohexadienyl radicals thus formed were converted into their corresponding peroxyl radicals. Pulse radiolysis has shown the oxygen addition (forward reaction, f) to be reversible (reverse reaction, r) [Eq. (1)]. The peroxyl radicals can eliminate $HO_2^{\cdot}$ to yield phenols, alongside some ring-fragmentation products (product-forming reaction, p). The rate constants for the forward and reverse reactions (k_f and k_r) and the corresponding stability constants K ($= k_f/k_r$) were determined for the hydroxycyclohexadienyl radicals derived from anisole, toluene, fluorobenzene, benzene, chlorobenzene, benzyl chloride, benzoate ion, phenylalanine, and terephthalate ion. The constants k_f lie between 8×10^8 (anisole) and $1.6 \times 10^7\ dm^3 mol^{-1} s^{-1}$ (terephthalate ion), and k_r between 7.5×10^4 (toluene) and $3.4 \times 10^3\ s^{-1}$ (terephthalate ion). The stability constants lie between 2.6×10^4 (benzene) and $3.3 \times 10^3\ dm^3 mol^{-1}$ (phenylalanine). The rate constants for the product-forming reactions k_p are between 5.5×10^3 (anisole) and $3.4 \times 10^2\ s^{-1}$ (benzoate). For the peroxyl radical derived from phenylalanine, a bond dissociation energy of 5.5 kcal mol^{-1} has been derived. A number of hydroxycyclohexadienyl radicals (e.g., those derived from benzoic acid, ethylbenzoate, benzonitrile, and nitrobenzene) react too slowly to allow the equilibrium constant to be determined by means of pulse radiolysis. These reactions have rate constants k_f in the order of $5 \times 10^6\ dm^3 mol^{-1} s^{-1}$, except for nitrobenzene where the reaction is too slow for measurement. The rate constants k_r are below $500\ s^{-1}$, and the product-forming reaction is too slow to be detected by pulse radiolysis. γ-Radiolysis of N_2O/O_2(4:1)-saturated aqueous solutions of benzonitrile gave dimeric compounds (e.g., dicyanobiphenyls) in low yield, alongside the three isomeric phenols; this again proves the low reactivity of its hydroxycyclohexadienyl radical toward oxygen.

Keywords
kinetics · peroxyl radicals · pulse radiolysis · radicals · superoxide radicals

Introduction

Oxygen is omnipresent in the environment, and whenever free radicals are generated, peroxyl radicals are likely to ensue. For the study of their reactions, especially in aqueous solution, radiation techniques such as pulse radiolysis are very often the method of choice.[1] The rate of reaction of carbon-centered radicals with molecular oxygen in aqueous solutions is usually close to diffusion-controlled ($k_f \approx 2 \times 10^9\ dm^3 mol^{-1} s^{-1}$) and irreversible at room temperature.[2, 3] An exception to this rule of thumb is encountered with carbon-centered radicals that have a high spin density at a hetero atom, such as phenoxyl-type radicals[4, 5a] and radicals derived from tryptophan[5b] and from purines.[6, 7] These radicals either do not react with O_2 at all, or do so much more slowly than the diffusion-controlled rate.

An interesting class of carbon-centered radical is the cyclohexadienyl radical. The prototype adds oxygen very rapidly ($k_f = 1.2 \times 10^9\ dm^3 mol^{-1} s^{-1}$); this is followed by rapid elimination of $HO_2^{\cdot}$ and other competing reactions ($k_p \geq 8 \times 10^5\ s^{-1}$).[8] This is in contrast to the hydroxycyclohexadienyl radical, formed by the addition of an OH radical to benzene, whose behavior can be summarized by reaction (1). Its reaction

$$HOPhH^{\cdot} + O_2 \underset{r}{\overset{f}{\rightleftharpoons}} HOPhHO_2^{\cdot} \xrightarrow{p} PhOH + HO_2^{\cdot} + \text{other products} \qquad (1)$$

with O_2 is slower ($k_f = 3.1 \times 10^8\ dm^3 mol^{-1} s^{-1}$) and reversible ($k_r = 1.2 \times 10^4\ s^{-1}$).[9] Further, the $HO_2^{\cdot}$ elimination reactions, which lead to the phenols, and other competing reactions are much slower ($k_p = 800\ s^{-1}$)[9b] than in the prototypic case. This holds for the hydroxycyclohexadienyl radicals of phenylalanine as well.[10]

We have now extended the study to other substituted hydroxycyclohexadienyl radicals.[11] It will be shown that some of these, such as the cyano-substituted radicals, react with O_2 much more slowly, so slowly, in fact, that the reaction can be monitored by pulse radiolysis only at relatively high O_2 concentrations and low doses per pulse (low in order to reduce the relative importance of the bimolecular decay). Their reactivity toward O_2 can, however, be readily established by product studies carried out at the still lower dose rates of γ-radiolysis, that is, at lower steady-state concentrations of radicals.

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0947-6539/95/0107-0423 $ 30.00 + .25/0

Experimental Procedure

The chemicals used were of the highest purity commercially available. Solutions were made up in Milli-Q-filtered (Millipore) water. Prior to irradiation the solutions were saturated with either O_2-free N_2O or with mixtures of N_2O and O_2 (4:1 mixture available from Messer Griesheim; mixtures in other proportions were made up from N_2O and O_2 by means of a Brooks (Hatfield, USA) mixing device).

The pulse radiolysis setup has been described recently [12]. In such experiments the substrate concentration was typically 10^{-3} mol dm^{-3}, and 10^{-4} mol dm^{-3} whenever it was required to avoid spectral interference caused by the electron adducts, which, in the case of benzonitrile, absorb an order of magnitude more strongly in the wavelength region of interest than the hydroxycyclohexadienyl radicals [13]. To minimize the importance of hydroxycyclohexadienyl and peroxyl radical termination reactions relative to the first-order decay processes, low doses per pulse were used (in most cases 1–2 Gy pulse^{-1}; even lower doses per pulse were used when the hydroxycyclohexadienyl radical reacted very slowly with oxygen, e.g., with cyanohydroxycyclohexadienyl radical). The product-forming reactions were monitored by means of the fast reaction of $O_2^{\cdot-}$ [in neutral to weakly basic solutions, $HO_2^{\cdot}$ ($pK_a = 4.8$) [14] is fully dissociated] with tetranitromethane [TNM, 1×10^{-5} mol dm^{-3}; $k(O_2^{\cdot-} + \mathrm{TNM}) = 1.9 \times 10^9$ dm^3 mol^{-1} s^{-1}] [14], which gives rise to the strongly absorbing nitroform anion [$\varepsilon(350\,\mathrm{nm}) = 15000$ dm^3 mol^{-1} cm^{-1}] [15]. The formation kinetics of nitroform was followed at 400 nm whenever it was required to avoid spectral interference with the hydroxycyclohexadienyl radicals, which usually have a sharp absorption band around 320 nm (cf. Fig. 1 below).

γ-Irradiation of benzonitrile solutions was carried out in a ^{137}Cs source (Oris, IBL-437C) at a dose rate of 0.17 Gy s^{-1} up to a dose of 200 Gy. Products were isolated from the irradiated solutions by continuous extraction with diethyl ether in a Ludwig extractor (Normag). The extracts were dried over sodium sulfate, concentrated, and analyzed by GC-MS (Hewlett Packard GC5890SII/MSD). The three isomeric hydroxybenzonitriles and 5 out of 6 possible dicyanobiphenyl isomers were separated on a 12 m HPultra 1 capillary column. Reference material was available for the three hydroxybenzonitriles (EGA, Janssen). The dicyanobiphenyls (MW = 204 dalton) were identified on the basis of their mass spectra, which are very similar. The most abundant ions are *m/z* (%): 204 (100), 177 (20), 150 (6), 75 (7). After trimethylsilylation, isomeric cyanophenylcyanohydroxycyclohexadienes (MW 294) and bis(cyanohydroxycyclohexadienyl)(s) (MW 384) were also observed, albeit at lower concentrations. Their mass spectra are characterized by *m/z* (%): 294 (50), 252 (83), 204 (17), 176 (15), 73 (100) and 384 (13), 369 (6), 294 (13), 204 (25), 176 (23), 147 (30), 73 (100), respectively. The yields of the phenolic compounds were quantified on the basis of the corresponding reference material by high-performance liquid chromatography. Complete baseline separation of the isomers was achieved on a 125 mm Nucleosil 5C18 column (Merck) with water/10% methanol as eluent. Detection was at 222 nm. The yields of the dimeric compounds were estimated by gas chromatography, with biphenyl as an internal standard in the absence of the proper reference material, under the assumption that they show the same gas-chromatic response as the biphenyl. *G* values were calculated from yield vs. dose plots, which were linear at the low conversions used in these experiments.

The O_2-uptake was measured with the help of an oxygen-sensitive electrode (Wissenschaftlich-Technische Werkstätten, Weilheim). These measurements were carried out in situ in a ^{60}Co-γ panorama source (Nuclear Engineering) at a dose rate of 0.14 Gy s^{-1}.

Results and Discussion

Generation of the hydroxycyclohexadienyl-type radicals: The radiolysis of water leads to the formation of OH radicals, solvated electrons, and H atoms [Eq. (2)].[16] The radiation chemical

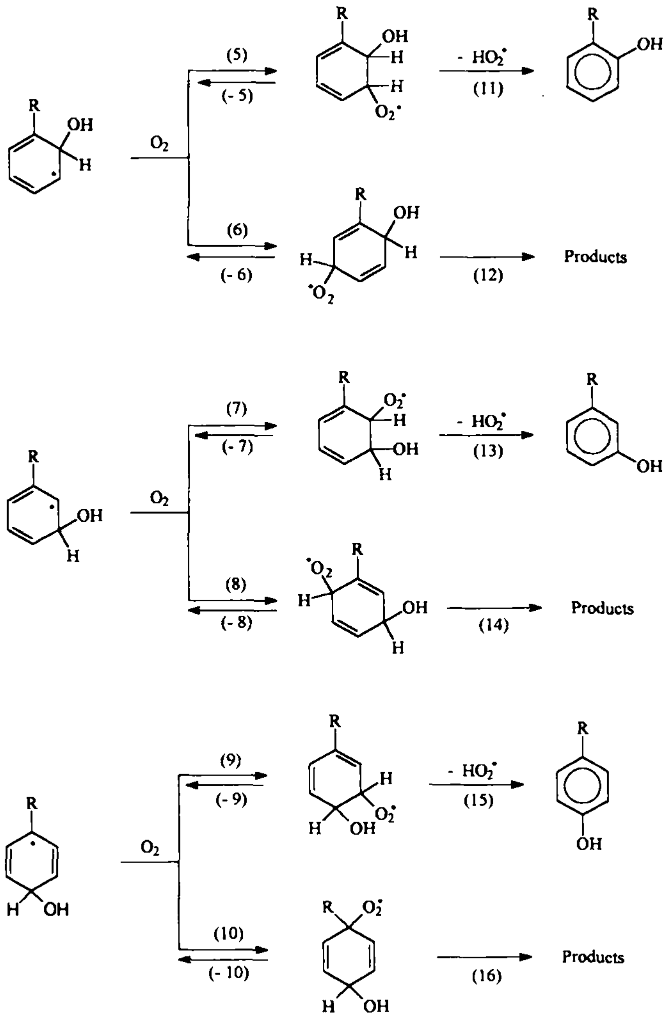
$$H_2O \xrightarrow[\text{radiator}]{\text{ionizing}} {}^{\cdot}OH + e^-_{aq} + H^{\cdot} + H^+ + H_2 + H_2O_2 \qquad (2)$$

yields (*G* values) of these primary radicals are $G(^{\cdot}OH) \approx G(e^-_{aq}) \approx 2.8 \times 10^{-7}$ mol J^{-1} and $G(H^{\cdot}) = 0.6 \times 10^{-7}$ mol J^{-1}. The solvated electron can be converted with N_2O into a further OH radical [Eq. (3)]. The OH radicals react with the aromatic

$$N_2O + e^-_{aq} \longrightarrow {}^{\cdot}OH + N_2 + OH^- \qquad (3)$$

substrates to form the corresponding hydroxycyclohexadienyl radicals HOPhH$^{\cdot}$ (cf. Scheme 1). The H atoms are scavenged by O_2 [Eq. (4)]. In the electron pulse, the ionizing radiation is delivered within 400 ns, and the reactions described above occur within pulse duration and shortly afterwards (for rate constants see ref. [17]). The subsequent reactions were followed spectrophotometrically.

$$O_2 + H^{\cdot} \longrightarrow HO_2^{\cdot} \qquad (4)$$



Scheme 1. Reactions (5)–(16).

Buildup and decay reactions of intermediates: Depending on ring substitution, the OH radicals give rise to several isomeric hydroxycyclohexadienyl radicals. On reacting with oxygen, each of these may in turn yield two different peroxyl radicals, namely, the 1,3- and 1,4-cyclohexadienyl-type species (Scheme 1). Reaction (1) is therefore a simplified representation of the reaction, but it can be shown that the kinetically complex situation where the forward and reverse reactions are both much faster than the product-forming reaction can formally, as an approximation, be treated in the same fashion as if there were only a single forward and reverse reaction, provided that the oxygen concentration is not too low (see Appendix). In particular, it is necessary to establish that, even if the rate constants of the individual forward (and reverse) reactions are quite different, the reciprocal of $t_{1/2}$ remains, for practical purposes, a linear function of the oxygen concentration; this is by no means immediately evident.

The kinetic analysis of the pulse radiolysis data is complicated by radical-termination reactions (17), which contribute to

$$R^{\cdot}, RO_2^{\cdot} + R^{\cdot}, RO_2^{\cdot} \longrightarrow \text{products} \qquad (17)$$

the decay of the absorbance. If these are disregarded, the kinetics is formally identical to that discussed in ref. [18] (cf. explanation in Appendix). In principle it is possible to eliminate the second-order complications by extrapolating the observed time constants k_{obs} (dimension, s^{-1}) to zero dose, but this multiplies the requirements with regard to pulse-radiolysis machine time. In the present case, where a series of substrates have been studied, it seemed sufficient for our purpose to carry out the experiments at a lowish pulse dose (1–2 Gy, unless specified otherwise as being yet lower). Neglecting the radical-termination reactions makes the time constants appear larger than they would be in the absence of termination. Consequently, the rate constants k_f, k_r, and k_p assigned to reaction (1) will also come out somewhat too large. The distortion will be less important for the faster initial phase of the decay (Fig. 1, inset); this is also the case when the first-order rate constants of the individual steps are large relative to the inverse of $t_{1/2}$ of pure second-order decay. This qualification notwithstanding, it is thought that the rate parameters implicit in reaction (1) and extracted in this manner are close enough to their actual values to allow insight to be gained by comparing them.

The slower decay process, which largely reflects the product-forming reaction (p) in equation (1), is adequately monitored by the reaction of TNM with $O_2^{\cdot -}$ released in this process. It can be shown that, under these experimental conditions, this monitoring reaction detects the $O_2^{\cdot -}$ release very accurately.

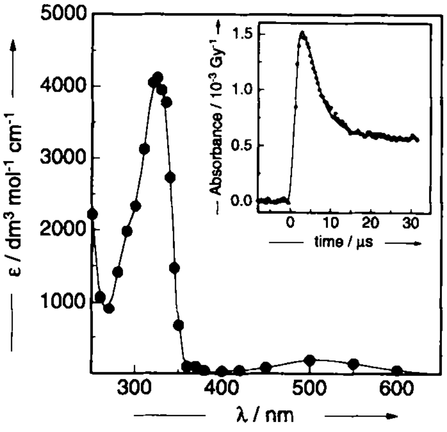


Fig. 1. Pulse radiolysis of N_2O-saturated aqueous solutions of anisole (10^{-3} mol dm^{-3}). Spectrum of the sum of the OH- and H-adduct radicals. Inset: Decay of the anisole hydroxycyclohexadienyl radicals at 325 nm in the presence of 15% O_2 and formation of the "plateau".

Anisole provides an example of a system in which the forward and reverse reactions are relatively fast and a state of approximate equilibrium is therefore rapidly attained. Its hydroxycyclohexadienyl radical is characterized by an absorption maximum at 325 nm (Fig. 1). In the absence of oxygen these radicals decay bimolecularly ($2k = 1.3 \times 10^9$ dm^3 mol^{-1} s^{-1}); in the presence of oxygen they show rapid, essentially first-order decay reaching a "plateau" (inset in Fig. 1), followed by a much slower decay of mixed first/second-order kinetics (cf. ref. [9b]). Based on reaction (1) and disregarding termination reactions (17), algebraic analysis[18] shows that the decay of hydroxycyclohexadienyl (cf. Fig. 1, inset) is governed by two rate constants: the larger one (fast first phase) can be approximated by expression (18) and the smaller one (slow second phase) by expression (19). The rate of the relatively rapid first-order decay depends on the oxygen concentration (Fig. 2), as does the height

$$k_{obs}^{+} = k_f[O_2] + k_r \tag{18}$$

$$k_{obs}^{-} = k_f k_p[O_2]/(k_f[O_2] + k_r + k_p) \tag{19}$$

of the plateau value. It can be seen from Figure 2 that the plot of k_{obs}^{+} vs. oxygen concentration is a straight line with an intercept of 3.9×10^4 s^{-1} and a slope of 8×10^8 dm^3 mol^{-1} s^{-1}. The slope represents k_f (it may be larger than the real value in the absence of termination reactions by at most 5% in the most unfavorable case), while the intercept essentially corresponds to k_r (it may be larger than the real value by a similar amount). From data of this type, a stability constant K ($= k_f/k_r$) can be calculated, for example, 2.1×10^4 dm^3 mol^{-1} in the case of anisole.

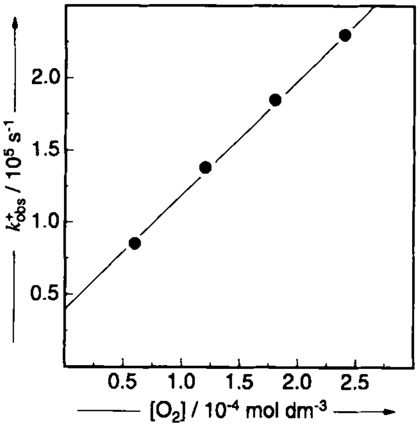


Fig. 2. Pulse radiolysis of N_2O/O_2-saturated aqueous solutions of anisole (10^{-3} mol dm^{-3}). Plot of the fast decay at 325 nm as a function of the oxygen concentration.

The stability constant can also be obtained by a different approach. K is defined by expression (20), where $[R^\cdot]$ and

$$K = [RO_2^\cdot]_{eq}/([R^\cdot]_{eq}[O_2]) = ([R^\cdot]_0 - [R^\cdot]_{eq})/([R^\cdot]_{eq}[O_2]) \tag{20}$$

$[RO_2^\cdot]$ are the concentrations of the hydroxycyclohexadienyl radicals and their corresponding peroxyl radicals, and the subscripts "eq" and "0" signify "equilibrium" and "initial", respectively. The initial absorbance is $A_0 = [R^\cdot]\varepsilon(R^\cdot)$ [$\varepsilon(R^\cdot) =$ 4000 dm^3 mol^{-1} cm^{-1}, cf. Fig. 1]. The absorbance at equilibrium is given by expression (21). Expressions (20) and (21) lead to expression (22). When the parameter $\varepsilon(RO_2^\cdot)$ is chosen correctly, the plot of A' vs. $[O_2]$ is linear; if $\varepsilon(RO_2^\cdot)$ is set too high, the curve bends upward, and if too low, downward. In the case of the unsubstituted hydroxycyclohexadienyl radical system an analysis of this type has shown that $\varepsilon(RO_2^\cdot) =$ 500 dm^3 mol^{-1} cm^{-1}, that is, it is about 13% of $\varepsilon(R^\cdot)$.[9a] The present system has been analyzed in the same way, and $\varepsilon(RO_2^\cdot) = 520$ dm^3 mol^{-1} cm^{-1} gives a straight line (Fig. 3). From these data, $K = 2.4 \times 10^4$ dm^3 mol^{-1} is obtained, in good agreement with the value 2.1×10^4 dm^3 mol^{-1} s^{-1} obtained from the kinetic data.

$$A_{eq} = [R^\cdot]_{eq}\varepsilon(R^\cdot) + [RO_2^\cdot]_{eq}\varepsilon(RO_2^\cdot) = [R^\cdot]_{eq}\varepsilon(R^\cdot) + \varepsilon(RO_2^\cdot)([R^\cdot]_0 - [R^\cdot]_{eq}) \tag{21}$$

$$1 + K[O_2] = [\varepsilon(R^\cdot) - \varepsilon(RO_2^\cdot)]A_0/[\varepsilon(R^\cdot)A_{eq} - \varepsilon(RO_2^\cdot)A_0] = A' \tag{22}$$

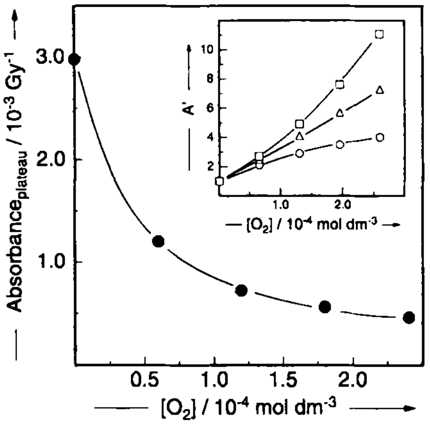


Fig. 3. Pulse radiolysis of N_2O/O_2-saturated aqueous solutions of anisole (10^{-3} mol dm^{-3}). Absorbance at 325 nm at the "plateau" (cf. Fig. 1) as a function of the O_2 concentration. Inset: The same data plotted as A' (see text) against the O_2 concentration; $\varepsilon(RO_2^{\cdot})$: □ = 700 dm^3 mol^{-1} cm^{-1}, △ = 520 dm^3 mol^{-1} cm^{-1}, ○ = zero.

The presence of impurities that might give rise to kinetics such as that shown in Figure 2 can be ruled out, because, for instance, the stability constants "by plateau values" (cf. Fig. 3) obey equation (20), which presupposes a non-zero absorption coefficient of the peroxyl radical, and are essentially equal to those obtained kinetically.

The anisole-derived hydroxycyclohexadienyl radicals display properties similar to the benzene- and phenylalanine-derived ones (Table 1).[9b, 10] Equally amenable to this approach is the determination of the stability constants of the hydroxycyclohexadienyl radicals derived from toluene, fluorobenzene, chlorobenzene, benzylchloride, benzoate ions and terephthalate ions (Table 1). While O_2 addition to the hydroxycyclohexadienyl radical derived from the terephthalate ion is only slow and the eqilibrium not very rapidly attained, the equilibrium constant can still be determined, since the bimolecular decay of these hydroxycyclohexadienyl radicals is very slow ($2k = 4 \times 10^7$ dm^3 mol^{-1} s^{-1}).[19]

Table 1. Reactions of substituted hydroxycyclohexadienyl radicals with oxygen. Rate constants of forward ($k_f/10^8$ dm^3 mol^{-1} s^{-1}) and reverse ($k_r/10^4$ s^{-1}) reactions, the stability constant ($K/10^4$ dm^3 mol^{-1}), and the rate constant of peroxyl radical decomposition ($k_p/10^3$ s^{-1}) (n.d. = not determined).

Substituent	k_f	k_r	K	k_p
OCH_3	8.0	3.9	2.1	5.5
CH_3	4.8	7.5	0.64	1.0
F	4.6	5.5	0.84	0.59
H [a]	3.1	1.2	2.6	0.80
Cl	2.6	5.5	0.47	1.1
CH_2Cl	2.2	6.4	0.34	1.1
CO_2^-	2.0	1.3	1.5	0.34
alanyl [b]	1.7 [c]; 1.8	5.2 [c]; 5.4	0.33	1.5
1,4-$(CO_2^-)_2$	0.16	0.34	0.47	0.39
CO_2H	0.03	n.d.	n.d.	n.d.
CO_2Et	0.07	n.d.	n.d.	n.d.
CN	0.05	n.d.	n.d.	n.d.
NO_2	$\leq$0.02	n.d.	n.d.	n.d.

[a] From ref. [9a]. [b] From ref. [10]. [c] Measured at 15 °C, this work.

The temperature dependence of the stability constant K [$= k_f/k_r = [RO_2^{\cdot}]_{eq}/([R^{\cdot}]_{eq}[O_2])$] of the phenylalanine-derived hydroxycyclohexadienyl radicals has also been determined. At an oxygen concentration of about 3×10^{-4} mol dm^{-3}, the equilibrium is reached rapidly compared to the rates of the product-forming reaction (p) and radical termination reactions (17). This leads to the formation of the "plateau" (cf. inset, Fig. 1); from the height of the plateau at different temperatures a van't Hoff plot of the stability constant has been constructed (Fig. 4). From the slope, a dissociation energy of 5.5 kcal mol^{-1} is derived, which reflects the pronounced weakness of the C–$O_2^{\cdot}$ bond in these hydroxycyclohexadienylperoxyl radicals compared to most other peroxyl radicals; this is expected for these species, which are either of the bisallylic or pentadienyl type. For the reasons that have been emphasized above, K is a collective parameter (see also Appendix). Owing to this fact, the attempt to draw further thermodynamic conclusions from it seems unpromising.

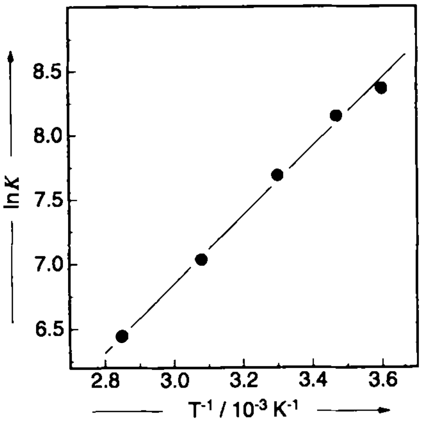


Fig. 4. Pulse radiolysis of N_2O/O_2-saturated aqueous solutions of phenylalanine (10^{-3} mol dm^{-3}). van't Hoff plot of the stability constant obtained from "plateau" values.

In order to obtain k_p, the slow mixed-order decay was monitored. Its rate constant is k_{obs}^- [Eq. (19)]. To simplify the kinetic analysis, a relatively high oxygen concentration (6.5×10^{-4} mol dm^{-3}) was used to speed up the forward reaction (f). The rate constant k_{obs}^- is then accurately reflected by the rate constant of the buildup of nitroform anion and should approximate k_p with an error of at most 20 % in the most unfavorable case. These values are also listed in Table 1.

With some benzenes carrying electron-withdrawing substituents, the rate constants for the disappearance of hydroxycyclohexadienyl radical are very small, still smaller than with terephthalate, and the question arises whether the rate constant one observes corresponds to k_{obs}^+ or k_{obs}^- [Eqs. (18) and (19)]. The hydroxycyclohexadienyl radical derived from benzonitrile is a case in point. Upon extrapolation of the reciprocal of the first half-life to zero dose, there is an O_2-concentration-dependent intercept (Fig. 5). A plot of the value of this intercept vs. [O_2] (Fig. 5, inset) yields a slope of 5×10^6 dm^3 mol^{-1} s^{-1}, but a definite value of any possible intercept in this inset plot cannot be extracted. If the slope of this plot were indeed to represent k_f, the rate of the reverse reaction would be too small to be monitored by means of pulse radiolysis.

Further information has been obtained that allows k_{obs} ($= \ln(2)/t_{1/2}$; cf. Fig. 5, inset) to be linked to the reaction of the hydroxycyclohexadienyl radical with oxygen (k_f), rather than to the elimination of $O_2^{\cdot -}$ from the corresponding peroxyl radical (k_p): 1) initially, the decay of the hydroxycyclohexadienyl radical, monitored at 320 nm, matches the growth of the corre-

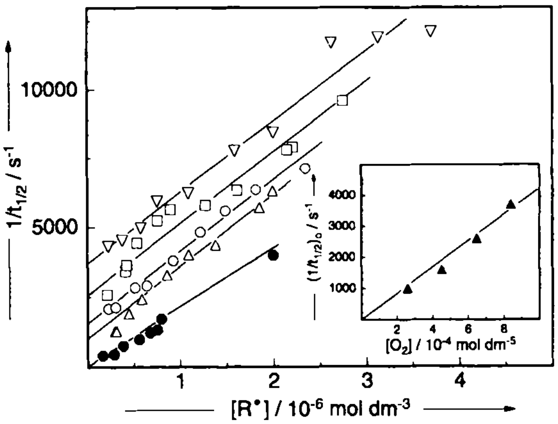


Fig. 5. Pulse radiolysis of N_2O- (●) and N_2O/O_2-saturated (O_2 percentage: △, 20%; ▽, 35%; ○, 50%; □, 65%) aqueous solutions of benzonitrile (10^{-4} mol dm^{-3}). Inverse of the first half-life of the (mainly bimolecular) decay of the hydroxycyclohexadienyl radicals as a function of the dose per pulse. Inset: Dependence of intercept on O_2 concentration.

sponding peroxyl radical, monitored at 290 nm (Fig. 6); and 2) on the time scale of the disappearance of the hydroxycyclohexadienyl radical, there is no buildup of nitroform in the presence of TNM. With nitrobenzene, the rate of hydroxycyclohexadienyl-radical consumption by O_2 is too slow to be observed, but O_2-uptake measurements at the low dose rate of 0.14 Gy s^{-1} [$G(O_2$ uptake$) = 2.6 \times 10^{-7}$ mol J^{-1}] indicate that these radicals too react with oxygen.

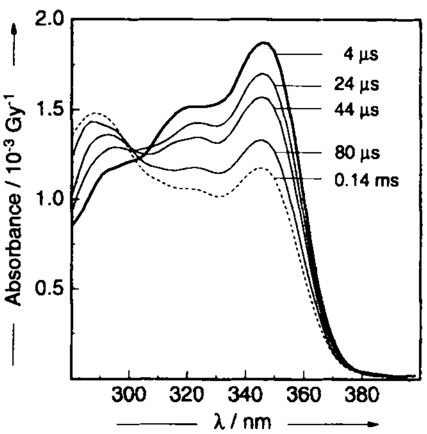
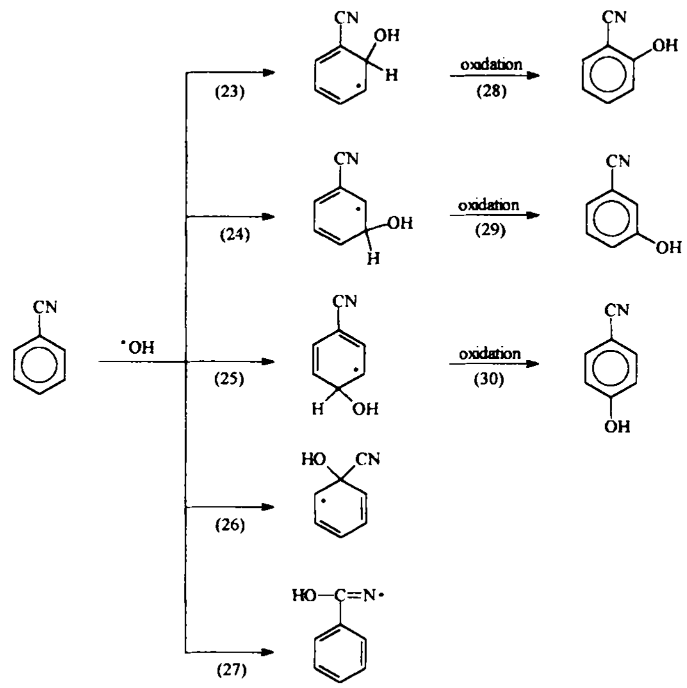


Fig. 6. Pulse radiolysis of N_2O/O_2(1:1)-saturated aqueous solutions of benzonitrile (2×10^{-4} mol dm^{-3}). Absorbance decay at 340 nm (cyanohydroxycyclohexadienyl radicals) and buildup at 290 nm (peroxyl radicals plus products).

We can conclude that the hydroxycyclohexadienyl radicals fall roughly into two groups regarding their reactivity toward oxygen and the ease of elimination of superoxide from the corresponding peroxyl radical, namely, those with electron-donating substituents (reactive) and those with electron-withdrawing substituents (less reactive) (see Table 1).

Further information through product studies in the benzonitrile system: It has been seen that oxygen reacts very slowly ($k_{obs} = 5 \times 10^6$ dm^3 mol^{-1} s^{-1}) with the benzonitrile-derived hydroxycyclohexadienyl radical. Information about the distribution of OH attack at the various positions in the aromatic ring and about the subsequent reactions has been obtained by a product study at the low dose rate of γ-radiolysis.

Five primary OH-adduct radicals can be formed from benzonitrile [Scheme 2, Eqs. (23)–(27), $k = 4.4 \times 10^9$ dm^3 mol^{-1} s^{-1}]. The material balance in the presence of an oxidant such as $Fe(CN)_6^{3-}$ compares favorably with that under N_2O alone, and, as a consequence, the sites of initial OH attack can be more precisely apportioned. The results obtained with $Fe(CN)_6^{3-}$ will therefore be discussed first. All of the hydroxycyclohexadienyl radicals except the *ipso*-OH adduct can be oxidized to the corresponding phenol by an oxidant such as $Fe(CN)_6^{3-}$ [Scheme 2, Eqs. (28)–(30), cf. also ref. [20,21]]. The oxidation of these hydroxycyclohexadienyl radicals is relatively slow ($k_{28-30} < 2 \times 10^5$ dm^3 mol^{-1} s^{-1}),[22] compared to the reaction of $Fe(CN)_6^{3-}$ with the unsubstituted hydroxycyclohexadienyl radical ($k = 1.5 \times 10^7$ dm^3 mol^{-1} s^{-1}). Nevertheless, at low dose rates (in these experiments, γ-radiolysis was performed at a dose rate of 0.17 Gy s^{-1}), oxidation is apparently practically quantitative; the reaction scheme is thus relatively simple, since radical termination reactions are largely precluded. The yield-vs.-dose plots are linear; the G values obtained from the slope are compiled in Table 2.



Scheme 2. Reactions (23)–(30).

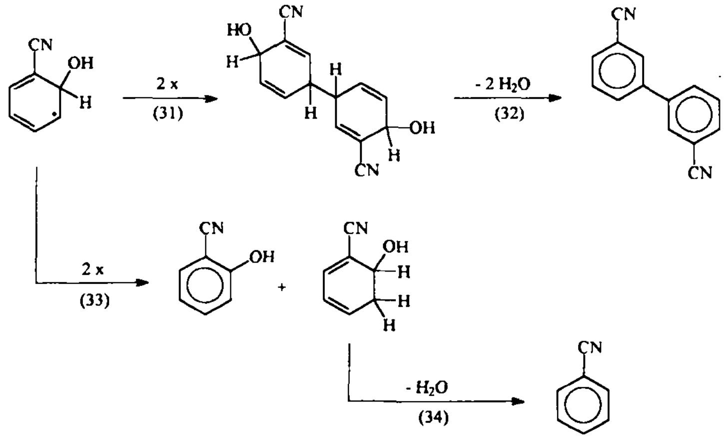
The combined yield G(total phenols) is 4.7×10^{-7} mol J^{-1}, that is, about 85% of the OH-radical yield. The phenol yields are thought to reflect the yields of the corresponding primary hydroxycyclohexadienyl radicals, on the assumption that the

Table 2. γ-Radiolysis of benzonitrile (10^{-3} mol dm^{-3}) in N_2O-saturated (no additive), N_2O-saturated (10^{-4} mol dm^{-3} $Fe(CN)_6^{3-}$), and N_2O/O_2(4:1)-saturated aqueous solutions. Products and their G values (in units of 10^{-7} mol J^{-1}; yields relative to the OH-radical yield in parentheses).

Product	N_2O	$N_2O/Fe(CN)_6^{3-}$	N_2O/O_2
o-hydroxybenzonitrile	0.12 (2.1%)	2.1 (38%)	1.7 (30%)
m-hydroxybenzonitrile	0.07 (1.25%)	1.5 (27%)	0.7 (13%)
p-hydroxybenzonitrile	0.09 (1.6%)	1.1 (20%)	0.9 (16%)
total hydroxybenzonitriles	0.28 (5%)	4.7 (85%)	3.3 (59%)
total dicyanobiphenyls	0.8 (30%)	absent	≈0.03 (1%)

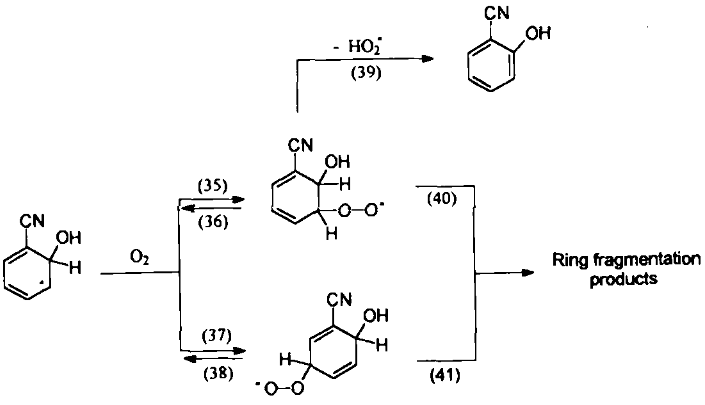
carbocation formed upon oxidation of the hydroxycyclohexadienyl radical does not undergo an OH shift.[22] The *ipso*-OH adduct cannot be oxidized in this way, but on the basis of material balance considerations, it can be concluded that its yield (plus the yield of any exocyclic OH adduct) does not exceed 15%. Addition of the OH radical to the exocyclic carbon [Scheme 2, Eq. (27)] must be a very minor process and can be disregarded, considering the relatively low rate constant for the reaction of the OH radical with acetonitrile ($k = 2.2 \times 10^7\,\mathrm{dm^3\,mol^{-1}\,s^{-1}}$).[17] It follows from this reasoning that the *para*-, *meta*-, *ortho*-, and *ipso*-OH adducts are formed in a ratio of 1:1.4:1.9:0.8 in the benzonitrile system (electron-withdrawing substituent). As there are two *ortho* and *meta* positions, the ratio per available site is 1:0.7:0.95:0.8, that is, there is very little preference for any of the positions in the ring. In contrast, in the case of electron-donating substituents, there is a strong preference of OH addition to the *ortho* and *para* positions.[23]

In the absence of any oxidant, the major products are isomers of dicyanobiphenyl, while the three isomeric cyanophenols are formed in low yields only (Table 2). The dicyanobiphenyls arise from the combination of the cyanohydroxycyclohexadienyl radicals followed by elimination of water, perhaps during the workup (cf. ref. [24]), and the cyanophenols from disproportionation reactions [Scheme 3, Eqs. (31)–(34)]. In contrast to the *meta*-OH adduct, the *ortho*- and *para*-OH adducts may additionally undergo recombination at the cyano-substituted carbon. Such dimers cannot eliminate water. In fact, cyanophenylcyanohydroxycyclohexadienes and bis(cyanohydroxycyclohexadienyl)s, which were expected from this reaction, have been observed among the products, and are stable even after prolonged heating of the irradiated solutions. The material balance in the absence of an oxidant is poor, probably because the 1,4- and 1,3-cyclohexadiene precursors of the dicyanobiphenyl are good radical scavengers. The resulting products of higher molecular weight would have escaped our analysis; nevertheless, the formation of such material has been reported.[25]



Scheme 3. Reactions (31)–(34).

If O_2 instead of $Fe(CN)_6^{3-}$ is used as the oxidant, the conversion of the hydroxycyclohexadienyl radicals into the corresponding phenols is no longer quantitative. In the benzene and phenylalanine systems, only about 50% of the hydroxycyclohexadienyl-radical yield is converted by O_2 into phenols by elimination of $HO_2^{\bullet}$ from the 1,3-cyclohexadienylperoxyl radical,[9] and other ring-fragmentation reactions play an important role.[9b] These occur upon intramolecular addition of the peroxyl radical across the ring to one of the remaining double bonds, followed by further O_2 addition. Apparently in the present system this reaction is slow compared to the reverse of the O_2 addition and the elimination of $HO_2^{\bullet}$. Scheme 4 illustrates this point.



Scheme 4. Reactions (35)–(41).

Oxygen addition to the hydroxycyclohexadienyl radicals can result in the formation of 1,3- as well as 1,4-cyclohexadienylperoxyl-type radicals [Scheme 4, Eqs. (35) and (37)]. Only the hydroxy-1,3-cyclohexadienylperoxyl radical can eliminate $HO_2^{\bullet}$ [Eq. (39); cf. ref. [9b]]. Rapid O_2 elimination from the hydroxy-1,4-cyclohexadienylperoxyl radical regenerates the OH adduct [Eq. (38)], which may then react again with O_2 to yield the 1,3-cyclohexadienylperoxyl radical. If the intramolecular peroxidation and subsequent fragmentation reactions [e.g., Eqs. (40) and (41)] are slow compared to the competing reaction (35) followed by (39) all of the *ortho*-, *meta*- and *para*-OH-cyclohexadienyl radicals would ultimately yield the corresponding phenols. This is, however, not the case. In the present system, G(total phenols) $= 3.3 \times 10^{-7}\,\mathrm{mol\,J^{-1}}$ is below the value found with $Fe(CN)_6^{3-}$ as the oxidant. This is to a large extent due to a reduction in the *m*-hydroxybenzonitrile yield (see Table 2). Since the mechanism of phenol formation and its competing reaction is so complex,[9b] it is premature to advance a mechanistic explanation for this observation.

It is worth noting that, in N_2O/O_2(4:1)-saturated solutions at the low dose rate of γ-radiolysis, dicyanobiphenyl is still formed in the low-percent range (Table 2). This shows that the termination reactions (31) and (33) are not entirely suppressed and is in agreement with the low value estimated from pulse radiolysis for the rate constant of the reaction of oxygen with these hydroxycyclohexadienyl radicals.

Appendix

The faster of the two rate constants that describe the reaction system (i) is given by (ii) if the forward (f) and reverse (r) reactions are much faster than the product-forming one (p).

$$R^{\bullet} + O_2 \underset{r}{\overset{f}{\rightleftharpoons}} RO_2^{\bullet} \xrightarrow{p} P \qquad \text{(i)}$$

$$k^{+} = k_f[O_2] + k_r \qquad \text{(ii)}$$

The time dependence of the fast mode of some characteristic quantity of the system (e.g., absorbance) is then given by (iii).

$$f(t) = a e^{-(k_f[O_2] + k_r)t} \qquad \text{(iii)}$$

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For the more general case of N parallel reaction systems such as (i), we write (iv) (ν, index of summation).

$$f(t) = \sum_{\nu=1}^{N} a_\nu e^{-(k_{f,\nu}[O_2] + k_{r,\nu})t} \tag{iv}$$

Differentiation of (iv) gives (v).

$$df = \frac{\partial f(t)}{\partial [O_2]}\, d[O_2] + \frac{\partial f(t)}{\partial t}\, dt \tag{v}$$

Upon replacement of t by $t_{1/2}$, by definition, $f(t)$ is replaced by $f(t_{1/2})$ and ceases to be a variable, and (v) is transformed into (vi), which provides an analytical expression for $dt_{1/2}/d[O_2]$.

$$0 = \frac{\partial f(t_{1/2})}{\partial [O_2]} + \frac{\partial f(t_{1/2})}{\partial t_{1/2}} \frac{dt_{1/2}}{d[O_2]} \tag{vi}$$

Upon substitution and rearrangement, we obtain (vii).

$$d\ln(1/t_{1/2}) = d[O_2] \Bigg/ \left([O_2] + \frac{\sum_{\nu=1}^{N} a_\nu k_{r,\nu} e^{-(k_{f,\nu}[O_2] + k_{r,\nu})t_{1/2}}}{\sum_{\nu=1}^{N} a_\nu k_{f,\nu} e^{-(k_{f,\nu}[O_2] + k_{r,\nu})t_{1/2}}} \right) \tag{vii}$$

A solution to this differential equation may be approximated by assuming that the ratios k_f/k_r of the individual constituent reaction systems are similar, that is, by substituting $k_{r,\nu} = q k_{f,\nu}$ (q constant). Then, integrating (vii) we obtain (viii), where ln(C) is the constant of integration.

$$\ln([O_2] + q) = \ln(1/t_{1/2}) + \ln(C) \tag{viii}$$

This represents a linear relationship between $1/t_{1/2}$ and $[O_2]$.

Even if the condition $k_{r,\nu} = q k_{f,\nu}$ is relaxed (which is realistic in view of Table 1), one may still suppose that, in the second term of the denominator in expression (vii), the effect of the variations in the $k_{r,\nu}$ and $k_{f,\nu}$ should to a considerable extent average out; thus, even in the general case, this term should not depend strongly on the oxygen concentration. Owing to its exponential functions, this term will be biased towards those reaction systems where both the forward and reverse reaction are relatively slow.

Comparison of expression (viii) with the special case $N = 1$ [cf. Eq. (ii)] shows that the term C must be identified with the quantity $\ln(2)/k_{f,\text{effective}}$, so that with $q = k_{r,\text{effective}}/k_{f,\text{effective}}$ we can finally derive equation (ix).

$$\ln(2)/t_{1/2} = k_{f,\text{effective}}[O_2] + k_{r,\text{effective}} = k^{+}_{\text{obs}} \tag{ix}$$

In the text (and Table 2) where there is no distinction made between the individual $k_{f,\nu}$ and $k_{r,\nu}$, respectively; $k_{f,\text{effective}}$ ($k_{r,\text{effective}}$) are simply designated k_f (k_r).

The supposition that the effect of the variations in the individual $k_{r,\nu}$ and $k_{f,\nu}$ might largely average out is supported by the fact that kinetically determined K (i.e., $k_{f,\text{effective}}/k_{r,\text{effective}}$) closely resembles K determined by the measurement of the equilibrium absorbance (i.e., $\sum[RO_2^{\cdot}]_{eq,\nu}/([O_2]\sum[R^{\cdot}]_{eq,\nu})$).

Acknowledgment: Xingwang Fang thanks the Volkswagenwerk Foundation for their support of this work (Project I/64 964).

Received: February 14, 1995 [F 87]

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