trimethyl orthoformate using the above procedure. The product was obtained in 50–60% yields as an oil: bp 77.5–79 °C (0.05 mm); NMR (neat) δ 5.67 (s, 0.44 H), 5.57 (s, 0.56 H), 4.3–3.8 (m, 2 H), 3.56 (s, 0.56 H), 3.30 (s, 0.44 H), 2.1–0.67 (m, 14 H).

Anal. Calcd for $C_{12}H_{20}O_3$: C, 67.89; H, 9.50. Found: C, 68.00; H, 9.27.

Thermolysis of 2 in Phenyl Isocyanate. A solution of ca. 60 mg of **2** in 0.5 mL of phenyl isocyanate was prepared and examined immediately by NMR spectroscopy. The spectrum showed separate resonances for the epimeric methoxyl protons at δ 3.30 and 3.15 (area ratio 3.0:2.1) and methine protons at δ 5.55 and 5.45 (area ratio 0.64:1.0). The sample was sealed and kept at 25 °C for 4 days whereupon the ratio of the methoxyl proton areas changed to 1:8. The sample was heated at 100 °C for 40 h after which time the area ratio of the methoxy protons was 1:12.5. The tube was heated at 155 °C for 17 h whereupon all peaks attributed to **2** disappeared and new peaks appeared which were assigned to bornylene (**9**) and methyl phenylcarbamate (**10**). Bornylene resonances appeared at δ 5.83 (m, 2 H), 2.25 (t, 1 H) 2.0–1.1 (m, 4 H), 0.98 (s, 3 H), 0.85 (s, 3 H), and 0.73 (s, 3 H).

The other component of the reaction mixture showed two singlets at δ 3.60 and 3.47 (relative area 2:1). An authentic sample of **10** prepared from methanol and phenyl isocyanate showed only the peak at δ 3.60 in phenyl isocyanate at room temperature. After heating for 2 h at 160 °C the other peak appeared with relative area 3:1. Further heating led to a 1.8:1 mixture after 7 h at 165 °C.

Thermolysis of 3 in Phenyl Isocyanate. A solution of ca. 0.050 g of **3** in 0.5 mL of phenyl isocyanate was heated at 110 °C for 1 h. No significant changes were observed in the NMR spectrum. The sample was heated at 165 °C and periodically monitored by NMR. After 1 h there was observed peaks attributable to norbornene (**8**) and it was estimated that the reaction was ca. 50% complete using the solvent peaks as an internal standard. After 4 h the reaction was ca. 70% completed. Heating for 22 h led to complete destruction of **3** and to ca. quantitative formation of norbornene. The latter was identified by comparison of the NMR spectrum with that of an authentic sample in phenyl isocyanate [e.g. δ 6.0 (t) and 2.8 (m)]. The only significant extra peaks in the spectrum were those attributable to phenylethylurethane; δ 4.10 (q, J = 7 Hz) and 1.12 (t, J = 7 Hz).

Acknowledgment. We thank Ms. Yiang I for a sample of compound **2**.

Registry No. 2a, 70644-36-9; **2b**, 70701-40-5; **3** isomer 1, 70644-37-0; **3** isomer 2, 70701-41-6; **4** isomer 1, 70701-42-7; **4** isomer 2, 70701-43-8; **5**, 70644-38-1; **6** isomer 1, 70644-39-2; **6** isomer 2, 70701-44-9; **7** isomer 1, 70644-40-5; **7** isomer 2, 70701-45-0; **8**, 498-66-8; **9**, 464-17-5; **10**, 2603-10-3; *cis,exo*-2,3-norbornanediol, 16329-23-0; triethyl orthoformate, 122-51-0; *exo,exo*-2-(acetyloxy)-3-(formyloxy)norbornane, 70644-41-6; *cis,exo*-2,3-norbornanediol acetone ketal, 16329-26-3; cyclohexanone, 108-94-1; *cis,endo*-2,3-norbornanediol, 21462-06-6; *cis,exo*-2,3-bornanediol, 56614-57-4; trimethyl orthoformate, 149-73-5; phenyl isocyanate, 103-71-9.

Base-Catalyzed Oxygenation of *tert*-Butylated Phenols. 3.[1] Base-Catalyzed Reaction of Peroxyquinols Derived from Oxygenation of 2,6-Di-*tert*-butylphenols and Mechanism of Regioselective Formation of Epoxy-*o*-quinol from 2,4,6-Tri-*tert*-butylphenol

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The chemical reactivities of peroxy anions of two types of hydroperoxides, 4-hydroperoxy-2,5-cyclohexadienones (**2**) and 6-hydroperoxy-2,4-cyclohexadienones (**3**) regioselectively derived from the oxygenation of 2,6-di-*tert*-butylphenols (**1**), toward bases with three countercations (K^+, Na^+, Li^+) are systematically investigated. In *N,N*-dimethylformamide with *tert*-butoxides, hydroperoxides **2** liberate predominantly molecular oxygen, whereas **3** are significantly decomposed leading to 4,5-epoxy-6-hydroxy-2-cyclohexenones (**5**). In *t*-BuOH or tetrahydrofuran (THF) with *t*-BuOK or *t*-BuONa, hydroperoxides **2** are converted to **3** which then undergo decomposition to **5** exclusively. With *t*-BuOLi, a reductive cleavage of the peroxy bond is a significant reaction pathway. In ethanol containing alkali, oxygen liberation and the reaction path depend on the nature of the substituent at the 4 position of the hydroperoxides. With 4-*t*-Bu substitution, an equilibrium between **2** and **3** is established. With a 4-Me group, a reductive cleavage of the peroxy bond takes place. 4-(4-MeOPh) substitution on **3** gives predominantly the product of type **5**. These results are principally interpreted in terms of solvation of the peroxy anions and the countercations. It is found that the ortho regioselective hydroperoxylation of 2,4,6-tri-*tert*-butylphenol with molecular oxygen in *t*-BuOK/*t*-BuOH involves the formation of hydroperoxide of type **2** in the first step followed by the exclusive conversion of **2** to that of type **3** via a π-complex intermediate.

In previous papers,[1,2] we reported base-catalyzed regioselective dioxygen incorporation into 2,6-di-*tert*-butylphenols (**1**). The dioxygen incorporation depends on the nature of the para substituent in **1** and the solvent used. In aprotic solvents such as *N,N*-dimethylformamide (DMF), dimethyl sulfoxide (Me_2SO), and hexamethylphosphoric triamide (HMPT) with *t*-BuOK, **1a,b** gave exclusively epoxy-*p*-quinols **4**, whereas in *tert*-butyl alcohol with *t*-BuOK, **1a,c** gave predominantly epoxy-*o*-quinols **5**. The reaction involves intramolecular decomposition of peroxy anions **2′** and **3′** regioselectively formed (Scheme I).[1,2] On the other hand, oxygenation of **1** (R = alkyl) in ethanol with KOH at 0 °C gives *p*-hydroperoxides **2** and in a mixture of *tert*-butyl alcohol and pentane with *t*-BuOK at 0 °C **1** (R = *t*-Bu, substituted phenyl) gives *o*-hydroperoxides **3**.[1,2]

With a view to obtaining insight into the mechanism of the oxygenation of **1** in more detail, we have investigated systematically the influence of solvents and countercations on the base-catalyzed reaction of hydroperoxides **2** and **3**. *tert*-Butoxides (*t*-BuOK, *t*-BuONa, *t*-BuOLi) have been

(1) Part 2: A. Nishinaga, T. Itahara, T. Matsuura, A. Rieker, D. Koch, K. Albert, and P. B. Hitchcock, *J. Am. Chem. Soc.*, **100**, 1826 (1978).
(2) A. Nishinaga, T. Itahara, T. Shimizu, and T. Matsuura, *J. Am. Chem. Soc.* **100**, 1820 (1978).

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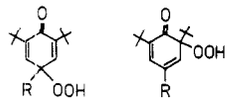


2 3

a; R = t-Bu a; R = t-Bu
b; R = Me b; R = 4-MeOPh

employed in DMF, tetrahydrofuran (THF), and *tert*-butyl alcohol, whereas alkalies (KOH, NaOH, LiOH) have been used in ethanol. It is found that the reactivity of the hydroperoxides varies depending on the nature of the solvent and base used. Kinetic studies on the oxygenation of **1a** and on the base-catalyzed reaction of **2a** in *tert*-butyl alcohol have elucidated the ortho regioselective hydroperoxylation. A novel π complex of phenolate anion with O_2 is proposed as an intermediate in the hydroperoxylation of **1**.

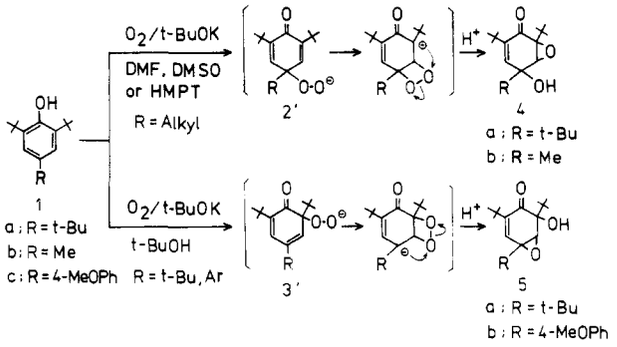
Results and Discussion

In solution, hydroperoxides **2** and **3** are quite stable in the absence of base. However, upon treatment with strong bases in various solvents, they give various products, depending on the reaction conditions. Tables I–IV show the results obtained in the individual cases. As seen from the tables, the base-catalyzed reaction of the hydroperoxides can be roughly classified into four categories: (i) deoxygenation (reduction to the parent phenol), (ii) intramolecular decomposition (formation of epoxyquinol), (iii) migration of the hydroperoxy group (equilibrium between **2** and **3**), and (iv) reductive cleavage of the peroxy bond (formation of quinol) (Scheme II). *o*-Quinol **7** is quite unstable and undergoes easily debutylation to give catechol **8**.

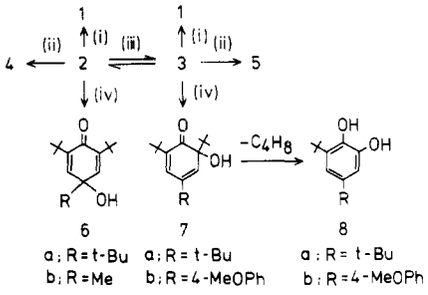
Reactions with *tert*-Butoxides in DMF. In DMF the countercations of the bases are strongly solvated[3] so that the reactivity of **2** and **3** in a free state may be observed in this solvent. They decompose rapidly. In all cases, the deoxygenation of **2** and **3** takes place predominantly to give the corresponding parent phenol **1** regardless of the nature of the countercation, along with some of the corresponding epoxyquinols **4** and **5**. The predominant formation of **1** from **2** and **3** is consistent with the suggestion that the hydroperoxylation of **1** by the base-catalyzed oxygenation is reversible[4] and that the equilibrium is shifted to a great extent to the phenolate anion (**9**) when the peroxy anion **2′** is in a free state (**10**) (Scheme III).

The formation of the epoxyquinol is due to the strong nucleophilicity of free peroxy anion, which undergoes the intramolecular Michael addition to the dienone system followed by an asymmetric decomposition of the resulting dioxetane intermediate (Scheme I). Because **3** has a linear conjugated dienone system while **2** has a cross-conjugated dienone system, the Michael addition is naturally more significant with **3** (see tables). The formation of the epoxyquinol becomes a main reaction for **3b**, because the aromatic substituent in **3b** increases the polarity of the dienone system leading to the acceleration of the Michael reaction. The reaction of **2** depends also on the size of the substituent R. With **2b** an intermolecular nucleophilic attack by the peroxy anion also takes place. Thus, **2b** gave a somewhat complex reaction mixture including *p*-quinol **6b** and diepoxide **11**, both of which are obtained by the reaction between **2b′** and **4b** (Scheme IV). The low yield of **6b** compared to that of **11** in the reaction with *t*-BuOK

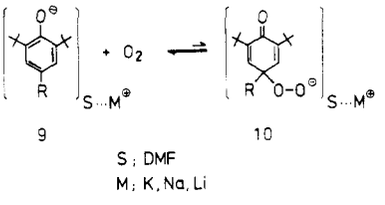
Scheme I



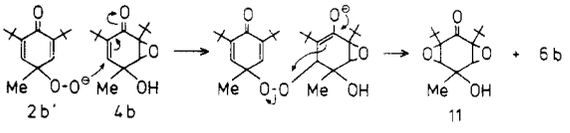
Scheme II



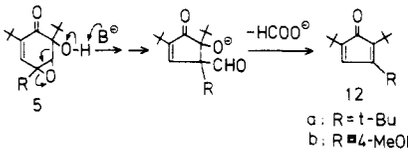
Scheme III



Scheme IV



Scheme V



(Table II) is due to a further reaction of **6b** involving acyloin rearrangement under the reaction conditions.[3] The formation of cyclopentadienone **12b** in the reaction of **3b** (Table IV) results from the further decomposition of **5b** initiated by the cleavage of the epoxy ring[2,5] (Scheme V). Although the reason why the formation of **13b** increases with *t*-BuOLi is not clear, the affinity of Li^+ toward the epoxy oxygen may be greater than the other countercations and may accelerate epoxy ring cleavage.

Reactions with *tert*-Butoxides in THF. Contrary to the case of DMF, the countercations of the bases are associated with the peroxy anions **2′** and **3′** in THF. Such solvent effects on the association and dissociation of anionic species with countercations in solutions are well documented.[6-8] Therefore, the reactivity of **2′** and **3′** in

(3) A. Nishinaga, T. Itahara, T. Matsuura, S. Berger, G. Henes, and A. Rieker, *Chem. Ber.*, **109**, 1530 (1976).
(4) A. Nishinaga, T. Shimizu, and T. Matsuura, *Chem. Lett.*, 547 (1977).
(5) A. Nishinaga and A. Rieker, *J. Am. Chem. Soc.*, **98**, 4667 (1976).
(6) T. E. Hogen-Esh and J. Smith, *J. Am. Chem. Soc.*, **87**, 669 1965); **88**, 307, 318 (1966).
(7) N. Kornblum and R. Seltzer, *J. Am. Chem. Soc.*, **83**, 3668 (1961).
(8) A. J. Parker, *Q. Rev., Chem. Soc.*, **16**, 163 (1962).

Table I. Base-Catalyzed Reaction of 2a[a]

solvent	base	% convrsn	product, % yield[b] 1a	4a	6a	23[e]	3a	5a	7a	others[c]
DMF	*t*-BuOK	100	84	13	2			1		
DMF	*t*-BuONa	100	92	8						
DMF	*t*-BuOLi	100	86	13	1					
THF	*t*-BuOK	100	37			3		57	3	
THF	*t*-BuONa	100	50	17	9	6		5	5	8
THF	*t*-BuOLi	50	28		56					16
t-BuOH	*t*-BuOK	97	11	2			36	51		
t-BuOH	*t*-BuONa	99	11			9	54	17		8
t-BuOH	*t*-BuOLi	31	20	9	68	3				
90% EtOH	KOH	60[d]	10[d]		2[d]		28[d]			
90% EtOH	NaOH	54[d]	19[d]		1[d]		26[d]			
90% EtOH	LiOH	73[d]	12[d]		1[d]		14[d]			

[a] Molar ratio of base/2a 5, reaction time 2 h, room temperature under N_2. [b] Determined by ^1H NMR based on the conversion unless otherwise noted. [c] Unidentified products probably resulting from the acyloin rearrangement and further reaction. [d] Product ratio in the reaction mixture. [e] 23, 2,6-di-*tert*-butyl-*p*-benzoquinone.

Table II. Base-Catalyzed Reaction of 2b[a]

solvent	base	% convrsn	product, % yield[b] 1b	4b	6b	1d	11	13b	others[c]
DMF	*t*-BuOK	100	70	7	6		14		3
DMF	*t*-BuONa	100	85	2	6		6		
DMF	*t*-BuOLi	100	84	6	8		2		
THF	*t*-BuOK	100	33		29	8		15	16
THF	*t*-BuONa	100	31		40	3		20	6
THF	*t*-BuOLi	100	5		93	2			
t-BuOH	*t*-BuOK	100	36		41			12	11
t-BuOH	*t*-BuONa	100	10		59			31	
t-BuOH	*t*-BuOLi	89	7	9	67		9		8
90% EtOH	KOH	48[d]	42[d]		20[d]				
90% EtOH	NaOH	47[d]	34[d]		19[d]				
90% EtOH	LiOH	38[d]	42[d]		20[d]				

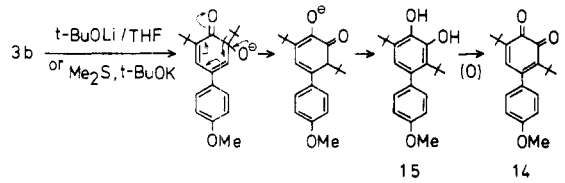
[a] Molar ratio of base/2b 5, reaction time 2 h, room temperature under N_2. [b] Determined by ^1H NMR based on the conversion unless otherwise noted. [c] Unidentified products. [d] Product ratio in the reaction mixture.

Table III. Base-Catalyzed Reaction of 3a[a]

solvent	base	% convrsn	product, % yield[b] 1a	2a	4a	6a	23[f]	5a	8a	24[g]	others
DMF	*t*-BuOK	100	76					24			
DMF	*t*-BuONa	100	59		3			39			
DMF	*t*-BuOLi	100	64		9	1		26			
THF	*t*-BuOK	100	4		trace		1	86	6		
THF	*t*-BuONa	100			8		2	55	10	13	12
THF	*t*-BuOLi	100							100		
t-BuOH	*t*-BuOK	62	6	3				91			
t-BuOH	*t*-BuONa	47	5	1				94			
t-BuOH	*t*-BuOLi	*c*							*d*	*d*	
90% EtOH	KOH	41[e]	12[e]	32[e]		3[e]	5[e]	7[e]			
90% EtOH	NaOH	34[e]	13[e]	40[e]		2[e]	1[e]	10[e]			
90% EtOH	LiOH	28[e]	17[e]	49[e]		3[e]	2[e]	1[e]			

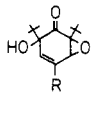
[a] Molar ratio of base/3a 5, reaction time 2 h, room temperature under N_2. [b] Determined by ^1H NMR based on the conversion unless otherwise noted. [c] The conversion could not be determined because the reaction mixture contained the semiquinone radical of 8a. [d] Not determined. [e] Product ratio in the reaction mixture. [f] 23, 2,6-di-*tert*-butyl-*p*-benzoquinone. [g] 24, 3,5-di-*tert*-butyl-*o*-benzoquinone.

Scheme VI



15 14

an associated state can be observed in THF. The reaction in this solvent depends strongly on the nature of the countercation, the base, and the substituent R in 2 and 3. Hydroperoxides 2 gave the corresponding parent phenol 1 but in lower yield than in DMF, and 3 did not give 1, indicating that the association of 2′ and 3′ with the countercations depress the deoxygenation. With *t*-BuOK, 2a gave 5a as a main product, and 2b gave 6b and an epoxide, 13b. Although the isolation of 13b was not



13

a; R = t-Bu
b; R = Me
c; R = 4-MeOPh

successful, its structure was confirmed by examining the

Table IV. Base-Catalyzed Reaction of 3b[a]

solvent	base	% convrsn	product, % yield[b] 1c	5b	8b	13c	12b	14
DMF	*t*-BuOK	100	4	92			trace	
DMF	*t*-BuONa	100	4	95			trace	
DMF	*t*-BuOLi	100	3	71			25	
THF	*t*-BuOK	100	3	63		10	trace	18
THF	*t*-BuONa	100		66		20	trace	10
THF	*t*-BuOLi	100			58	16	trace	20
t-BuOH	*t*-BuOK	100	3	76			20	
t-BuOH	*t*-BuONa	100	3	70			26	
t-BuOH	*t*-BuOLi	100			17	17		30
90% EtOH	KOH	100	56	26				
90% EtOH	NaOH	100	50	20				
90% EtOH	LiOH	100	79	9				

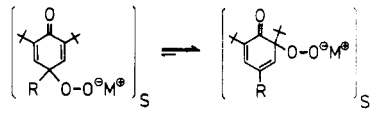
[a] Molar ratio of base/3b 5, reaction time 2 h, room temperature under N_2. [b] Determined by ^1H NMR base on the conversion.

^1H NMR spectrum of a mixture of **6b** and **13b** obtained by chromatographic separation of the reaction mixture with silica gel: ($CDCl_3$) δ 1.00 (s, 9 H), 1.13 (s, 9 H), 2.00 (d, 3 H, J = 1.5 Hz), 3.43 (d, 1 H, J = 2 Hz), 5.73 (dd, 1 H, J = 2, 1.5 Hz). The signals for the olefinic and methine protons correspond to those for analogous compounds **13a**[9] and **13c**,[9] supporting the structure **13b**. Obviously, **5** and **13** are derived from **3**. These results therefore indicate that the efficient migration of hydroperoxy group in **2** to the ortho position is one of significant reactions in this system. With *t*-BuONa, however, **2a** gave a complex reaction mixture. With *t*-BuOLi, **2** gave unexpectedly the corresponding *p*-quinols **6** in quantitative yield. The mechanism of this interesting reduction is not yet clear. A homolysis of the peroxy bond followed by the reduction of the resulting quinoxy radical may be ruled out, because the quinoxy radical from **2b** easily undergoes an intramolecular rearrangement in basic media leading to ring expansion.[10] No such ring-expanded product was found in the present experiments. Since *t*-BuOLi is not very soluble in THF (not completely dissolved under the present experimental conditions), quinol **6** may result from a bimolecular reaction between **2b** and its anion **2b'** as suggested for some other base-catalyzed reactions of hydroperoxides.[11] However, a mixture of equimolar amounts of **2b** and its potassium salt in THF gave a complex reaction mixture.

The reaction of **3** with *t*-BuOK in THF effectively gave the corresponding epoxy-*o*-quinols **5** as expected.[1,2] With *t*-BuOLi, **3** gave the corresponding catechols **8** in excellent yield. The formation of **8** from **3** probably proceeds through an *o*-quinol intermediate (**7**). In fact, **7a** readily gives **8a**.[1] A further interesting product in this system is a quinone, **14**, which is the result of an acyloin rearrangement of **7b** giving catechol **15** followed by an oxidation under the reaction conditions. Actually, catechol **15** was obtained in good yield by the reaction of **3b** with dimethyl sulfide followed by treatment with *t*-BuOK in DMF under a nitrogen atmosphere; **15** is easily oxidized by air to **14** (Scheme VI)

Reactions with *tert*-Butoxides in *tert*-Butyl Alcohol. The results were quite analogous to those obtained in THF including the characteristic reductive cleavage of the peroxy bond with *t*-BuOLi. These results may also be interpreted roughly in terms of the association of the peroxy anions. In contrast to the results in THF, however, **3a** was obtained from **2a**, indicating that **3a** is stabilized to some extent in *tert*-butyl alcohol compared to the THF case, probably due to the solvation of the peroxy anion. In the reaction of **2b**, the migration of the hydroperoxy group to the ortho position also occurs but the product is **13b**. The formation of **2a** in a small amount from **3a** (Table III) as well as the results obtained in THF suggests that when the peroxy anions are associated with the countercation K^+ or Na^+ (**16** and **17**), an equilibrium between these peroxy anions is established. The equilibrium lies strongly to the side of **17** (Scheme VII). The formation of cyclopentadienone **12b** from **3b** is a notable reaction in this solvent with *t*-BuOK or *t*-BuONa; **12b** is the result of further decomposition of **5b**. The mechanism by which **12** is formed from **3** or **5** has been published previously.[5] Although **5a** is fairly stable under the present reaction conditions, refluxing a solution of **3a** or **5a** for a long time gave **12a** in a high yield.

Scheme VII



16 17

S; t-BuOH, THF
M; K, Na

Reactions with Alkalies in Ethanol. A solution of MOH (M, = K, Na, Li) in 90% ethanol was employed. In this system, it is expected that both of the peroxy anions and the countercations are solvated. Therefore, the reactivity of the peroxy anions solvated through a hydrogen bond can be observed. As seen from the tables, the liberation of O_2 to give **1** is a major reaction path regardless of the nature of the countercation. The result indicates that the countercations are strongly solvated as expected to give the free state of the peroxy anions. The free anions liberate oxygen easily as would be expected from the findings in DMF. The rate of oxygen liberation in ethanol is slower than that in DMF due to hydrogen bonding of the peroxy anions, which also depresses the rate of the other reactions of the peroxy anions. The reactions of the hydroperoxides, other than the oxygen liberation, depend strongly on the nature of the substituent R but not on the countercation. This dependence indicates that the reactivity of the hydroperoxides in MOH/EtOH can be regarded as depending only on the solvated peroxy anions.

(9) Compounds **13a,c** were obtained from **3a,c**, respectively, by acetylation followed by alkaline hydrolysis: ^1H NMR ($CDCl_3$) δ(**13a**) 3.70 (d, 1 H, J = 2 Hz), 5.72 (d, 1 H, J = 2 Hz); δ(**13c**) 3.93 (d, 1 H, J = 2 Hz), 6.13 (d, 1 H, J = 2 Hz). A. Nishinaga, K. Nakamura, and T. Matsuura, *Tetrahedron Lett.*, in press.

(10) A. Nishinaga, K. Nakamura, and T. Matsuura, *Tetrahedron Lett.*, 3557 (1978).

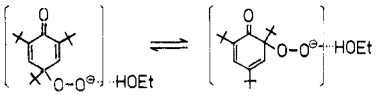
(11) R. Hiatt, "Organic Peroxides", Vol. 2, D. Swern, Ed., Wiley-Interscience, New York, London, Sydney, Toronto, 1971, p 1.

Table V. *t*-BuOK-Catalyzed Oxygenation of 1a in *t*-BuOH–Hexane (1:1)

temp, °C	[*t*-BuOK]/1a, mol/mol	reacn time, min	% convrsn	product, % yield[a] 2a	3a	5a
0	5	30	68	86	14	
10	5	20	85	69	31	
20	5	15	97	53	47	
30	5	10	98	27	65	8
40	5	10	98	3	59	39

[a] Yields were determined by ^{1}H NMR spectra of the reaction mixtures.

Scheme VIII



18 19

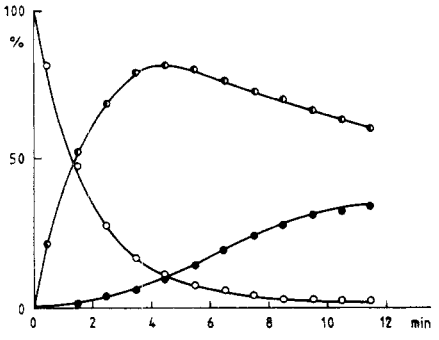


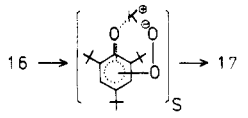
Figure 1. Time course of oxygenation of **1a** in *t*-BuOH-hexane (1:1) containing *t*-BuOK (0.25 M) at 20 °C: ○, **1a**; ◐, **2a**; ●, **3a**.

Hydroperoxide **2** as well as **3** gave a mixture of comparable amounts of **2** and **3** suggesting that the solvated peroxy anions **18** and **19** are energetically equivalent and that the conversion is reversible (Scheme VIII).[13] The reversibility has also been observed in methanol.[4] Other notable reactions are the formation of **6b** from **2b** and of **5b** from **3b**.

Oxygenation of 1a in *tert*-Butyl Alcohol Containing *t*-BuOK. The effective conversion of **2a** to **3a** in the *t*-BuOK/*t*-BuOH system prompted us to investigate systematically the oxygenation of **1a** in the same system in order to determine the mechanism of the regioselective formation of **5a** from **1a**.[1] It has now been found that the oxygenation of **1a** at 0 °C in *t*-BuOK/*t*-BuOH mainly gives **2a** and that the amount of **2a** decreases with a rise in the reaction temperature while the amount of **3a** and **5a** increase (Table V). The time course of the oxygenation of **1a** with *t*-BuOK in *tert*-butyl alcohol–hexane (1:1) at 20 °C showed that hydroperoxide **2a** is first formed in the initial step with the same rate as that for the consumption of **1a** and in the following step **3a** is formed at the expense of **2a** (Figure 1). At higher temperatures the formation of **5a** increases. It is therefore clear that the selective formation of **5a** from **1a** involves the effective isomerization of **2a** to **3a**. The isomerization was found to follow first-order kinetics with a rate constant of 3.14×10^{-3} s^{-1} at 30 °C, strongly suggesting that the migration is an intramolecular reaction.

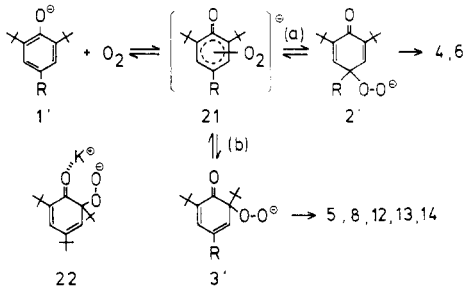
Two possible mechanisms for the migration can be considered: (i) a radical process involving the corresponding phenoxy radical and superoxide anion resulting from the homolysis of the C–O bond in the anionic form **16**, and (ii) a nonradical process involving a π-complex intermediate (**20**) (Scheme IX). The possibility of nucleophilic attack by the peroxy anion on the 2 position in **16** should not be the case since the peroxy anion preferably attacks the 3 position giving **4a**. Mechanism (i) can be ruled out because the reaction of the phenoxy radical derived from **1a** with potassium superoxide results only in electron transfer from the superoxide anion to the phenoxy radical to give molecular oxygen and **1a**.[4] Mechanism (ii) is therefore proposed for the migration. Since the intermediate **20** is not experimentally detectable, the rate-determining step should be the initial step (**16** → **20**), which is consistent with the kinetic data.

Scheme IX



20

Scheme X



1′ 21 2′ 22 3′

Summary

Results in the present work may principally be rationalized by assuming equilibria among the phenolate and peroxy anions 1′–3′ involving a π-complex intermediate (**21**) (Scheme X). Reactivities of the peroxy anions **2′** and **3′** are eventually interpreted in terms of the state of **21** (solvation, association, dissociation). Oxygen liberation occurs regardless of the situation. The equilibrium among the anions 1′–3′ is influenced by the solvent and the substituent R. Under the conditions where **21** is in the free state (in DMF), the equilibrium is shifted strongly to 1′ and oxygenation takes place only along path a.[14] Therefore, it is understandable that the unreactivity of **1c** toward the oxygenation in *t*-BuOK/DMF[2] is attributed to the unstability of the carbanion (free state) adjacent to the aromatic substituent. With the associated form of **21** (in *t*-BuOH, THF), the equilibrium between **2′** and **3′** is strongly shifted to **3′**, probably due to stabilization of **3′**

(12) A. Nishinaga, T. Itahara, T. Matsuura, A. Rieker, and D. Koch, *Angew. Chem.*, 88, 154 (1976); *Angew. Chem., Int. Ed. Engl.*, 15, 160 (1976).

(13) Similar argument on the quilibrium has been made but without descisive evidence: A. F. Bickel and H. R. Gersmann, *J. Chem. Soc.*, 2711 (1959).

(14) For the oxygen liberation, a homolysis of the C–O bond giving phenoxy radical and superoxide anion followed by electron transfer from the latter to the former has been suggested.[4] However, it may be reasonable to assume the intermediate **21** in view of the present findings.

by chelate formation (22). Under these conditions, the oxygenation of **1a** with path a seems to be kinetically preferable and **3'** is subsequently formed from **2'**, the ortho regioselective hydroperoxylation of **1a** being thus accomplished. However, in the oxygenation of **1a** in *t*-BuOK/THF or of **1c** in *t*-BuOK/*t*-BuOH, **2'** is not detectable at all. Therefore, direct formation of **3'** via path b may also be possible in these cases. The reactivities of **2'** and **3'** when **21** is solvated are seen in ethanol. Characteristic findings in this system are that **2'** (R = *t*-Bu) and **3'** (R = *t*-Bu) are thermodynamically equivalent and the oxygenation of **1a** in KOH/EtOH takes place along with path a in a kinetically controlled reaction giving **2'**, which gives in the following thermodynamic process a mixture of nearly equimolar amounts of **2'** and **3'**.

Experimental Section

All melting points are uncorrected. Elemental analyses were performed by the Analytical Center of Kyoto University, Pharmaceutical Department. Infrared spectra were recorded on a Jasco IRA-1 spectrophotometer. Ultraviolet spectra were recorded on a Shimazu UV 200 spectrophotometer. Proton magnetic resonance spectra were determined on a Varian T-60 spectrometer.

Preparation of Hydroperoxides 2 and 3. Hydroperoxides **2** were prepared by the oxygenation of **1a,b** in ethanol containing KOH. Oxygen was bubbled through a solution of **1a,b** (10 mmol) in ethanol (100 mL) containing KOH (40 mmol) at 0 °C for 2–4 h. The reaction mixture was diluted with an excess of cold water, acidified with dilute hydrochloric acid, and extracted with ether. The extract was dried (Na_2SO_4) and evaporated to leave a crystalline mass, which was recrystallized from petroleum ether to give **2** as colorless prisms (yield, 80–95%), identical with authentic samples.[13,15] Hydroperoxides **3** were prepared according to the method reported previously[1,2] and were purified by repeated recrystallization from petroleum ether.

Base-Catalyzed Reaction of 2 and 3. General Procedure. A solution of an appropriate base (2.5 mmol) in the prescribed solvent (10 mL) was bubbled with nitrogen for 10 min to purge oxygen from the system. To the solution was added the hydroperoxide **2** or **3** (0.5 mmol), and the resulting solution was allowed to stand at room temperature under nitrogen for 2 h. The reaction mixture was acidified with a large excess of cold aqueous NH_4Cl solution and extracted with ether. The extract was dried (Na_2SO_4) and evaporated. Products in the resulting residue were analyzed by ^1H NMR spectroscopy and TLC. Compounds **4–9**, **11**, and **12b** were identical with authentic samples.[1,2]

2,3,5-Tri-*tert*-butylcyclopentadienone (12a). A solution of **3a** or **5a** (0.88 g, 3 mmol) in *tert*-butyl alcohol (30 mL) containing *t*-BuOK (1.01 g, 9 mmol) was refluxed for 30 h with exclusion of moisture. The reaction mixture was acidified with a large excess of aqueous NH_4Cl solution and extracted with ether. The extract was dried (Na_2SO_4) and evaporated to leave an oily residue (0.83 g), which was chromatographed on a silica gel column. Elution with petroleum ether gave **1a** as orange-yellow crystals (0.3 g, quantitative yield based on the reacted **5a**). Recrystallization from methanol gave orange-yellow prisms: mp 53–53.5 °C; IR (Nujol) 1710 cm^{-1}; UV λ_{max} (cyclohexane) 417 (2.67), 220 (3.68) nm (log ϵ); ^1H NMR ($CDCl_3$) δ 1.13 (s, 9 H), 1.32 (s, 18 H), 6.65 (s, 1 H). Anal. Calcd for $C_{17}H_{28}O$: C, 82.20; H, 11.36. Found: C, 81.91; H, 11.31. Elution with ether gave **5a** (0.5 g).

3,6-Di-*tert*-butyl-4-(4-methoxyphenyl)-*o*-benzoquinone (14). From the Base-Catalyzed Reaction of 3b. The reaction mixture obtained from the reaction of **3b** in *tert*-butyl alcohol containing *t*-BuOLi was separated on a TLC plate by developing with a mixture of petroleum ether and CH_2Cl_2 (1:1). Elution of a yellow band (R_f 0.5) with ether gave **14** as red-brown crystals (30% yield). Recrystallization from petroleum ether gave red-brown needles: mp 159–160 °C; IR (Nujol) 1680, 1660 cm^{-1}; UV λ_{max} (cyclohexane) 357 nm (log ϵ 3.6); ^1H NMR ($CDCl_3$) δ 1.08 (s, 9 H), 1.22 (s, 9 H), 3.85 (s, 3 H), 6.57 (s, 1 H), 6.7–7.2 (m, 4 H). Anal. Calcd for $C_{21}H_{26}O_3$: C, 77.27; H, 8.03. Found: C, 77.36; H, 8.09.

From the Acyloin Rearrangement of 7 Followed by Oxidation. *o*-Quinol **7b** was obtained by the reduction of **3b** with Me_2S and employed for the acyloin rearrangement without isolation. Hydroperoxide **3b** (0.17 g, 0.5 mmol) was dissolved in Me_2S (10 mL) at −78 °C and the resulting solution was kept at 0 °C for 1 h. To the solution was added a solution of *t*-BuOK (0.17 g, 1.5 mmol) in DMF (10 mL) over 10 min at 0 °C under a nitrogen atmosphere. The solution was allowed to stand at 0 °C for 30 min. The reaction mixture was acidified with cold dilute hydrochloric acid and diluted with water. Evaporation of Me_2S gave **15** as a crystalline mass (0.14 g, 86% yield), which was recrystallized from a mixture of CH_2Cl_2 and petroleum ether (1:3) to give colorless needles: mp 174–175 °C; IR (Nujol) 3500 cm^{-1}; UV λ_{max} (EtOH) 279 nm (log ϵ 3.5); ^1H NMR ($CDCl_3$) δ 1.27 (s, 9 H), 1.40 (s, 9 H), 3.85 (s, 3 H), 5.38 (s, 1 H, OH), 5.67 (s, 1 H), 6.9–7.2 (m, 4 H). Anal. Calcd for $C_{21}H_{28}O_3$: C, 76.79; H, 8.59. Found: C, 76.75; H, 8.73.

Oxygen was bubbled through a solution of **15** (20 mg, 0.6 mmol) in DMF (1 mL) containing *t*-BuOK (34 mg, 0.3 mmol) at room temperature for 10 min. The reaction mixture was acidified with dilute hydrochloric acid and extracted with ether. The extract gave **14** in quantitative yield, identical with a sample obtained in the base-catalyzed reaction of **3b** (vide supra).

Kinetics of Base-Catalyzed Oxygenation of 1a. Oxygen was bubbled through a solution of **1a** (0.25 M) in a mixture of *tert*-butyl alcohol and hexane (1:1, 100 mL) in a closed system at 20 °C. Aliquots (5 mL) were taken out at 1-min intervals, acidified with cold aqueous NH_4Cl solution (20 mL), and extracted with ether (10 mL). The extract was evaporated and the products were analyzed by ^1H NMR spectroscopy.

Registry No. **1a**, 732-26-3; **1b**, 128-37-0; **1c**, 6257-22-3; **2a**, 33919-05-0; **2b**, 6485-57-0; **3a**, 61077-25-6; **3b**, 60647-21-4; **4a**, 52922-80-2; **4b**, 52922-83-5; **5a**, 55276-86-3; **5b**, 58282-04-5; **6a**, 4971-61-3; **6b**, 10396-80-2; **7a**, 70702-91-9; **7b**, 70702-92-0; **8a**, 1020-31-1; **8b**, 60647-24-7; **11**, 52922-87-9; **12a**, 36319-95-6; **12b**, 58282-06-7; **13b**, 70702-93-1; **13c**, 70702-94-2; **14**, 70702-95-3; **15**, 70702-96-4; **23**, 719-22-2; **24**, 3383-21-9.

(15) M. S. Kharash and B. S. Joshi, *J. Org. Chem.*, **22**, 1439 (1957).